ISEM

International Conference on Industrial Engineering, Systems Engineering and Engineering Management

Proceedings

2 – 4 October 2023

'be the piece'

ISEM 2023

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International Conference on Industrial Engineering, Systems Engineering and Engineering Management

Proceedings

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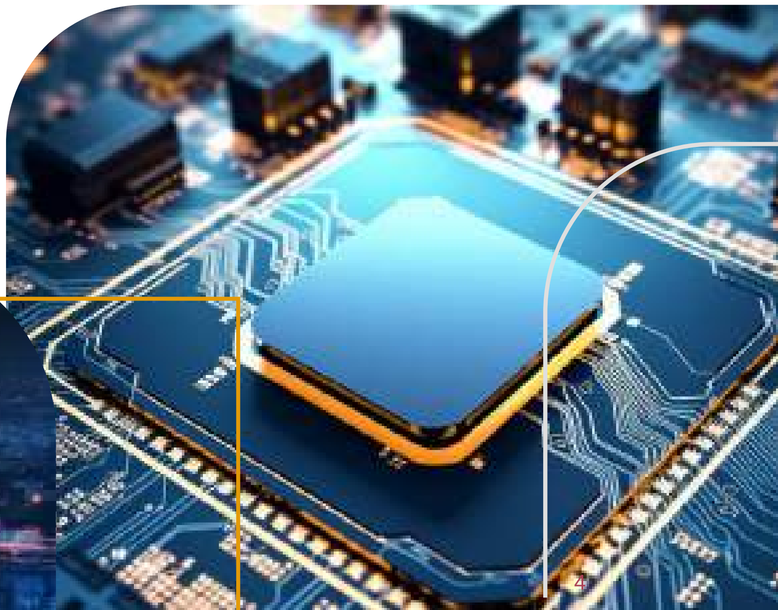

Preface

I am delighted to welcome you to ISEM2023. Some of the older hands in industrial engineering, systems engineering and engineering management may still remember ISEM2011, the first such event jointly organized by SAIIE, INCOSE (SA Chapter) and the University of Pretoria's Graduate School of Technology Management (GSTM) more than a decade ago. This took place at the Spier Wine Estate. With the enthusiasm so prevalent when something new happens it was hoped to organize an ISEM conference every two years. But reality prevailed and it was not to be. Every year following that first ISEM conference "another ISEM" was mooted whenever SAIIE and INCOSE members touched sides. Then, a once in a century global disaster struck. The dark clouds of Covid-19 put paid to any hope repeating the success of ISEM2011. Late one afternoon in November 2021 I received a phone call from Dieter Hartmann now the ISEM2023 Organizing Committee Chair suggesting that we really must do something towards another ISEM. This resulted in an early 2022 meeting, drinking lots of coffee at the dairy farm in Irene - my favourite "business meeting venue" – at which we agreed that the time has come for the next ISEM conference. Now, almost two years later, ISEM2023 is a reality.

In the light of many things happening in our country - good and bad - our theme for ISEM2023 – *be the piece* - is appropriate and fits the immense challenges South Africa face. Especially now that the world is busy building a new puzzle, one in which we all can, and should, play the role of a (puzzle) piece. Incidentally, the early seeds for the ISEM2023 conference theme and logo were planted during another coffee drinking meeting at the dairy farm! (dairy farms have turned out to be truly productive places!).

Back in 2011 ISEM2011 attracted some 120 paper abstracts. For ISEM2023, aware of the fact that the country just emerged from the Covid-19 pandemic and ongoing energy shortages, we hoped to attract at least close to the 100 abstract submissions of ISEM2011. We were pleasantly surprised when, at reaching the abstract deadline, we had 282 abstract submissions! Despite some attrition we still ended with 215 draft full paper submissions. Following a number of withdrawals and a paper review cycle we ended with 146 accepted final papers. These, together with 19 abstract-based presentations, 7 workshops, 1 panel, a number of keynote addresses and social events promise a trendsetting conference!

We invite you to enjoy ISEM2023 in the fairest Cape of them all! And accept the challenge to be a piece in the puzzle!

The submission and review process

For this conference, prospective speakers were invited to submit full papers or abstracts only.

Abstracts for the full-paper track were initially screened based on suitability, with successful authors invited to submit a draft full-length paper. These were reviewed by reviewers from our ISEM2023 Reviewer Panel (121 reviewers), all of whom were carefully selected after an open invitation to experts in the fields of industrial engineering, systems engineering and engineering management. All submitted papers were screened using the Turnitin plagiarism software tool to uphold academic integrity. Submissions that passed this screening process were then reviewed using a double-blind, peer-review process. The review process was managed through an online conference system (Easychair) that allowed reviewers to provide online feedback and recorded all reviewer feedback and editorial decisions taken during the process. All papers were allocated at least two reviewers, often teaming up academics and industry experts to facilitate a true peer-review process. Only papers that passed the peer-review process are published in the conference proceedings. As has become the tradition of SAIIE conferences, the best papers were selected to appear in a special edition of the South African Journal of Industrial Engineering (SAJIE). The selection process of these papers considered reviewer feedback, reviewer ratings and suitability checks by the journal's editor. These conference proceedings contain submissions from 10 of the 11 academic institutions with industrial engineering departments in South Africa. Added to this are 3 institutions who also offer post-graduate programmes in engineering management as well as systems engineering. No institution contributes more than 30% towards the papers published in the proceedings.

A total of 146 full paper submissions were accepted after the peer-review process, by far exceeding the number of conference papers accepted for any previous SAIIE or INCOSE conference. Twenty-four of these papers were selected for the special edition of the journal that will be published separately. As a consequence, these papers were withdrawn from the proceedings. A full list of these papers is included on the next page.

The conference, therefore, has three outputs:

- The ***Conference Event*** This includes an abstract of each paper shared with conference delegates using the online conference app and programme and abstract book. The conference event also includes interactive discussions in parallel sessions, themed by paper topic at the conference.
- The ***Conference Proceedings*** (this document) is an electronic document distributed to all delegates and contains full papers submitted, reviewed and approved for the full paper track. The purpose of the proceedings is to give full open access to the output from the conference. The proceedings are available online via the SAIIE website.
- The **Special Edition of the South African Journal of Industrial Engineering (SAJIE)** will be published in November 2023, honouring the best work submitted to this conference. The Special Edition also contains submissions from other related conferences.

Acknowledgements

To organize a conference as large as this takes many people. It is not possible to name each person but be assured we owe our thanks to each and every one who contributed, no matter how large or small your contribution was – you made a difference. But the following people deserve a special word of thanks:

- Thank you to our authors for sharing your magic with us through this conference. And for truly embedding yourselves as a piece of the puzzle! You make a difference.
- Thank you to our many reviewers whose time, experience and wisdom made a positive contribution to every paper. You truly embody the concept of sharing. Without you it will not be possible for our authors to deliver quality papers.
- Thank you to the sub-editors who administered the review process: Chanel Bisset, Chantelle du Plessis, Hanneke Meijer and Philani Zincume. These four people slaved away behind the scenes for many many hours! Much of your work happened late at night and over weekends. You give true meaning to the word "commitment"!
- Thank you to Chantelle du Plessis for putting together the final conference proceedings and Lynette Pieterse for your tireless administrative support. And of course Teresa Hattingh who always was ready with support and suggestions when needed.
- Thank you to the entire conference organising committee, whose enthusiasm and unwavering standards make the conference what it is.
- And lastly, thank you to Dieter Hartmann who, so long ago, called me to insist it is time for another ISEM, and when the going got tough motivated me to continue amidst late submissions, non-compliance to templates and some reviewers going AWOL! Danke Schön!

I trust that you will find the work presented as part of this conference truly outstanding – welcome to our marvellous engineering world. And remember to be a piece of the puzzle!

Dr Jörg Lalk PrEng

ISEM2023 Editor
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CREATING VALUE USING TOYOTA PRODUCTION SYSTEMS IN A LEADING AUTOMOTIVE MANUFACTURER

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ABSTRACT

Despite research demonstrating the operational benefits of lowering the number of product offerings, manufacturing companies commonly service markets where customers require a wide range of products with various feature options at unpredictable intervals. While lean manufacturing principles have been recognised as enablers of operational excellence in high-volume manufacturing operations, doubts remain concerning the concepts' application in high-mix, low-volume, make-to-order contexts. This project investigates the applicability of Toyota Production Systems within this manufacturing environment. To be competitive, the company must produce high-quality, low-cost goods that fulfil customer standards with short lead times. Using a qualitative research design with a case study analogy and implementing waste elimination, mistake proofing and pull methods, a production cell increased the percentage of sales delivered on time to the customer by 15%.

Keywords: Toyota Production Systems, lean thinking, customer satisfaction

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1 INTRODUCTION AND BACKGROUND

The study was conducted at a company that provides competitive manufacturing solutions to major original equipment manufacturers (OEM)'s and 1st tier suppliers in the South African automotive industry and export markets. A variety of operations are conducted in the company's plant, and they include metal stamping and welding, polymer injection moulding, metalworking, forging, tube bending, synthetic leather stitching, and various surface treatment processes (galvanizing, e-coating, powder coating, wet spray painting), as well as many highly automated assembly processes. The company is currently experiencing major production related problems such high work in progress between the workstations of the e-coating line, inconsistent operation times, frequent machine breakdowns, inconsistent quality of coated products and high overtime cost.

This study was conducted at the e-coating plant and the approach would be to focus on a monthly based study for analysis. A standardized production data collection sheet which is was used to identify problems such as machine breaksdowns, poor productivity on the production line. In order to ensure data validity, physical observations were also conducted.Statistical analysis were also conducted to analyse production related data, including cross tabulation of collected machine downtime data. A cause and effect diagram was used to investigate potential causes of machine downtimes

2 LITERATURE REVIEW

This section of the paper focuses on the literature around the strategies that are commonly used for improving of manufacturing performance and these include the lean philosophy, six sigma, theory of constraints and just in time. These concepts inform some of the recommendations proposed to improve productivity and reduce machine breakdowns.

2.1. The concept of lean manufacturing

The discovery and removal of waste from processes to improve the overall value supplied to the customer are commonly understood principles in the lean methodology. Table 1 depicts the seven wastes as defined by Taiichi Ohno in the Toyota Production System, as well as Liker's definitions in The Toyota Way [1]. High-Mix Low-Volume (HMLV) and Make-to-Order (MTO) manufacturing environments can create a variety of challenges for organisations adopting these principles and removing waste in the production process. HMLV environments must deal with product line cycle time variability as well as increased volatility in demand and delivery dates. An MTO firm, by definition, manufactures solely to client order, but the actual batch size in the customer order can vary significantly. The value stream mapping is particularly complex in MTO businesses due to the enormous number of product lines that must be designed for flow [2]. These variables might make locating and eliminating waste challenging.

Table 1: The 7 Wastes of the Toyota Production System

Waste	Definition
Over-production	Producing ahead of demand
Waiting	Idle for a machine, key inputs, or slack with no deadlines
Transportation	Moving materials or information inefficiently
Over-processing	Performing unnecessary steps in process
Inventory	Excess material, work in process or finished goods

Waste	Definition
Movement	Wasted motion employees perform during work
Defects	Production of defects and correction

Making value-creating steps flow while allowing the client to pull value is risky without expensive inventory. Another operational disadvantage is that the economies of scale associated with bulk ordering are not achieved. According to Biller et al. [3], low-volume commodities usually have poor prediction accuracy, resulting in higher safety stock and higher procurement and shipping costs. All businesses must strike a balance between inventory and service level, but these businesses have a higher percentage of stock keeping units (SKUs) with high prediction error.

Despite the difficulties in implementing lean to the manufacturing process in this setting, there are instances of successful implementations in investigated use cases and useful beginning points to explore for implementation. Mudgal et al. [4], discovered that doing a commonality study based on Bills of Materials (BOMs) and shared sub-processes was beneficial in grouping the various assemblies in an MTO manufacturing environment to comprehend the product families.

Irani [5] categorises classic lean tools based on whether they have proven use cases to decrease waste and increase flow in HMLV contexts. Although Biller et al. [3] does not specifically mention lean methodology, he does highlight two benefits that modular product architecture provides to a production system with a large number of product variations: it requires part standardisation across products to reduce the SKU level.

There are also inventory models that have the ability to reduce inventory waste while still allowing customers to pull value. Most HMLV or MTO firms have stochastic demand at component level, lead times for components are more than zero and the replenishment model is multi-period, indicating that orders can be fulfilled in the next period if there is a backlog. The continuous review policy appears to be more appropriate for this setting than the periodic review model because it ensures item availability at the lowest inventory holding cost level for the items. In general, a continuous review policy improves inventory control since products are tracked instantly during transactions and reordered in optimal quantities only when they reach predetermined reorder points. One significant disadvantage of this strategy is that it can be more expensive to track inventories in real time, although in this case, the organisation already has a system that accomplishes this and procures in the best manner described by this model. As the literature implies, inventory holding costs for HMLV and MTO enterprises can be significant due to fluctuation and service requirements; this type of approach should reduce such costs. There have been studies that showed the usefulness of continuous review policies in organisations facing similar issues, such as an automotive factory with volatile demand and a hospital that provides pharmaceuticals and medical equipment.According to the literature, lean principles and methodologies need care in application, but when used appropriately, they can provide value for organisations functioning in an HMLV and MTO environment.

3 RESEARCH METHODOLOGY

A qualitative approach was used with a case study analogy to gain insight into the daily performance of work using the Gemba walk during working hours. During the Gemba walk, notable observations were recorded, and discussions were held with operators and supervisors to gain an understanding of the current phenomena. These records were critically analysed to identify shortcomings in the process.

Interviews were conducted to gather the necessary information on how the organisation reached its daily production targets. The departmental employees and supervisors were consulted from the beginning of the project, where the aims and objectives of the study were outlined. A sample of 15 operations personnel and five supervisors was consulted on a regular basis to extract the required information on the current performance of the department.

Time study is a work measurement technique used to establish the time necessary to perform a task. Time study was used in this research to find line efficiencies and to determine cycle time and takt time in order to identify bottlenecks in the modification processes. Current processes were analysed to find the root cause of the problems.

Observation through the Gemba walk was used to gather more information and to help identify bottlenecks and areas of improvement, and to gain a better understanding of the processes while engaging with those who do the actual job.

A process flowchart is used in a variety of industries to analyse, create, document and manage a process or programme [6]. In this project, the process flowchart was used to evaluate the movement of the elements of each fitment.

Control charts are used to evaluate a process and to check if the process is stable or needs intervention. These charts are achieved using statistical process control, which is a quantitative approach, or analysing data. An X-bar chart is used to evaluate the averages in order to identify problems relating to the stability of a process to avoid assembling defective products. A cause and effect diagram was used in this study to identify the root cause of the problems faced in the organisation.

4 RESULTS AND DISCUSSION

The data analysis process summarises the information gathered. It entails the use of analytical and logical reasoning to data in order to identify patterns, correlations and trends. In order to provide value to customers, obtain a competitive edge and grow, the company attempted to enhance material and information flows to achieve operational excellence. This project examined numerous aspects of the organisation's operations using Lean concepts, with the ultimate goal of increasing responsiveness to its customers. The key mechanisms for achieving this goal were as follows:

4.1. Lead times for components

Lead times in days ranged from 0 to 60 for these items at the plant for the 12 months ending in May 2022. Customers' expectations of lead times can vary due to variances in the quality of engineering or design that an order requires, the uniqueness of components contained in the product or the perceived differences in assembly hours. This truth has a couple of ramifications for how the production team operates. First, when the customer demand rate is not reasonably steady, it is exceedingly difficult for the organisation to use lean approaches derived from takt time analysis. Furthermore, one can imagine a scenario in which orders with customer lead times of 7, 14 and 21 days all result in the same needed date by the customer, placing a burden on the ability to deliver. Given these circumstances, the organisation can maintain client flexibility by reducing processing times per product.

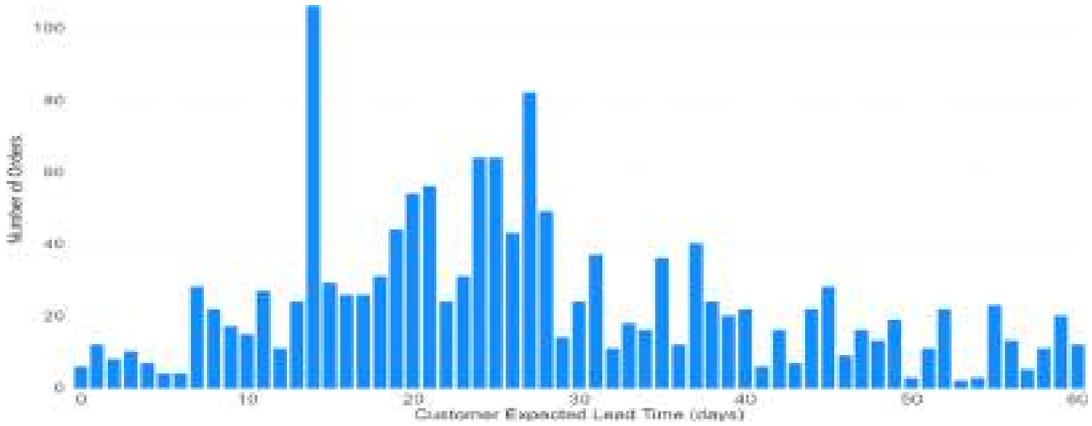

Figure 1: Number of orders by customer expected lead time in days, June 2021 – May 2022, limited to 60

4.2. Commonality based on BOMs

The first step in specifying the product lines is to perform a commonality analysis utilising the BOM data from the client specifications and the business system. Table 2 displays the number of possible product codes and filter housings, as well as the assembled products and unique product codes ordered in the 12 months before 1 June 2022, to offer context for the product diversity and low volume.

Table 2: Characteristics of the product variation and volumes within production cell. The volume and unique codes ordered are from June 2021 – May 2022

Item	Number
Possible product codes	Z212
Possible filter housings	15
Production volume	426
Unique product codes ordered	70

Thirteen of the 15 available filter housings in the customers' design were ordered in the same 12-month period. This mix, as proposed, allowed the classification of the various filter housings as runners, repeaters and strangers, with the actual occurrence of the filter housings among orders given. Upon evaluation of the production steps of the product families, it was discovered that almost 70% of the volume came from four of the top five filter housings that follow similar processes. This helps to appreciate both the mix and the opportunity to focus on efforts to improve.

Two separate pairs of filter housings belong to the same product family because their configurations are identical and safe for the filter housing; however, one filter housing is limited by component size requirements. Aside from the filter housing, the number of available combinations varies by product family, based on the configurations required for system integration. Figure 2 displays the possible configuration choices that allow end customers to choose from hundreds of product codes as an example of how the product family can vary.

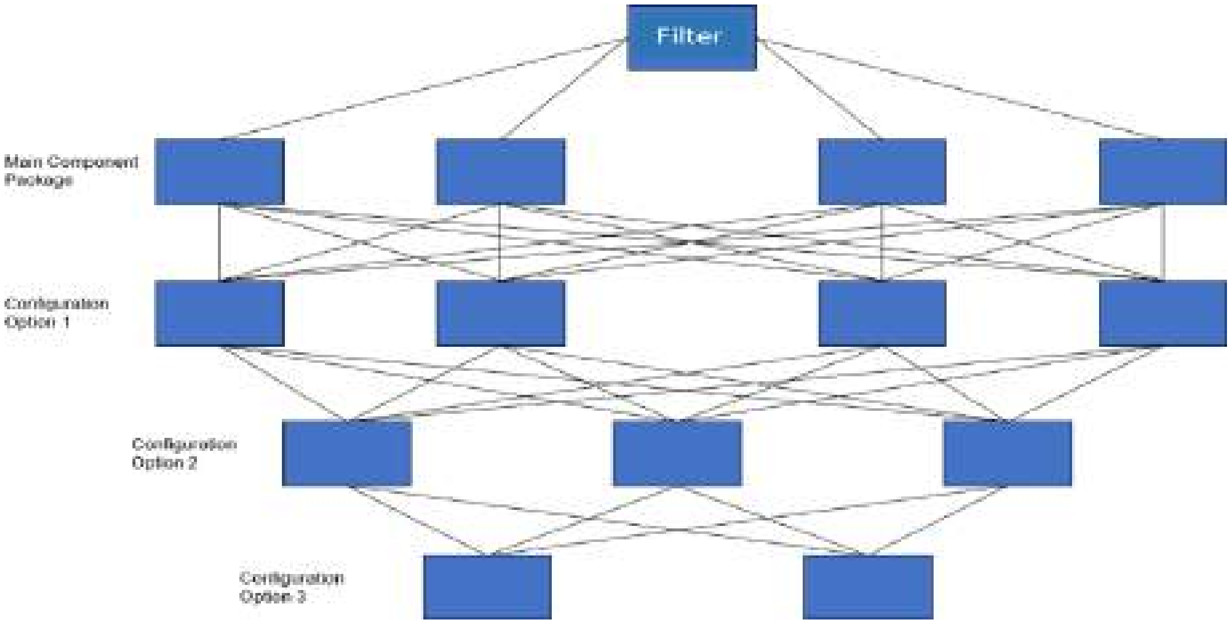

Figure 2: Configuration options for one product family that has 96 end product codes

Upon reflection, it was reassuring to see that of the 13 product families, three accounted for 68% of the volume and ten accounted for 88% of the volume. This depiction of actual production data assisted team members to understand the relative value of the various families in addition to their most recent experience. It also showed that, while variety occurred in the Z212 end product assemblies, genuine variation was less common since certain families were far more popular than others.

4.2.1. Visualising Order Flow

As an MTO company, the organisation provides a product in the form of an assembled filter. This section maps the process flow diagrams connected with the order and product status changes from order receipt to shipment.

4.2.2. Process Flow Diagrams

The organisation combines many of its processes through its business system and has adapted the business system to improve visibility of production progress in addition to the usual order processing. The results show that the flow of the business system standard "order status" processing at a high level. The diagram shows that the majority of the information required to understand the operational procedures is contained in the "Pending Fulfilment" stage, where production takes place [7].

The order is sent to the manufacturing team via the business system, the product is assembled and dispatched, and the sales staff update the business system to reflect the shipment and invoice issuing. The manufacturing process is depicted with the customised "work status" stages.

The business system did not prevent the user from changing the employment status from one status to another; therefore, the paths were the most typical paths based on conversations with employees and observations. In addition, some of these stages could be skipped. Some production cells, for example, employed "New Order" and "Need to Assemble" to sort visibility on forthcoming orders, while others began with "Need to Print Pick Ticket" and progressed immediately from "Parts Pulled" to "In Assembly." Overall, updating an order's job status created a shared understanding among employees across the organisation. It is also worth noting that five of the nine stages that reflect a deviation from the optimum path are related to parts shortages. Because the organisation designated this list of stages, one can deduce that parts availability was a likely source of frustration for the manufacturing crew.

4.3. Production Process Mining

Figure 3 was generated as a preliminary pass to comprehend the quantity of orders that are "In Assembly Waiting for Parts" and "In Assembly" at each window. Figure 3 shows how, at various points, particularly in 2022, orders in production began to encounter increased interruption due to missing parts

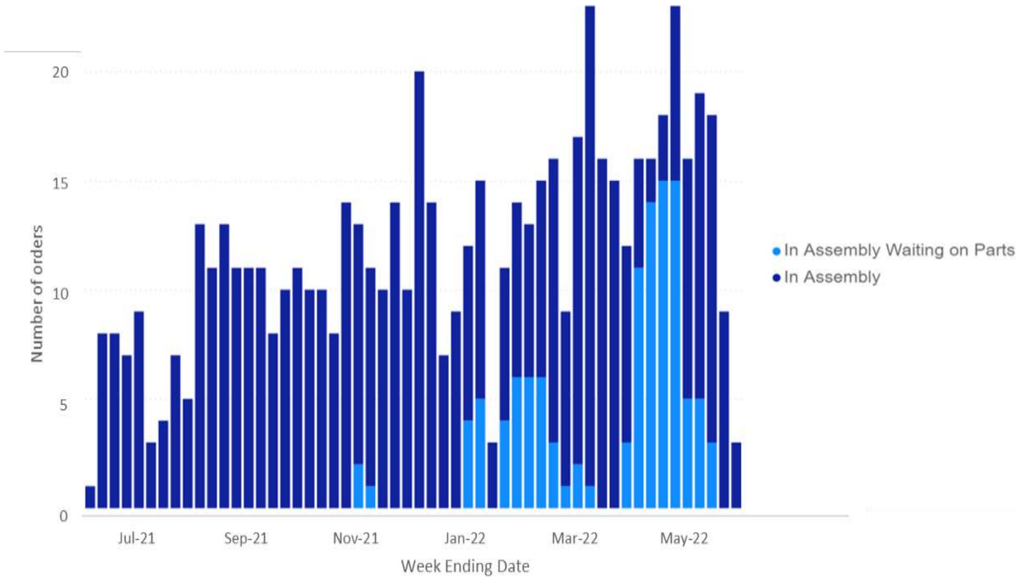

Figure 3: Comparison of quantity of orders in assembly with quantity of orders in assembly waiting on parts, June 2021 – May 2022

Because there were so many distinct end product assemblies that were offered at varying prices, it was critical to assess whether the impacted orders were reflective of the total mix, as opposed to solely affecting orders of lower or higher price. To do this, a ratio indicator that compares the number or value of impacted orders to the total number or value of orders at this point was implemented.

Equation 1 represents this measure.

$$Waiting\ Ratio = \frac{Order\ in\ assembly\ waiting}{Orders\ in\ assembly\ waiting + Orders\ in\ assembly} \quad (1)$$

Figure 4 depicts this ratio in terms of both order quantity and order sales amount. Parts shortages clearly affected sales order amounts, or revenue to be gained, with the same frequency as sales order quantity.

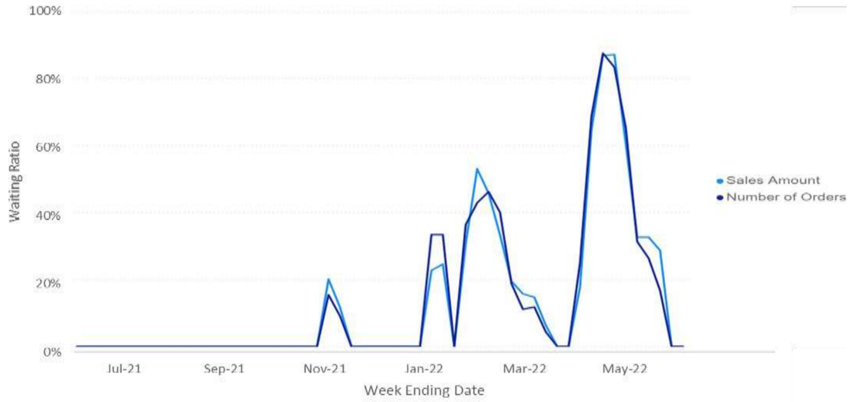

Figure 4: Waiting ratios of quantity of orders and sales amount of orders, June 2021 - May 2022

These numbers indicate that it is difficult to have the proper parts accessible for assembly when needed. Parts shortages have on impact on delivery performance.

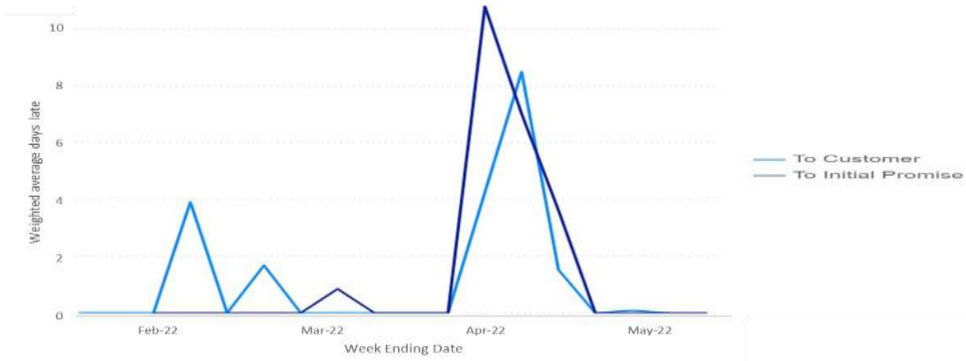

Figure 5: Weighted average days late to want and to initial promise, February - May 2022

4.4. Visualising Material Flow

The spaghetti diagram is a handy tool for visualising how materials move through a manufacturing facility as they are changed from raw ingredients to final goods. In this situation, it will provide a general overview of the material placements within the facility as well as the first steps towards identifying transportation or movement wastes. The spaghetti diagram in Figure 6 uses red lines to indicate the movement of the parts in final assembly.

The cell arrangement within the huge panel assembly area is intended to support U-shaped product flow. Several product families require the installation of components weighing more than 500 kg in the filter housing; therefore, racks of the required sizes are available to allow the rotation and bracing of filter housings, and a top-running crane is used to safely transport heavy goods within the crane area [7].

Estimates of the distance spent on material movement are done by taking into account the fact that these movements require round trips for team members to move to and from the location with material, estimating the number of trips required during production of each product from runner or repeater families, and measuring the distance involved in the movement. Table 3 indicates the results from applying this strategy to the material movements.

It is also crucial to evaluate how the material is stored in the facility and how it is transferred, in addition to where it is stored. Based on the feedback from team members and personal experience, it was discovered that the filter housings, their accompanying pieces and panels, and two of the bigger internal components caused problems for the warehouse team and production cell [8].

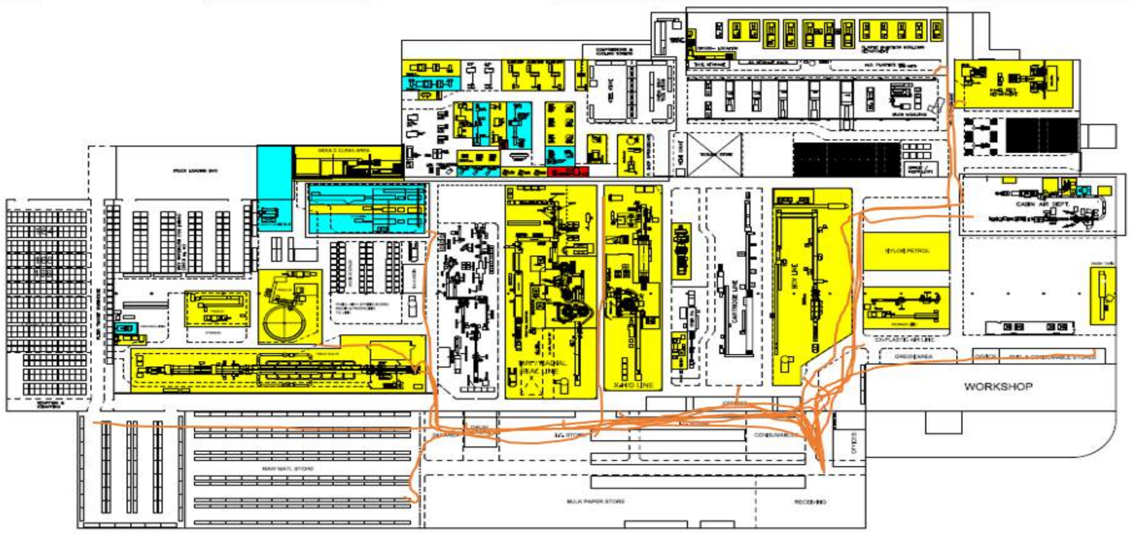

Figure 6: Spaghetti diagram of material movements within the factory

Table 3: Current state of material transportation and employee movement distances for various components common to products from runner and repeater families

Material	Per Product	Distance [m]	Total [m]
Cans	1	150	300
Seals	2	185	740
Washers	1	185	370
Element assembly	1	175	350
Centre tube	1	50	100
End caps	2	220	880
Media	1	40	800
Labels	1	80	160

4.5. Picking, Sub Assembly Production, Testing, and Shipping

The next step in the fulfilment process is to pick the order and gather the necessary components for assembly. Employees from the warehousing department carried out this action after obtaining a picking ticket from the manufacturing cell's team leader. All of the required smaller components were loaded onto a cart, labelled with the matching order information and a status form, and staged in allocated open space in the warehouse room until carried to the assembly area by a member of the production cell. Larger components housed in the storage bay or outside were fetched immediately by production cell members when needed for the order.

Four of the seven product families that were runners or repeaters necessitated the creation of sub-assemblies in different portions of the facility. If a sub-assembly was necessary for an order, the business system created a work order, and the production cell team leader filed a picking ticket to the warehouse section to gather those components. Team members who built the sub-assembly drew the staged cart and assembled the sub-assembly in their work locations. The sub-assembly work for this production cell mostly consisted of cables and smaller filters that were later placed into the bigger filter. Team members from the production cell would pull these sub-assemblies for installation as needed when finishing the final assembly [9].

The final product assemblies were tested for safety and quality by the production cell team leader. When an assembling team member finished the product they were working on, they would transport it to the testing part of the cell so they could start working on the next order. The Quality Management System classified problems into four basic categories: Wiring failures occur when components are not properly connected; connections fail when terminal connections are not secure; component failures occur when incorrect components are used within the product; and label failures occur when labels fail to reflect correct panel ratings or information about the product or components within the product. The team leader offered input on any problems discovered to the team member who assembled the product so that it might be corrected in future for that product and similar items. The quality system used a variety of measures, including panel first pass yield and defect kinds. Figure 7 depicts the production cell assembly error type per month [10].

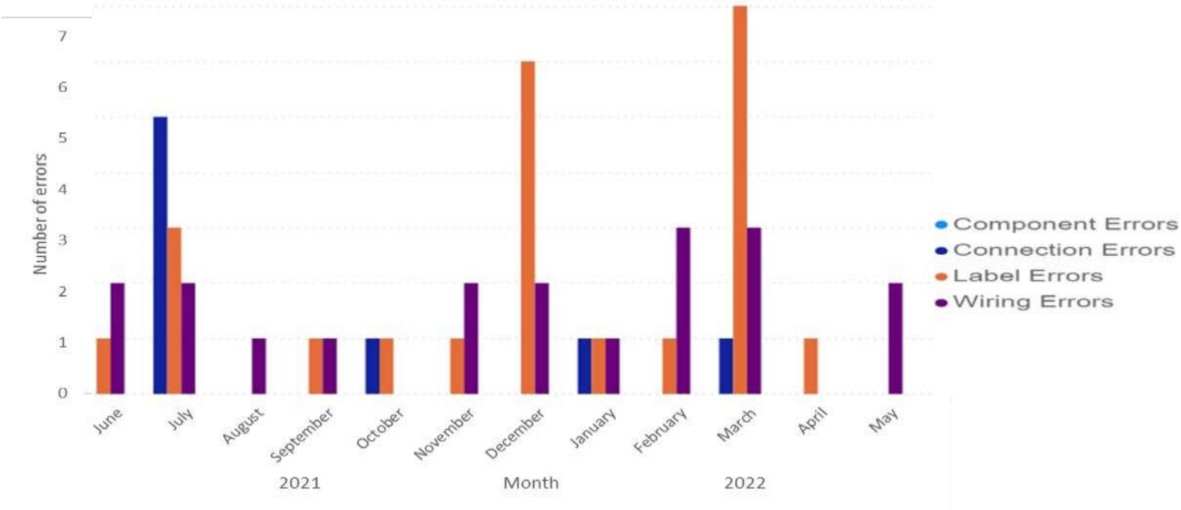

Figure 7: Breakdown of production cell assembly error type per month, June 2021 - May 2022

5 RECOMMENDATION AND CONCLUSION

This research revealed the complexity of the processes involved in the filter industry. Lessons about which strategies are effective as well as the limitations of the methods that the organisation can use were revealed in this investigation.

5.1. Theme 1 - standardisation

The first theme that can be effective across the multiple dimensions of product manufacture was standardising the products and processes as much as is feasible. This enabled the discussion and execution of standard work, reduced time spent due to seeking and enhanced team members' perceptions of operational processes and interactions.

The modular design offered by suppliers was one of the most effective techniques of enabling flexibility and pooling volatility in demand. This decreased the need to handle each order based on its unique requirements rather than a set of known requirements, allowing for advances in capacity and quality. According to the research literature, the supply chain was easier to manage when the parts were shared across multiple product versions.

5.2. Theme 2 – improved service

Improved service levels were experienced by internal and external customers while reducing inventory levels for numerous items with higher holding costs by learning how to extract data linked to lead times and demand and implementing the continuous review inventory replenishment policy. The results show that such a model may be effective in this environment despite the complexity of SKUs and demand.

5.3. Theme 3 – improved information flow

Efforts to improve information flow centred on enhancing access to the information required each team member to make choices and create redundancy in the communication that already occurred between team members. The greater understanding of how their actions affected the value stream boosted team members' skills to make individual judgments that were more helpful to the entire system. These advancements were also aimed at leveraging the business system as the one source of truth, so that each team member could relate to the issue from the same contextual perspective [11].

5.4. Theme 4 – automation

Team members appreciated the relatively basic automation created for the quality it ensured, the annoyance it alleviated and the capacity it added to the operations. The key to this automation was that it was not limited to specific use cases but could be applied to any product variation experienced by the team members. As a result, rather than being regarded as a step with significant setup costs and limited impact, it could become ordinary and standard.

Using data from the business system in process mining assisted in visualising the steps of the manufacturing process and alleviating the shortage of data surrounding the manufacturing processes. This was a workaround, but it might be used in conjunction with a system to track actual production times to better evaluate operational performance.

5.5. Theme 5 - groupings

The whole menu of product variations was understood and characterised by product codes and groupings, which was a vital condition for the deployment of many of the initiatives that enhanced efficiency. This enabled one to structure the analysis around product families, collect and categorise usage data, take advantage of modular design opportunities and automate numerous phases in the process. None of these efficiencies could be reached without product codes or a complete grasp of the number of different configurations, what they have in common or how they differ and what the product family groupings are.

5.6. Theme 6 – data integrity

The inability to track actual production times using business system data and the data integrity underlying the analysis limit the use of the process data analytics. Understanding the lead time or demand characteristics at the SKU location level would have been impossible if the business system had not been a trustworthy source of data for how components flowed in and out of the plant. Further examination of operational performance would be possible if there is continuance to refine which metrics are tracked and how data are recorded.

5.7. Theme 7 - investing in fixture or production automation

Clarifying the influence of machine automation investment on various steps of this manufacturing process is one area for future investigation. Because of the variance and confined places in which most of the assembly happens, the existing method is highly human, and there are several constraints to using fixture automation in this setting. This application potential will expand as robotic technology progresses and machine manufacturers continue to create and produce adaptable solutions. There are only a few case studies involving the effective deployment of machine tools in this type of HMLV and MTO setting with these production restrictions, and this research might benefit from them.

5.8. Theme 8 - information architecture

This study provides basic insights into how data processing can be used to create information architecture for individual team member decision making. There is more opportunity to investigate the implications of ideal information architecture for enterprises manufacturing in this environment and utilising approaches such as Industry 4.0. The applicability of establishing an information architecture throughout the production processes, like other decisions requiring investment in this technology, depends on how effectively the development will handle the mix and volume.

5.9. Theme 9 - replenishment model refinement

The supply chain modelling research revealed the early promise of the continuous review policy in an HMLV and MTO environment, but there is still room to learn about the following stages of supply chain evolution. Aside from simply applying the models presented in a more systematic manner throughout the organisation, there is a strong possibility that one could continue to improve performance at a lower cost by conducting a multi-echelon inventory optimisation analysis within the facility and treating on hand and available inventory as separate demand stages with different characterisations. Additional research into the appropriate length of historical demand to consider in the model best suited for this environment may be conducted [12].

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THE OPTIMISATION OF FOOD SUPPLY CHAIN PROCESSES IN E-COMMERCE RETAILING: A CASE STUDY

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ABSTRACT

The optimization of supply chain processes in the e-commerce retail food distribution environment is critical as it assists in ensuring optimal costs and profit for the companies. Furthermore, identification of bottlenecks ensures that any issues related to meeting customer orders and on time delivery. The increase in demand for doorstep delivery led to an increase e-commerce activity. This study was conducted at organization that had launched in South Africa to meet the increased demand for online shopping. The company experienced frequent complaints related to large quantities of stock being sent back to distribution centers, especially perishable goods such as fruits and vegetables and dairy products. These complaints include stale products, late orders, wrong orders. The cost implications of this have been very high as these products have had to be disposed of due to their low shelf life. The organization concerned is mainly a grocery retail store that delivers basic groceries and basic medication. A qualitative methodology in the form of a case study was employed for the study. The results of the study benefitted the organization in the form of improvements in process capability, brand loyalty, waste reduction and the management of products.

Keywords: optimisation, supply chain optimisation, e-commerce

* Corresponding Author

1. INTRODUCTION AND BACKGROUND

E-commerce can defined as the electronic process by which individuals or organisations buy, sell, transfer or exchange products, services and/or information and it effectively eliminates the need for large investments or outlays on physical infrastructure to develop a global presence, resulting in a revolution in the way in which business is conducted globally [1]. In this sense, e-commerce not only automates the transaction process by eliminating paper and unnecessary steps but also assists in moving organisations into a more efficient manner of operation by going fully electronic and utilising internet of things tools.

The research study was conducted in a start-up tech business in the South African market aimed at meeting the demand of people needing faster delivery services of their orders on essential groceries, fresh produce, medication, and more. The company originally established in one of the developing countries in Asia as a response to the high demand of people needing essentials delivered to their doorstep during the COVID19 pandemic. The company was very successful in its home state and therefore, decided to branch into other markets, which led the company to South Africa. The South African launch was successful, and it saw the company contribute to reducing the unemployment problem faced in the country by employing over 200 South African citizens and going into business partnerships with freelancers and delivery personnel.

The company experienced frequent complaints related to large quantities of stock being sent back to distribution centers, especially perishable goods such as fruits and vegetables and dairy products. These complaints include stale products, late orders, wrong orders. The cost implications of this have been very high as these products have had to be disposed of due to their low shelf life. Various issues ranging from incorrect stock management practices, inventory management at distribution centres, and the incorrect handling of perishable goods (fruits and vegetables) and other customer complaints that have negatively impacted the organization.

The large quantities of stock are being sent to back to the company distribution centres, especially perishable goods such as fruits and vegetables and dairy products. The cost implications of this have been very high as these products have had to be disposed of due to their low shelf life. Figure 1 chart shows a summary of the frequent customer complaints that the business is faced with.

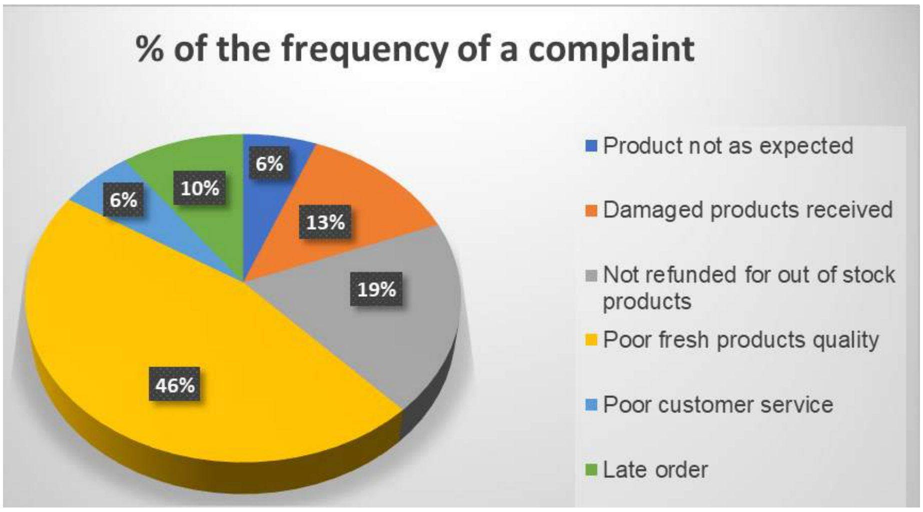

Figure 1: Most frequent customer complaints.

The study was aimed at developing an efficient optimized supply chain process in the e-commerce space and good inventory management practices that will result in businesses providing good and quality customer service. The study objectives include

- Developing a good stock management strategy for an E-commerce tech business to improve product quality.
- improving customer management practices to increase the number of loyal customers.
- reducing management costs

The study is significant because it would be of great benefit to the E-commerce businesses that are being launched in the following ways:

- It will help start-up businesses develop efficient inventory management standard operating procedures.
- It will help start-up businesses in this field determine the most important key performance areas, and how to ensure they excel in them to build a loyal customer base that trusts them.
- It will shed light on the state of the e-commerce business in South Africa and the South African online buyer's behaviour.

Furthermore, this research will help organisations offer customers shorter lead times and lower inventory costs because of optimized processes and improve on-time availability of stock.

2. LITERATURE REVIEW

This section covers the literature around supply chain, inventory management, electronic data interchange, product availability and last mile delivery.

2.1. Importance of supply chain and inventory management

To ensure the efficiency of an e-commerce business, its supply chain processes must be optimised and this can result in enterprises achieving smooth, real-time supply chain integration with a competitive edge [2]. Therefore, the e-commerce applications must be multi-layered and feature rapid decision-making to achieve real-time efficiency. Furthermore, versatile processes with high service levels should be fully linked to the international supply chain. Importantly, processes by which online retailers can achieve higher inventory turnover and just-in-time delivery practices is inventory management. In e-commerce, flexible systems that respond to customer demand and inventory uncertainty are critical [3].

2.2. Inventory management and order fulfilment strategies

Inventory management is a methodical approach to acquiring, storing and selling stock, which includes both raw materials (components) and finished goods. It means the right stock, at the right levels, in the right place, at the right time and at the right cost and price. Inventory management, as part of an organisation's supply chain, consists of elements such as controlling and overseeing purchases (from suppliers and customers), maintaining stock storage, controlling the number of products for sale and ensuring order fulfilment [4].

The primary goal of inventory management in a business is to monitor stock levels so that the business can balance the number of products without running out of stock or ordering products in excess. This is the most effective way to maintain profits while reducing retail waste [5]. The essential elements of inventory management are discussed next.

2.2.1. Traceability

It is very important for business owners to be aware of changes in the movement of their organisations' inventory, from product transfers to inventory losses such as damaged goods or missing products, so that when the time comes, they are in control of matters rather than overwhelmed by irregularities. It is also critical for a business to have detailed inventory management reports organised in one location. Collecting inventory data is important for determining areas for improvement. Therefore, it is essential to record all information available in order to optimise processes.

2.2.2. Stocktakes

Cycle counting is a check-and-balance method used by businesses to ensure that physical inventory counts match inventory records and entails performing regular counts, recording specific product adjustments, and have counted all of their possessions over time [6]. The purpose of cycle counting can then be summarised as identification and correcting any discrepancies in inventory records.

2.2.3. Out-of-stock products

Assisted by detailed cycle count, accurate demand forecast , an organisation may be able to identify which products are missing and which are selling the most, assisting with the determination of the reorder point for stock. This element of inventory management allows businesses to act quickly to remove out-of-stock products from e-commerce platforms, ensuring that they do not sell products that are not available.

2.2.4. Product identification and description

A major part of inventory management is being organised. Businesses should keep clear and informative descriptions, for example, names, sizes and colours, of their products. Without this detailed information, businesses will not be able to fully understand their reports and see the total picture. All products should be clearly labelled or marked so that the products can be identified at a quick glance. This aspect is vital for speeding up fulfilment processes, as well as making sure no mistakes are made when it comes to stock counts.

2.2.5. Storage space

A clean, spacious and well-kept work environment will help to limit the amount of time spent looking for products. According to research, such a work environment may improve the effectiveness of a business and its employees. If the storage or warehousing space of a business is not already well organised, it would be worthwhile to devote time to improving inventory management. There are no flaws in doing so, only pure profit.

2.3. Last-mile delivery

Last mile delivery includes all the activities required for the consumer to receive the items purchased. The last mile is the only point of contact between a customer and a company. The front door has evolved into the new marketplace. Giving shoppers what they want is essential, but providing a consistent experience from order to delivery has become the golden standard for retailers worldwide. Last-mile delivery is an important part of providing a world-class brand experience and keeping customers loyal to a brand. In the last mile, the consequences of poor service are incredibly high. Positive last-mile interaction leads to increased brand equity and loyalty. Last-mile delivery has several cost implications, which include the following:

- Last-mile delivery is estimated to account for 53% of the total cost of moving a product over the first, middle and last miles in delivering it to a customer [7].
- Returns are costly for retailers, especially when one considers the initial delivery cost as well as the return logistics. In addition, some orders that are returned must be reduced in price in order to be resold.

- Given that consumers demand fast and free delivery, online retailers must contend that “free to consumers” does not imply “free to the business”. To keep customers coming back, brands need to absorb delivery costs.

2.4. The last-mile logistical challenges in e-commerce

The final step in the delivery process is logistics. When a customer places an order, the last mile begins. The brand or logistics provider collects and prepares the order for delivery before delivering it to the customer via the method selected [8]. the following last-mile logistical challenges are commonly experienced by online retailers: order picking, order fulfilment and inventory strategies, last-mile delivery strategies, reverse logistics and delivery service quality. Most major retailers have storage facilities that are solely devoted to fulfilling online orders. The first step in ensuring that a customer's order is filled is order fulfilment process [9].

2.4.1. Order preparation and picking

Inventory management entails managing stock-keeping units (SKUs) in such a way that an online retailer can fulfil online orders in advance of consumer demand, which can be easy for dependent demand but difficult for independent demand. The main challenges that are encountered in order preparation and picking are as follows:

2.4.2. Substitution

Substitution entails having a variety of options that customers can pick from in case the items they want are out of stock. This is one of the biggest challenges most South African online grocery stores and omnichannel retailers face because, in such instances, the pickers do not know what items the customers would prefer as replacements. Start-ups, in particular, do not have the resources to have substitution built into the back end of their online applications. Methods of order picking can range from manual in-store picking to fully automated picking processes. Picking processes have significantly improved over time because of automated replenishment methods, improved order preparation methods and optimal vehicle utilisation [9].

2.4.3. Sensory quality

Sensory quality pertains to the quality of products that is difficult for consumers to evaluate online, particularly in the case of perishable food items that must be refrigerated. Groceries are touchable and perishable items, making the online evaluation of items, particularly items that are not enclosed in product packaging, more difficult.

Customers are generally sceptical of a retailer's ability to choose the best quality on their behalf. Grocery purchases involve physical interaction with products, implying that people would prefer to check the condition of items before purchasing them. It is thus clear that a big disadvantage of e-commerce entities that sell groceries is that they limit the sensory observation of products [9].

2.4.4. Order fulfilment

To be competitive in the e-commerce industry, it is important for an organisation to determine the methods of order fulfilment that will best suit its business structure. The products and the services that the organisation will sell to the public represent the main factor that will determine the best techniques to use.

The geographical market is another important factor to take into consideration in determining which order fulfilment methods to use. Online grocery retailers can use distribution centres and existing stores, partner with traditional grocers or offer a pick-up service to deliver products to customers. To achieve fulfilment, omnichannel retailers use a variety of strategies; however, food retailers tend to structure fulfilment and last-mile activities in-house, whereas non-food retailers are more likely to collaborate with external logistics providers.

2.5. Quality Management in the food retailing supply chains

2.5.1. The cold chain and customer expectations

Online retailers need to ensure that they meet the requirements of cold chain distribution, and that cold stock gets delivered to customers in a good and condition. Customers are frustrated and unhappy when they have to wait long before being served. Customers prefer a service that is flexible, on time , with correct quantities, reliable and customer-service orientated.

2.6. Reverse logistics

Among the main challenges that online grocery retailers face in the food industry is product return. Owing to the perishable nature of food products, they have expiry dates and require quick and effective distribution operations. Because of the unique characteristics and the perishability of certain grocery products, coupled with difficulty in tracking non-barcoded products, reverse logistics is extremely difficult. Product returns in an online food supply chain are even more complicated because it is simply not profitable for online grocery retailers to incur additional costs to collect food items that cannot be reused.

2.7. Electronic Data Interchange

Organisations use electronic data interchange (EDI) to bring trade online and this entails using computer technology to exchange information (or data) electronically [10]. EDI optimises the efficiency of a business by streamlining processes and improving the flow of information within the organisation. The advantages of implementing EDI in a business include:

- Reduced operating costs owing to the elimination of manual activities and unnecessary or non-value-adding processes
- Improved efficiency owing to streamlined processes
- Improved accuracy
- Greater visibility of supply chain activities
- Improved security of the organisation’s intellectual property
- Better business management processes

In EDI, data are structured according to a particular configuration that is recognised by both exchangers, allowing computers to exchange relevant information without human involvement or the need to re-enter details at both ends of the path [11]. The main components of EDI are:

2.7.1. Standards of EDI

EDI standards offer ways of encoding data to facilitate electronic transmissions. The exchange of electronic documents or data takes place in a ready-made format agreed upon by the two parties to the transaction. Great efforts have been made to develop such standards at the international level.

2.7.2. The software for EDI

The primary function of EDI software is to convert and format data and to send messages. A practical program is one of the most important and fundamental infrastructures for electronic commerce [11].

2.8. EDI Communication services

Communication services send and receive transmission files from and to trading partners directly or through a value-added network (VAN) [12]. A VAN is a telecommunications network that is primarily intended for data transmission but also processes data; as a result, the network provides services that go beyond simple data transmission [11].

2.9. Types of e-commerce businesses and EDI

E-commerce businesses can be categorised into different types based on the type of relationship between different sides of commerce [13]. The types of e-commerce businesses are as follows:

Table 1: Types of businesses in the e-commerce space

Type of e-commerce business	Description
Business-to-business (B2B)	Manufacturers that sell to distributors and wholesalers that sell to retailers are examples of companies that do business with one another. Pricing is determined by the number of orders placed and is, in many instances, negotiable.
Business-to-consumer (B2C)	Businesses that sell to the public fall in this category. They use catalogues and shopping cart software.
Consumer-to-business (C2B)	In the case of C2B, consumers post their work online with a set budget, and companies review the consumers' requirements and bid on the projects within hours.
Consumer-to-consumer (C2C)	In the case of C2C, customers make use of sites offering free classifications, auctions and forums where individuals can buy and sell their products.

3. RESULTS AND FINDINGS FROM THE STUDY

The results obtained using the method specified in the previous section are presented in this section. The first part of the findings deals with data obtained from historic company performance reviews. It dissects the company's order fulfilment process in relation to its efficiency and its contribution to cost implications in respect of product disposals owing to poor stock management. The second part of the findings focuses on the observations made by the researcher. The researcher made observations on stock management and reporting, the management of perishable goods, the training of employees and the utilisation of standard operating procedures (SOPs). The third part of the findings reviews the performance of the business in terms of customer management and the number of complaints received. This section also identifies and discusses the different types of service failures within last-mile delivery. It quantifies the data with a view to giving insight into the effectiveness of the relevant department and identifying opportunities for improvement. The fourth part of the findings relates to the results from the researcher's interviews and group discussions with the different members of the team.

3.1. Inventory Management – Performance Reviews

3.1.1. Order fulfilment

Data were collected regarding the amount of stock received by one of the organisation's 13 local distribution centres located in the north of Johannesburg, Gauteng, South Africa. The specific distribution centre (DC) services areas such as Sandton and Rosebank. Figure 2 indicates the amount of stock the DC received as against the amount of stock that was disposed on the same day, demonstrating the typically happens within the organisation's DCs on a daily basis. Almost all the stock that is received back to the distribution centre is disposed as it has reached its end of life.

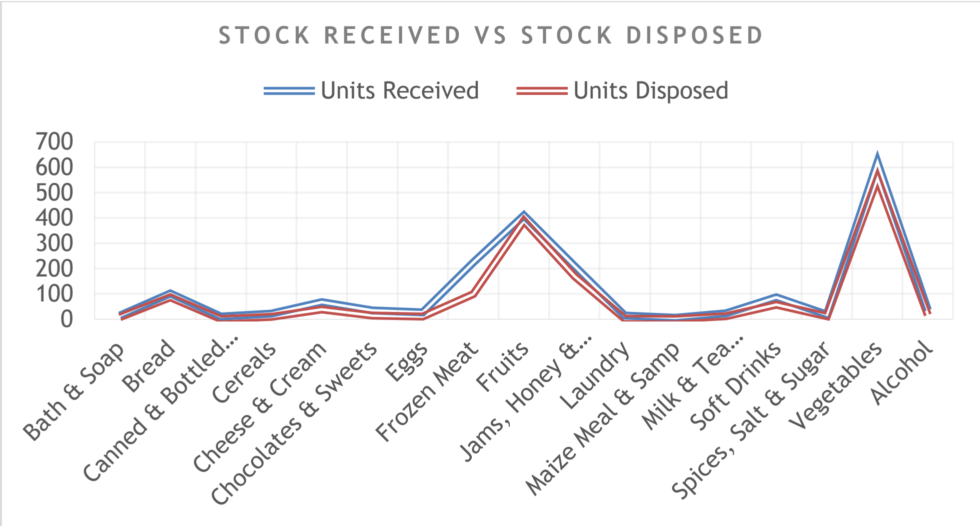

Figure 2: ***Stock received vs stock disposed at a certain distribution centre in Johannesburg***

Having either too much or too little inventory leads to a waste of money. Whether a business does not order enough stock or overorders stock, it could place itself in financial jeopardy if it does not have the right amount of inventory [14]. The pie chart below is a direct representation of the cost implications of the above-mentioned disposals at the DC.

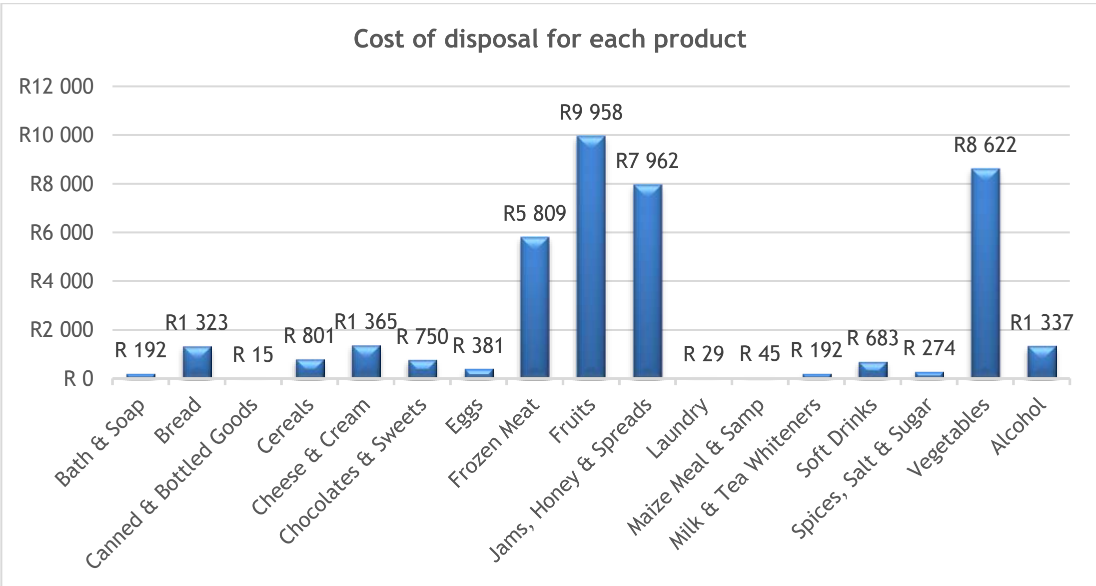

Figure 3: The cost implications of disposals

3.2. The Researcher's Observations

3.2.1. Inadequate stock-on-hand/out-of-stock report

The organisation has an enterprise resource planning (ERP) system that can be used to download stock data, but the report does not show exactly what each DC requires. Consequently, a lot of manual work is required. Supervisors and managers must, for example, indicate what products are needed at the DCs, what products they sell the most of and what new variations of certain products they need. As a result of so much manual work, human errors occur, leading to unnecessary stock being sent to distribution centres. Such stock takes up space and represents a waste since it is unutilised inventory.

3.2.2. Manual addition of stock to the ERP system

This practice is the result of every shipment being sent to distribution centres that have extra items that are not included in the systematic purchase orders used to receive the items. When stock is sent from the central mid-fulfilment centre, that centre is supposed to create purchase orders for all the DCs to use when checking in the stock. This procedure promotes the traceability of, and accountability for, each item checked into a DC. However, owing to the manual activities that the organisation performs, the mid-fulfilment centre ends up adding items that are not on the purchase orders and ships them to the distribution centres. The distribution centres are then required to check in these items ad hoc. Items checked in ad hoc are problematic because it is difficult to investigate an item that does not have a purchase order or any form of documentation as to why it is in the warehouse.

3.2.3. Management of perishable goods (fruit and vegetables)

The management of fruit and vegetables is an area that requires improvement and continuous monitoring. As per the data provided above, fruit and vegetables account for the largest portion of losses that occur as a result of disposals. It was observed that perishable items are not stored in the correct way at the DC. Fruit and vegetables are kept in a very cold area, which results in them rotting within the first two to three days of their arrival at the DC.

3.3. Training of employees

The warehouse operators require continuous refresher courses owing to regular system updates, the behaviour of employees and how quick they are to grasp new concepts.

3.3.1. Interviews with store managers and live operation leads

Store managers and live operation leads were interviewed to determine their views of the organisation's operations and policies. The main findings of the interview sessions are as follows:

- Platform integrity issues with the customer app vs the picker (dark store) are not coordinated for some products. As a result, the wrong items are picked for customers in some cases. This situation leads to increased operational costs at the warehouses because customers must either be credited or provided with exchanged items.
- The riders lack customer service etiquette, which leads to customers having unpleasant experiences in the last mile of delivery. This aspect directly contributes to whether a client will return to the business or not.
- Most of the riders are demotivated because they believe the income they split with the company is not a good deal. This leads to them not being on their best behaviour when they make deliveries, which harms the company's reputation directly. They would like a tip option added to the organisation's app.

- The training of store operators is not sufficient. The operators are sourced through a third-party agency, which is believed to have offered the people sent to express warehouse basic training on stock management, as the service level agreement. This has proved not to be the case – when the employees arrive at the dark store, they lack skills such as the ability to perform daily quality assurance checks, basic stock counting skills and the ability to use a digital scanner. As a result, the company receives orders for out-of-stock items, and products that are not of a good quality and that have packaging defects are picked.
- Owing to outsourced marketing resources, most of the dark stores are not living up to their potential because people are unaware of the availability of the service in their area.
- There are no standard operating procedures. The operators are supposedly trained by the agency they come from. However, upon their arrival at the dark stores, they are not familiar with the process to be followed, making it difficult to identify gaps in the process.
- There is a lack of live visibility of the operation; the ERP system only updates after 12 to 24 hours.

4. DISCUSSION

The findings of the study clearly indicate that there is a large market for e-commerce in the country in that the numbers presented show that customers do, indeed, buy from online grocery retail outlets. The most important aspect of the study is that it identifies gaps in the processes of the organisation that was studied. The organisation needs to implement measures to optimise its operations to be able to meet customers' expectations. The company's status as a start-up in South Africa might be a contributing factor to its current non-value-adding activities or inefficiencies, given that it is still in a phase of self-discovery and the solidification of its position in the country and on the African continent.

The company does not have SOPs, making it very difficult to identify opportunities for improvement or to determine who needs what training to be able to reach a desirable level of performance. This is why issues related to platform integrity are the leading causes of complaints received by the company. Employees do not have a standard to follow and merely perform tasks as per their contracts or offer letters.

From the literature review it is evident that the topic under investigation is fairly new to the South African market since there are gaps in the extant literature. This is something that became more popular during the COVID-19 pandemic, that is, from late 2019 to early 2022. The government restrictions forced citizens to use online modes of shopping.

The findings of the study will give South African online grocery retailers a better understanding of their customers' online grocery needs and service quality expectations. Based on the findings, online grocery shopping is still in an early stage of becoming a profitable business model.

Many factors were identified as contributing to a low level of confidence in online grocery shopping. Among these factors is order picking, in that consumers are still not confident that pickers will select the correct quality of perishable goods. Moreover, the return of goods may be an inconvenience for consumers, and consumers are not always able to receive their orders in person OR consumers are not always present to accept the delivery of their orders?. All these factors present an opportunity for retailers to capitalise on potential market opportunities that can help build consumer confidence while increasing their market share.

Consumers have high expectations regarding the level of service they receive based on their willingness to pay for delivery services. Meeting high service level expectations at a low cost poses a significant challenge for service retailers. Retailers should consider offering free delivery for orders exceeding a certain value as a way of increasing online orders.

this study provides valuable information for any retail company looking to increase its market share through a better understanding of consumer needs and expectations regarding online grocery shopping. These findings can help guide the development of grocery retailers' business strategies. The findings of this study also add to the limited information that the country has on the e-commerce industry, particularly the food and grocery sector.

5. RECOMMENDATIONS

5.1. Developing Standard Operating Procedures

A standard operating procedure is a set of written instructions that describes the step-by-step process that must be followed to perform a routine activity correctly. To ensure that an organisation remains consistent and in compliance with industry regulations and business standards, SOPs should be followed the same way every time. This will eliminate or reduce the level of complaints received, in that all departments will know what is required of them. From the platform integrity team to the delivery team, all the elements of the process will be noted. Every team member should sign an acknowledgement of the SOPs to show that they understand what is required of them.

This approach offers the following advantages:

- There could be a reduction in the number of complaints resulting from a lack of quality assurance because everyone will know how to perform quality assurance checks.
- There could be a reduction in instances where the wrong items are packed into customers' orders because the platform integrity team will have an SOP that gives step-by-step instructions on how to add an SKU to the app.
- Reporting on metrics could be improved, in which case it would no longer be necessary to wait 24 hours for management to refresh the app to see performance.
- The team will know how to conduct weekly cycle counts and daily stocktakes to ensure that the physical stock matches the customer app to prevent orders for out-of-stock items.
- Training provided to the store operators will help to create an efficient operation.

The use of SOPs has two major advantages: consistency and a reduction in the number of errors made. SOPs can also assist an organisation in evaluating employee performance, saving time and money and creating a safer workplace. Furthermore, SOPs can help to improve communication throughout an organisation. If a task changes, the relevant SOP is updated and redistributed to everyone who uses it, allowing the organisation to communicate the change to everyone who is affected in an efficient manner. SOPs also reduce the possibility of misunderstanding because the detailed steps leave little room for debate or questioning.

The implementation of SOPs may help an organisation by

- improving the efficiency of the operation
- helping improve management of the operation and employee training activities
- helping ensure the organisation produces reliable results
- aiding in the identification of areas for improvement
- improving internal communication
- helping with the implementation of a stock-on-hand reporting system

5.2. Developing Business Management Policies

It is general knowledge that customers manipulate systems once they figure them out. It is therefore very important to develop business management policies that clearly outline the procedures for a returned item, an exchange, a refund and the crediting of a customer's account.

5.3. Review the supply chain process

Steps for reviewing the supply chain process of online grocery retailers such as the organisation that was included in the study are as follows:

- On the basis of identified challenges, problems and bottlenecks, review the supply chain process on a high level to come up with a process that is optimised and saves the organisation money. Review the last mile of delivery to be able to provide riders with a market-related income split as the organisation's external logistics providers.
- Review the order fulfilment process and identify areas for improvement.
- Improve the cold chain of the organisation. From the above findings it is evident that a leading cause of customer complaints is the quality of perishable products and frozen meat.
- Optimise the digital scanners and have them linked to the platform integrity app or system.
- Implement daily stock-on-hand reporting to be able to track out-of-stock goods and to establish reorder points from the demand trend.
- Keep a stock-on-hand report or an out-of-stock report that reflects the fast movers in a certain DC, the rate of sale of products and a formulated reorder point to be able to manage the amount of each SKU being sent to the warehouses.
- Implement a delivery schedule plan in relation to stock availability and product rate of sale.

5.4. Improve online platform integrity

Steps for improving the platform integrity of the website of an online grocery retailer such as the organisation that was included in the study are as follows:

5.4.1. Creating a multilingual site

Having a multilingual site would promote diversity and inclusion, given that South Africa is a multicultural nation. Most customers would prefer being spoken to in their mother tongue. A connection is made with customers when they are communicated with in their own language. When it comes to e-commerce, the likelihood of making sales is higher when customers are communicated with in their mother tongue. Translating a website into different languages would not require much work, and the potential advantages of doing so are immense. Since the present markets are already saturated, making a website multilingual would aid in an organisation's exploration of new markets.

5.4.2. Improving the quality of product photographs

A high-quality picture can speak a thousand words. The best way to grab people's attention is by using appealing images. Every online store should make an investment in dependable, premium images. Images reassure online buyers and help them find the products they are looking for. E-commerce companies should take advantage of the visual nature of the world.

5.4.3. Adding a live chat option for customer support

A poor customer care experience results in the loss of a customer. The presence of a live chat option helps to convert browsers into customers of an online store. Customers are more likely to make purchases from an online store that provides online chat and support options, according to research.

5.4.4. Making site navigation better for simpler product searches

The navigation and the layout of a website must be consistent. A website must be simple to navigate and straightforward for users. An online store could lose clients because they cannot find products on its website and leave the site thinking the store does not carry those products. How simple it is for a visitor to find a product on an online store's site depends on the layout of the main website and the flow of products. In the case of a multilingual website, it is preferable to develop a landing page where customers can select a preferred language. The wording and the vocabulary used on a website should be consistent.

5.4.5. Optimising the site for speed

An online store can improve customer experience by optimising the speed of its site.

5.4.6. Focus on food safety

Many retailers focus on promoting food safety since e-commerce is growing and accounts for a relatively high share of overall sales, especially in the light of the shifting fulfilment landscape. Retailers will be compelled to modify their fulfilment procedures in order to comply with the requirements for food safety.

5.4.7. Reduce Capital Expenditure

While automation and micro-fulfilment facilities have their uses, most merchants will continue to run their businesses by using their physical locations as e-commerce distribution centres. Operating models will be developed that assist merchants in lowering capital expenditures and scaling up swiftly to meet surges in consumer demand, without having to set aside a sizable amount of space for order staging. As far as space is concerned, it is common practice for merchants to convert underperforming sites into dark stores in order to enable online orders.

5.4.8. Increase payment options

Many South Africans will continue to grapple with unemployment and underemployment during the economic recovery. Online stores should increase the payment options they offer by introducing, for example, non-fungible tokens or cryptocurrency, thereby opening up online purchasing to a rapidly expanding market segment

5.5. The future of e-commerce in South Africa

The value of e-commerce operations in South Africa is expected to increase by 150%, to R225 billion, by 2025 because of a significant shift in consumer behaviour and expectations brought about by COVID-19 unprecedented events [15]. First National Bank (FNB) has seen average e-commerce spend grow by 30% year-on-year during the first half of 2020 compared to 2019, whereas physical spending declined by 12% year-on-year during the first half of 2020 compared to 2019. The above statistics clearly indicate the growth that the country has seen in the e-commerce sector. It is therefore of the utmost importance to continue educating online retailers about this emerging market and to find ways of competing in it successfully to contribute towards the economic growth of the country.

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APPLICATION OF QUEUING THEORY TO AN AUTOMATIC TELLER MACHINE AT A SELECTED SHOPPING CENTRE IN GAUTENG PROVINCE OF SOUTH AFRICA

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ABSTRACT

Queuing is a common insight in the banking industry. The high demand for the use of Automated Teller Machines (ATMs) has posed some significant problems which includes poor service facilities and delivery which remains an unavoidable cause to the long waiting queues, poor service patterns which in turn affects queue discipline, and poor service delivery at the shopping centres in South Africa. This study describes the application of queuing theory designed to support the decision-making process by the banks to meet the demand. The study demonstrate how well queuing models can be applied to analyse and understand the behaviour of the queues particular in the banking sector. Considering our findings, we are of the view that there is a significant need for efficient ATMs service facilities and awareness of the benefits of automated teller machines to improve the adoption of a cashless policy in South Africa.

Keywords: automated teller machine, queuing theory, process optimization, industrial engineering

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1 INTRODUCTION AND BACKGROUND

The high demand for the utilisation of Automated Teller Machines (ATMs) in shopping centres has posed some significant challenges which comprises poor service facilities and delivery which remains an unavoidable cause to the wastage of customers' time, lengthy waiting queue discipline and poor service delivery which could result in poor service facilities affecting the overall bank performance. ATM machines can perform extra functions such as money transfer and cell phone recharge [1]. South Africans continue to use the most popular applications for bill payment, cash withdrawals and balance enquiries. Thus, the physical movement of currency is reduced, compared to regular bank visits [2]. The adoption of ATMs has brought major challenges to the banking industry in terms of risk exposure and long waiting times. Several studies have been carried out on the effect of ATMs on the performance of deposit money banks in South Africa with different conclusions and results [3]; [4]; [5]. These remain factors to the perception of consumers about the ATMs and their banking companies. The need to see how the ATMs can be more efficient and speedily servicing consumers has prompted this study to be conducted.

Queues are part of our daily lives and are one of the most inconvenient aspects of modern life. Queues are formed as a result of an increase in service demand. if a service facility is unable to fulfil the customer's service within a certain time frame, the client will require excessive time to receive service [6]. Customers often dislike having to wait for a service. Consumers frequently regard time-saving and convenience as two of the most essential reasons for acquiring a good service.

The world has witnessed an upsurge of ATMs instruments meant to facilitate trade and simplify payments [7]. Bank customers had to walk long distances to do transactions of all kinds. They had to queue up and spend hours to talk to a teller to make their transactions and inconveniences were caused by these long queues [8]. New information technology (IT) is turning into the most important factor in the future development of banking, influencing bank's business goals and marketing strategies. Information development comprises the data that a banking business makes and uses, similarly as a wider extent of more composed advances that communication of data offers [9]. Computerisation of consumers' accounts and information recuperation, store and withdrawal ATMs permit access to accounts from any Bank are generally examples of information advancement for Banks. The usage of ATMs makes financial transactions more convenient. As a result, it is not a surprise that the use of ATMs has grown in most South African shopping centres. The ability of a business to sustain and retain existing customers is more important than gaining new ones.

2 LITERATURE REVIEW

2.1 Concept of Queuing Theory

Queuing can be defined as a line of entities waiting to be assisted [5]. A queue occurs when a customer or an entity arrives faster than they can be served. Queuing theory can be described as the study of waiting lines. Queuing theory is one of the quantitative analysis techniques that is used to analyse queues [1;7]. Queuing theory is applied in situations where decisions need to be made to reduce waiting times with the least amount of investment [3]. Queuing models are used in a situation where a waiting line criterion is met. A waiting line criterion is met when a waiting line consists of the components of waiting line.

Queueing systems are simplified mathematical models to explain congestion. Broadly speaking, a queueing system occurs any time 'customers' demand 'service' from some facility; usually both the arrival of the customers and the service times are assumed to be random. There are four assumptions made when using the queuing model: 1) customers are infinite and patient, 2) customer arrivals follow an exponential distribution, 3) service rates follow an exponential distribution, and 4) the waiting line is handled on a first-come, first-serve basis

[11]. An ATM allows customers with credit or debit cards to carry out basic banking transactions without the aid of a human bank teller. Customers can use them to withdraw cash, and check their balance. Card readers, cash dispensers, PIN pads, receipt printers and monitors are some of the basic hardware components that go into all ATMs. Many ATMs also have components for wireless connectivity, check scanning, or even dispensing gift cards [11].

2.2 Multichannel Queuing Model -M/M/S MODEL

Queuing model is essential to decision making predominantly on how to manage queuing systems in the most effective and efficient manner. The queuing theory and the most-widely used model is the M/M/s model which is the single line, multi-server, single-phase model assuming there are 's' identical servers, the service time distribution for each server is exponential, and the mean service time is $1/^{\mu}$ [5];[10]. Further to this, Multichannel queuing systems mean when there is more than one counter to serve the same service to a different customer.

ATM Transaction Model:

The Queuing or waiting line is commonly labelled as M/M/c/K, where first M represents Markovian exponential distribution of inter-arrival times, second M represents Markovian exponential distribution of service times, a positive integer (c) represents the number of servers, and K is the specified number of customers in a queuing system [10].

M/M/1 queuing model:

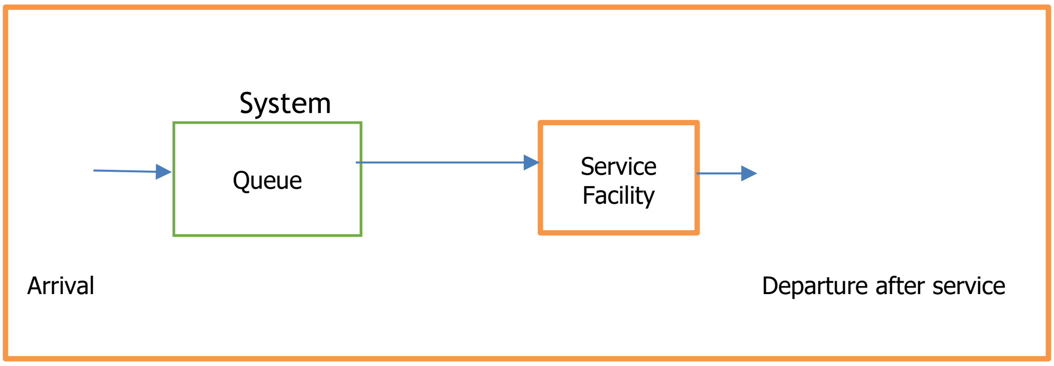

Figure 1: M/M/1 queuing model

M/M/1 queuing model means that the arrival and service time are exponentially distributed (Poisson process). For the analysis of the cash transaction counter M/M/1 queuing model, the following variables will be investigated:

λ: The mean customers arrival rate

μ: The mean service rate

$\rho = \frac{\lambda}{\mu}$: utilisation factor *(1)*

Probability of zero customers in the ATM: *(2)*

$P_0 = 1- \rho$

The probability of having customers in the ATM: *(3)*

$P_n = P_0 \rho^n$

The average number of customers in the ATM: *(4)*

$L_s = \frac{\rho}{\ } = \frac{\lambda}{\ }$

$1-\rho \qquad \mu-\lambda$

The average number of customers in the queue: *(5)*

$$L_q = L \times \rho = \frac{\rho^2}{1-\rho} = \frac{p\lambda}{\mu-\lambda}$$

W_q: The average waiting time in the queue: *(6)*

$$W_q = \frac{L_q}{\lambda} = \frac{\rho}{\mu-\lambda}$$

W_s: The average time spent in the ATM, including the waiting time *(7)*

$$W_s = \frac{L}{\lambda} = \frac{1}{\mu-\lambda}$$

Now, the study discusses the same for M/M/s Model

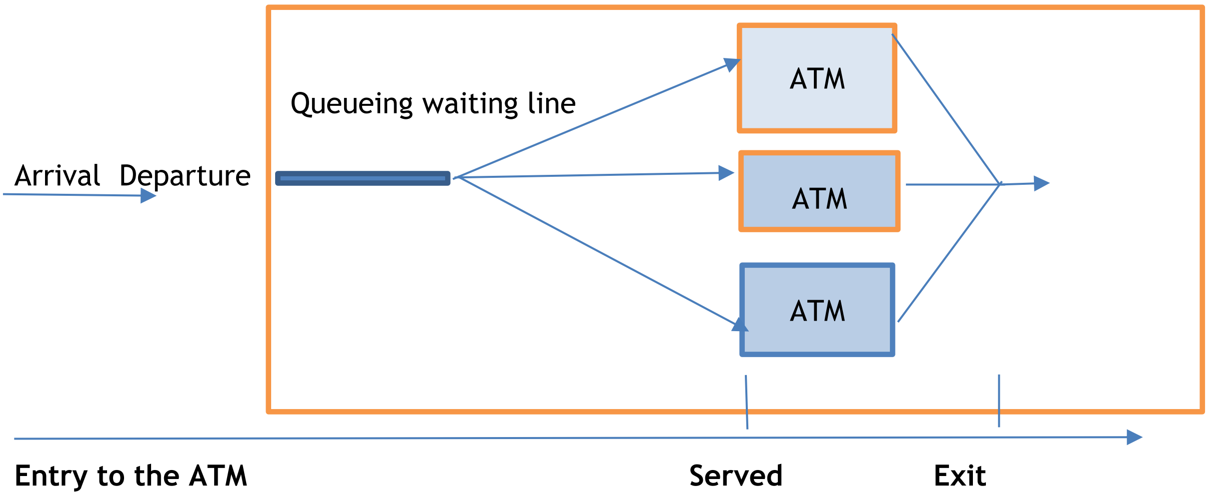

Figure 2: Single-Line, multi-server, single-phase model

The assumption that determines the parameters of the queuing model depicted in Figure 2 is subject to the following:

a) The customers' arrivals at the ATMs are random rather than schedule;

b) The customers' arrival time is unlimited or infinite;

c) Customers are service in the order they arrive and apply a notion of first come first serve (FCFS);

d) Customers arrive independently of each other and follow the Poisson distribution model;

e) Service times can differ from customer A to customer B, and are independent of each other and to note that customer A may have different service needs and times).

3 RESEARCH METHODOLOGY

3.1 Research Approach

A quantitative research approach was adopted to collect data, and analyse and answer the research questions. Furthermore, literature was reviewed to ascertain the current knowledge and data available on the effect of automated teller machines in the South African shopping centre. Participants from ABC Bank ATMs shopping centre consumers were selected using purposive sampling. The adoption of quantitative data analysis helped to turn raw numbers into meaningful data through the application of critical and rational thinking [12]. According to Creswell [13], quantitative data analysis may include the calculation of frequencies of variables and differences between variables.

3.2 Data collection

Data for this study were collected from ABC Bank in South Africa. The methods used for data collection were personal interview and observation by the researchers. Data were collected for two weeks. The following assumptions were made for queuing system which is in accordance with the queue theory. They are:

a) Arrivals follow a Poisson probability distribution at an average rate of customers per unit of time.

b) The queue discipline is First-Come, First-Served (FCFS) basis by any of the servers. There is no priority classification for any arrival.

c) Service times are distributed exponentially, with an average of customers per unit of time.

d) There is no limit to the number of the queue (infinite).

e) The service providers are working at their full capacity.

f) The average arrival rate is greater than average service rate.

g) ATMs here represent cash transactors.

h) Service rate is independent of line length; service providers do not go faster because the line is longer.

A set of both open ended and closed end questions were developed prior to the interview with the bank's consultant [14]. The questions were:

- How many days in a week does the ATMs operating?
- What are the operating hours for the ATMs?
- On average how long does a customer take when using the ATM?
- Do you have ATM statistics (how many people use the ATMs for an hour/day)?

For this study, the optimum number of ATMs in the Bank, two opposing costs must be considered in making these decisions: (i) Waiting time costs of customers and service costs. Economic analysis of these costs assists the Bank management to make a trade-off between the decreased waiting time costs and the increased costs of providing better service of customers from providing that service.

Expected Service Cost E (SC) = SC_s

Where, S =number of ATMs, C_s =service cost of each ATM

Expected Waiting Costs in the queue E (WC) = $(\lambda W_s) C_w$

Where λ = number of arrivals, W_s = Average time an equal spends in the queue

C_w = opportunity cost of waiting by customers

Adding (1) and (2) the study has,

Expected Total Costs E (TC) = E (SC) + E (WC)

Expected Total Costs E(TC) = SCs + (λW_s)

Other instruments - A watch was used to record the time. A clipboard and pen will also be used to assist with the data collection.

3.3 Data Analysis

The appropriate research design for the study had to be the one that addressed the 'what' and 'how' exploratory questions as unambiguously as possible in order to understand the concept of automated teller machines, the application of queuing theory using simulation tool in the South African shopping centre [15].

3.3.1 Customer Arrival and service rate

The average customer arrival rate in the system was computed based on the observation data [16]. An arrival distribution was determined and graphically displayed. A Poisson distribution was used to model the arrival distribution. The service rate at this point is the time it takes a customer to use the ATM.

3.3.2 Simulation Modelling

The queue system was simulated on Arena software to determine: a) the average number of customers in the queue b) average time customer spends waiting c) probability of waiting d) system utilisation factor.

3.3.3 Forecasting tool

The forecasting tool is populated on Microsoft Excel, and it consists of the moving average, weighted moving average, exponential smoothing and regression methods [17]. The actual hourly arrival rate was captured into the different models to measure the model's accuracy [11]. The accuracy of the model was tested using the different measures of accuracy methods. The results for each forecasting method were illustrated using a table and graphs. The following measures of accuracy methods were be used:

- Mean absolute deviation (MAD)
- Mean Squared Error (MSE)
- Mean absolute percentage error (MAPE)

4 RESULTS AND DISCUSSION

The ABC Bank had two ATMs and the first ATM handled withdrawals. The second on handled both deposits and withdrawals. Service time distribution for depositors and withdrawers was μ = 4 minutes/customer. The arrival rate for the depositors was λ =15/hour. The observers or researchers have assumed the opportunity cost of waiting by customers as Rs.1.6 per minute or Rs. 1/hour, as depicted in Table 1.

Table 1: Service time distribution for depositors and withdrawers

Performance Measures	For withdrawers (per hour	For depositors (per hour)
Arrival rate (λ)	16 customers	20 customers
Service rate (μ)	22 customers	22 customers
E (Service Cost)	Rs. 600	Rs. 600

Performance Measures	For withdrawers (per hour	For depositors (per hour)
E (Waiting Cost)	Rs. 250	Rs. 390
E (Total Cost)	Rs. 850	Rs.990
E (Grand Total)	Rs.1840	

If both the ATMs handle withdrawals as well as deposits, the following results are obtained using M/M/s model:

Table 2: Performance measures

Performance Measures	s=2
Arrival rate (λ)	36 customers
Service area (μ)	44 customers
E (Service Cost)	Rs. 1200
E (Waiting Cost)	Rs. 575
E (Total Cost)	Rs. 1775

The results show that optimal server level is achieved when both the ATMs handle deposits as well as withdrawals with a minimum total cost of Rs. 1775 per hour against the present total cost of R1840 per hour, as depicted in Table 2.

4.1 Verification and Validation of the Model

By definition, verification is the process of making sure the model operates as anticipated, based on the assumptions made during the modelling process. It is iteratively checking that the results of each stage in the construction of the simulation model meet all the criteria set forth by the preceding stage. Validation is making sure the model acts exactly like the real system. Validation entails ensuring the simulation model is developed in a way that represents the real system [1]; [7].

4.2 Verification and Validation Techniques

Historic data was used to validate the simulation model. The simulation results were compared with the collected historic data. Single entities were allowed to enter the model and proceed to go through the system. The results were monitored to ensure that the model data and logic is consistent and correct [5].

5 CONCLUSIONS AND RECOMMENDATIONS

The queuing characteristics at the ABC bank were analysed a Multi-server queuing Model and the waiting and service costs were determined with a view to determining the optimal service level. The results of the analysis indicated that the average queue length, waiting time of customers comprising the total cost could be reduced when the customers make deposits and withdrawals at the ABC bank ATMs. Th bank managers can recognise the trade-off that must be considered when dealing with the cost of customers waiting time and the cost of providing better service. Service cost rises as a business tries to increase its level of service, and the cost of time spent waiting on the line reduces. Thus, adding more ATMs in the same shopping centre could help optimise the operations of the ABC bank. Exploring on improving operational efficiencies and service quality through process improvements. Monitor/quantify the customers who leave the queue due to the length and waiting time. Hence, further studies can be conducted focusing on all ATMs from various banks in the same shopping centre, and the concept of online and mobile banking can be adopted in order to gather data will help to improve banking industry.

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USING A3 METHODOLOGY TO HIGHLIGHT CHALLENGES IN AN E-COATING PLANT

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ABSTRACT

Due to the nature of the research problem, this study focused on the application of A3 Methodology to investigate the root-cause to poor performance at an E-coating plant. Preliminary observations showed that there were too many complaints from the production management team regarding the poor performance of the production line. The selection of this method allowed the researcher to collect numerical data to examine the application of the methodology. Qualitative data was used to collect and analyse data in terms of the favourability of the approach. The investigation showed that the A3 methodology can be used as a methodology to improve processes in the production environment. The results of this study ratified that the e-coating plant is performing below the target due to process variations in the production line and constant monitoring of the production area is required to highlight problematic issues.

Keywords: industrial engineering, A3 methodology, process optimisation

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1 INTRODUCTION

The organization is a 3rd generation family business that has been providing competitive manufacturing solutions to major OEMs and Tier 1 suppliers in the South African automotive industry and export markets for approximately 50 years. The manufacturing facilities in Pietermaritzburg, KwaZulu-Natal, and Rosslyn, Gauteng, South Africa, produce a wide range of components using a variety of manufacturing technologies. Supplying some of the world's leading automotive companies requires world-class standards and a focus on continued competitiveness is driven daily.

In addition to metal stamping and welding, the organization encompasses a variety of manufacturing technologies to meet the needs of customers and products. Within the departments, the company offers polymer injection molding, metalworking, forging, tube bending, synthetic leather stitching, and various surface treatment processes (galvanizing, e-coating, powder coating, wet spray painting), as well as many highly automated assembly processes.

The pre-treatment process involves 13 tanks for cleaning the material and takes 38min. Pre-treatment is the first step of the process. This is where metal is cleaned and a phosphate is applied to prepare the surface for application of the e-coat. This process is significant to attaining the performance requirements anticipated by product customers. Electro coating applications use paint particles suspended in a fluid bath [1]. The process occurs as the metal part is dipped into the bath or paint tanks which allow these paint particles to mix and build up on the entire surface of that part which will form an even continuous, low-profile film.

2 LITERATURE REVIEW

2.1 Time studies and Capacity planning

Many companies still prioritize the application of work study when solving capacity planning problems. Work study is a universally accepted technique that includes method studies and work measurement to improve production effectiveness or productivity of the organisation by completely highlighting waste and unnecessary operations [2]. This technique is useful to identify non-value adding operations by looking at all the factors affecting the specific work performed [3].

2.2 Kanban boards:

The Kanban is a continuous improvement technique of materials handling in production that ensures a strong interrelationship between the assembly line or production line and the production support departments. The work Kanban is a Japanese version for visual record or visible documentation in English.

The Kanban which are represented as the production orders are collected in a box and it is called Kanban board. The board is completed comprise of a number of columns for each product and then separated into 3 different zones [4;5].

• There’s a Green Zone: This represents the highest production cost also means ahead of production. It has a low attention for following up to it which means it is a safe zone.

• There’s a White Zone (or Yellow): This represents production is normal. It receives the same attention as the green area, however it is a warning signal, and it cautions that are slowly about to be falling into the red zone arms.

• There’s a Red Zone: This zone represents an emergency and signals crucial production. This will immediately give an alert that there is a stock out for that specific product and means that instant container refill is required when the machine is available.

2.3 Gemba Walks

A Gemba Walk is a technique mostly used by a management team whereby they take a walk in the production line with the aim of observing and understanding how work either from the operators or the production supporting system is being performed [5]. Gemba is another word which is drawn from the Japanese word that is Gembutsu, and its English version means a real thing or real place [6].

A Gemba Walk has different elements to its function and the elements are:

Observation – This is watching the production team perform their tasks in-person.

Location – This is observing the production team at the actual location where their duties are performed.

Teaming – This is interacting with the production team performing the work.

The Gemba Walks approach offers an up-close, complete view of behaviours in action and also considered as useful tools for pinpointing process improvement opportunities and new possible ways to support the responsive team. This proves to be an effective method for the company's management to see how their active teams are demonstrating agile values [7].

2.4 A3 Methodology Evaluation

One of the most important ways to gather the necessary information to provide an effective solution is the A3 methodology. The A3 methodology was developed by Toyota in the early 1960s as a technique for problem solving and continuous improvement. In order to gather the necessary information and provide effective problem solutions, one of the main practices for identifying and solving problems is the A3 methodology, which originated from the systematic production of Toyota Motor Corporation [8].

In recent times, the pressure on the manufacturing industry to seek to run operations more efficiently has increased rapidly. Organizations realize that in order to help their organization achieve its goals or objectives, they need to improve their entire workforce [9].

The A3 report begins by identifying the problem, determining the current state of the process, determining the cause of the problem, determining how to solve the problem, evaluating improvements and determining the effectiveness of the process. The application of the A3 problem-solving process demonstrates the applicability and payoff of the approach in manufacturing [10].

Process reorganization and improvements have also increased the efficiency of assembly line balancing. The A3 technique was standardized so that it could be used for future improvement projects since it played an important part in the project and allowed for the monitoring of the efficacy of the various improvement activities undertaken [10]. In their never-ending quest for continuous development, Toyota has spent many years developing and perfecting this skill [11].

3 RESEARCH METHODOLOGY

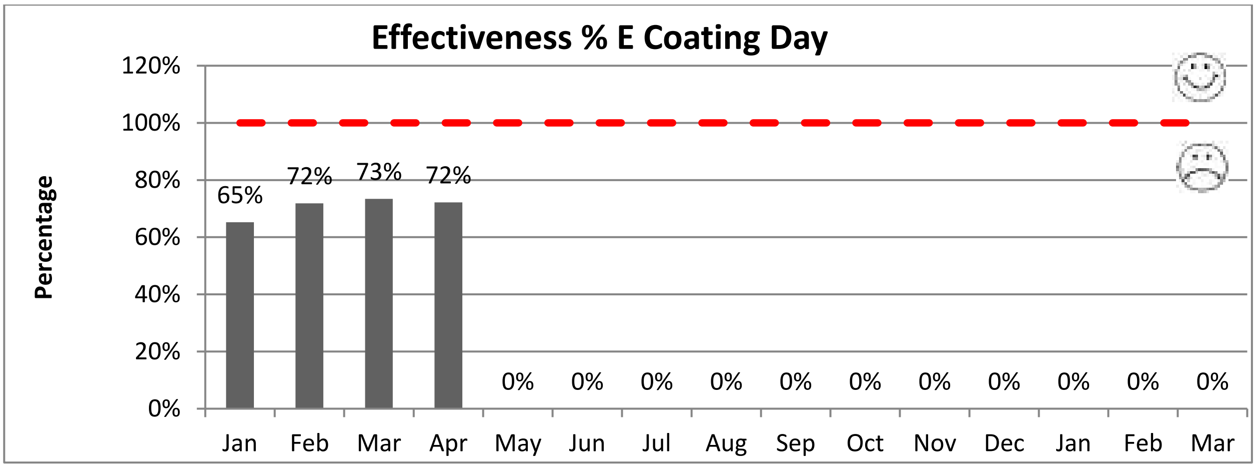
This research was conducted at an E-coating plant in Pietermaritzburg and the approach was based on a qualitative approach using case study analysis as a primary means of data collection. Direct observation using work-study principles were used to gather information from the production environment. Current data was collected through the recordings from production system. There's a total of 35 operators for the line, 4 for the Offline cleaning process (2 dayshift and 2 nightshift), 17 for the powder coating process (9 dayshift and 8 nightshift) and last is the 14 for the e-coating process (7 dayshift and 7 nightshift). The study is mainly focused on the 14 operators which would rotate weekly according to their production shift schedules.

4 DISCUSSION AND FINDINGS

4.1 Dayshift data collection and analysis

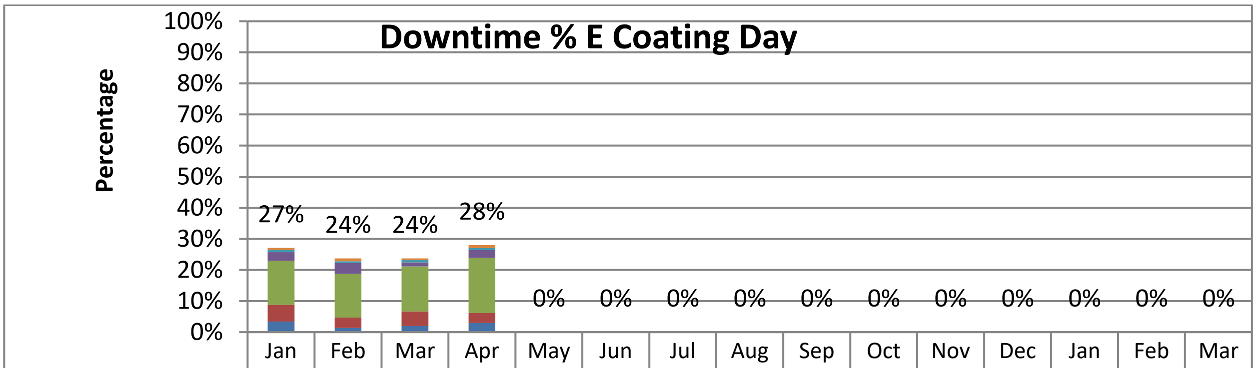
This primary data of the ethnographic study was captured using the production data collecting sheet was taken from the historical data of January, February, March and April which is the. The table below depicts the monthly trend of the E-coating production performance which shows that on average the dayshift does not reach the production target by at least **29%** compared to the **100%** target performance.

Table 1: Monthly E-coating production performance (Effectiveness %): Day - Shift



Following from the above effectiveness table is the Downtime percentages of the dayshift team which shows that on average the monthly percentage trend is **25%** with the highest downtime under Process with **18%.**

Table 2: Monthly E-coating production performance (Downtime %): Day - Shift



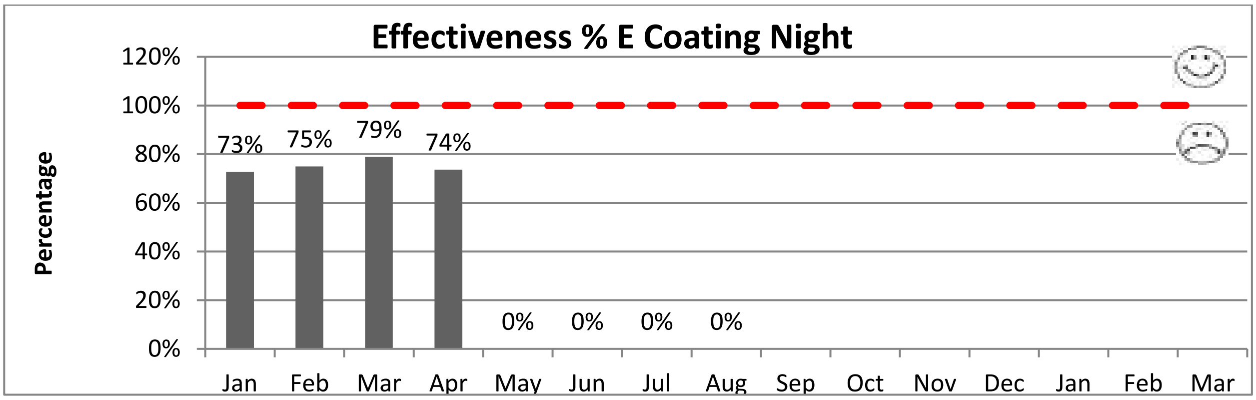
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
C/O %	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Rejects %	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Material %	3%	4%	1%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Process %	14%	14%	14%	18%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Machine %	5%	3%	5%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Man %	3%	1%	2%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Total downtime %	27%	24%	24%	28%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

4.2 Nightshift data collection and analysis

This primary data of the study was captured using the production data collecting sheet which was taken from the historical data of January, February, March and April which is the primary data of the study captured using the production data collecting sheet. The table below depicts

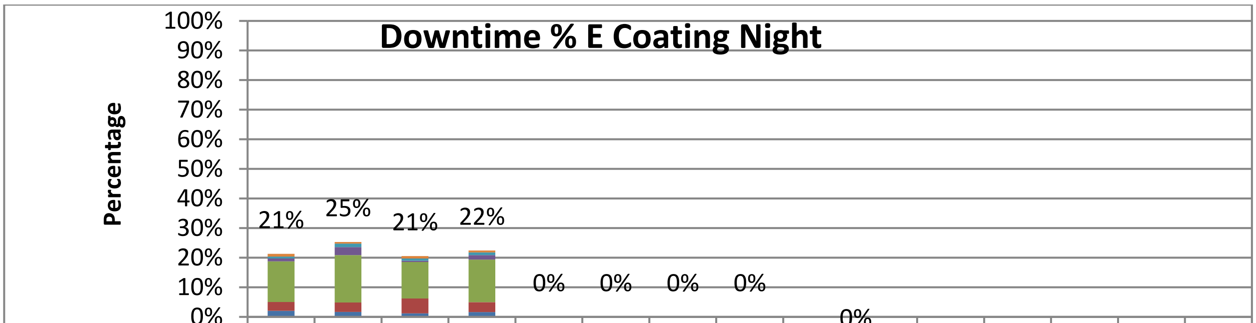
This process performance shows that on average the nightshift is at least **25%** below from reaching the **100%** target performance.

Table 3: Monthly E-coating production performance (Effectiveness %): Night - Shift



After studying the effectiveness table below is the downtime percentages of the nightshift team which again shows that on average the monthly percentage trend is **22%** with the highest downtime under Process with **14%.**

Table 4: Monthly E-coating production performance (Downtime %): Night - Shift



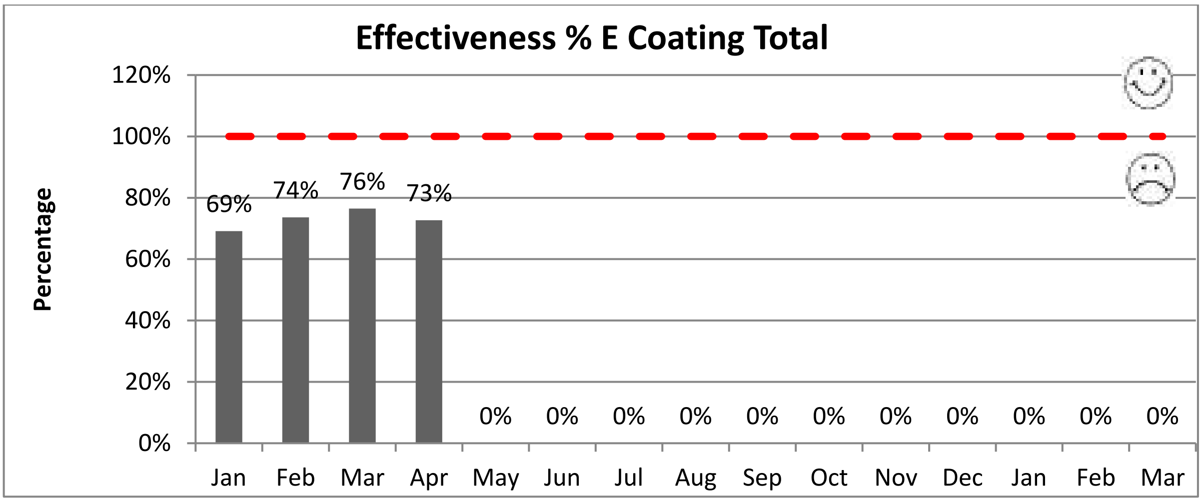
	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
C/O %	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Rejects %	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Material %	1%	3%	0%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Process %	14%	16%	12%	14%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Machine %	3%	3%	5%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Man %	2%	2%	1%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Total downtime %	21%	25%	21%	22%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

4.3 Dayshift and Nightshift data collection and analysis

When rating the total performance of the department, both dayshift and nightshift data is combined which is what gave a true reflection of the E-coating production performance. Normally the individual shifts data is separated for discussions during the shift's morning meetings whereby the shift-leader would be highlighting areas of improvements with the team in preparations to the Gemba Walks [12;13].

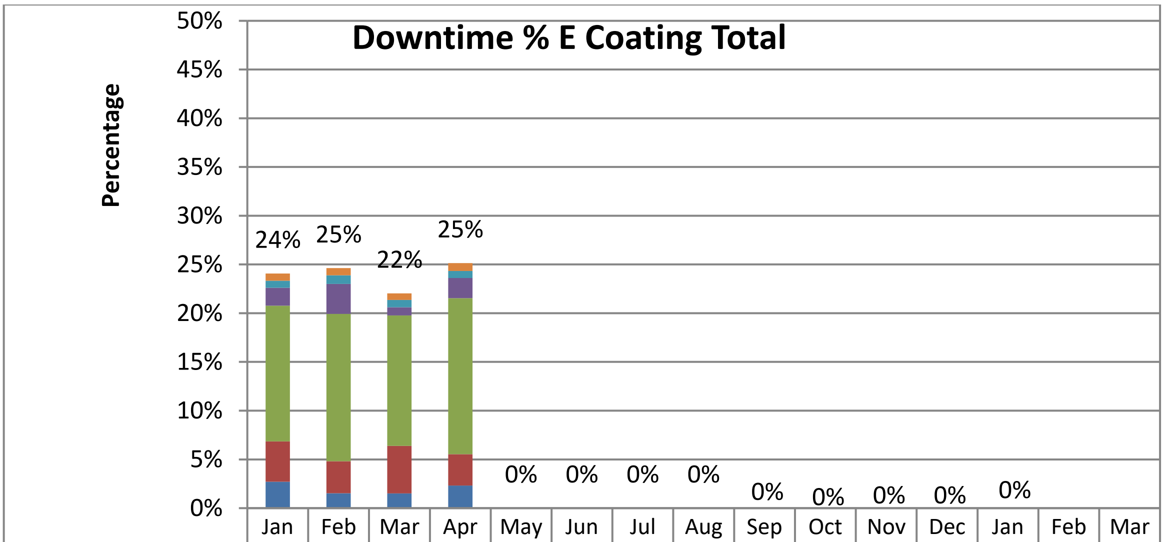
This is the continuous data from the individual shifts to show the combined results of the monthly trends for the 4 months. The results reflect that on average the department is at **27%** below from reaching the **100%** target performance.

Table 5: Monthly E-coating production performance (Effectiveness %): Day & Night - Shift



The below table reflecting the monthly trend for downtime percentage of the combined shifts, shows that on average the monthly percentage trend is **24%** with the highest downtime under Process with **16%.**

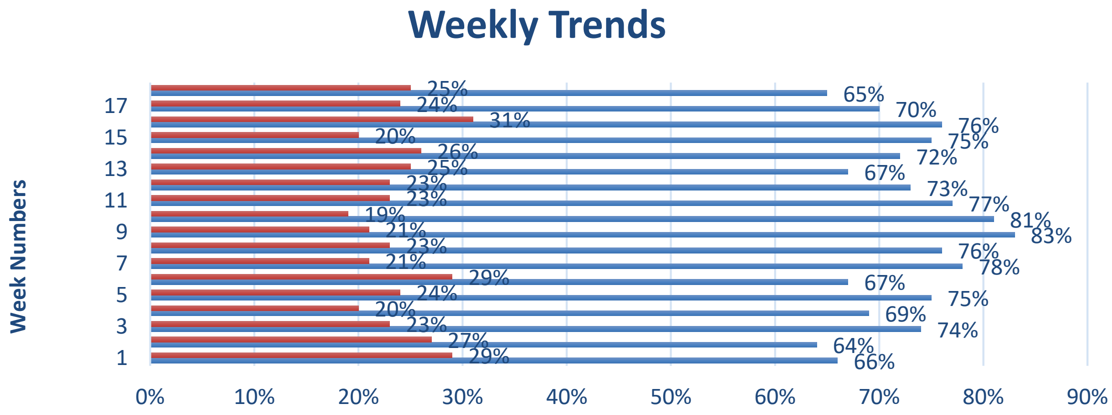
Table 6: Monthly E-coating production performance (Downtime %): Day & Night - Shift



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar
C/O %	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Rejects %	1%	1%	1%	1%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Material %	2%	3%	1%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Process %	14%	15%	13%	16%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Machine %	4%	3%	5%	3%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Man %	3%	2%	2%	2%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%
Total downtime %	24%	25%	22%	25%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%	0%

A3 Template

Table 7: Weekly effective and downtime trends



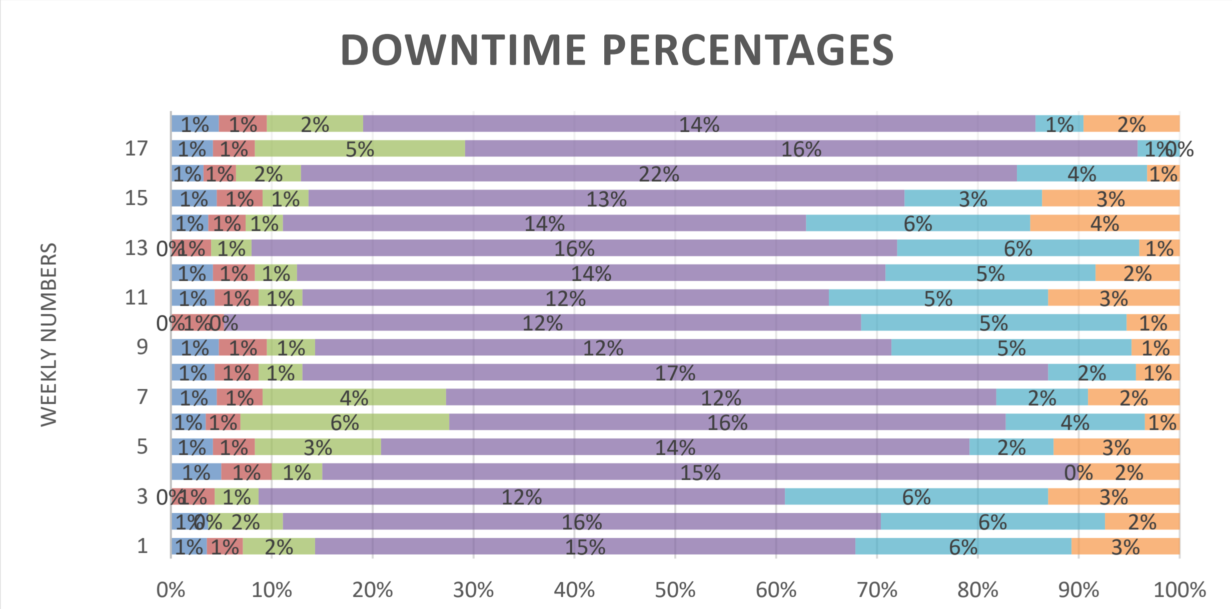
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Downtime %	29%	27%	23%	20%	24%	29%	21%	23%	21%	19%	23%	23%	25%	26%	20%	31%	24%	25%
Effectiveness %	66%	64%	74%	69%	75%	67%	78%	76%	83%	81%	77%	73%	67%	72%	75%	76%	70%	65%

Downtime % Effectiveness %

This is the weekly historical data of the e-coating production performance which reflect the background of the problem faced by the e-coating line. The graph shows that from a 100% target set, the line only achieved an effectiveness percentage of 83% and lowest downtime percentage of 19%.

This indicates that there are difficulties within the process that are affecting the production line to be fully utilized effectively. On analysis for possible root causes, the downtime percentages are then broken down to different categories to try and pinpoint the problem.

Table 8: Weekly downtime categories trend



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
C/O %	1%	1%	0%	1%	1%	1%	1%	1%	1%	0%	1%	1%	0%	1%	1%	1%	1%	1%
Reject %	1%	0%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%	1%
Material %	2%	2%	1%	1%	3%	6%	4%	1%	1%	0%	1%	1%	1%	1%	1%	2%	5%	2%
Process %	15%	16%	12%	15%	14%	16%	12%	17%	12%	12%	12%	14%	16%	14%	13%	22%	16%	14%
Machine %	6%	6%	6%	0%	2%	4%	2%	2%	5%	5%	5%	5%	6%	6%	3%	4%	1%	1%
Man %	3%	2%	3%	2%	3%	1%	2%	1%	1%	1%	3%	2%	1%	4%	3%	1%	0%	2%

C/O % Reject % Material % Process % Machine % Man %

The table and graph highlights that E-coating production line has a high downtime percentage under the category of Process. The weekly data collected identifies the main problem occurs under the process which affects the utilization of the line.

4.4 Process Flow

The E-coating plant comprises of 4 different departments (Offline cleaning, E-coating, Powder coating and Assembly. All these departments operate in connection to each other with a common denominator which is the Offline cleaning. This is a pre-preparation process which most of the parts go through and it is effective because of zinc-phosphate chemical cleaning.

Below is the offline cleaning process tanks, manually operated using a crane in transportation of the Jigs from one tank to another:

Offline cleaning tanks

Table 9: Offline cleaning process

Time (in Sec)	Operation
240	Loading parts onto the JIG
25	Moving the JIG
240	Loading the JIG onto Tank 1(DEGREASER)
25	Moving the JIG
60	Loading the JIG onto Tank 2(RINSE)

Time (in Sec)	Operation
25	Moving the JIG
60	Loading the JIG onto Tank 3(RINSE)
25	Moving the JIG
480	Loading the JIG onto Tank 4/5(ACID)
25	Moving the JIG
60	Loading the JIG onto Tank 6(DRAG OUT)
25	Moving the JIG
60	Loading the JIG onto Tank 7(RINSE)
25	Moving the JIG
60	Loading the JIG onto Tank 8(RINSE)
60	Moving the JIG
60	Loading the JIG onto Tank 9(GRAIN REFINER)
25	Moving the JIG
180	Loading the JIG onto Tank 10(PHOSPHATE)
25	Moving the JIG
60	Loading the JIG onto Tank 11(RINSE)
25	Moving the JIG
60	Loading the JIG onto Tank 12(RINSE)
240	Loading the JIG onto Tank 13(NEUTRALIZER)
25	Moving the JIG to the Offloading bay
574	Offloading parts from the JIG

The process is designed that not all the parts pass through the offline cleaning when it is going to go through e-coating since the e-coating process begins with the cleaning tanks on its own.

Below is the process flow for Cover, Sub-Assembly Steering Column Hole RH & LH which is one of the components being manufactured.

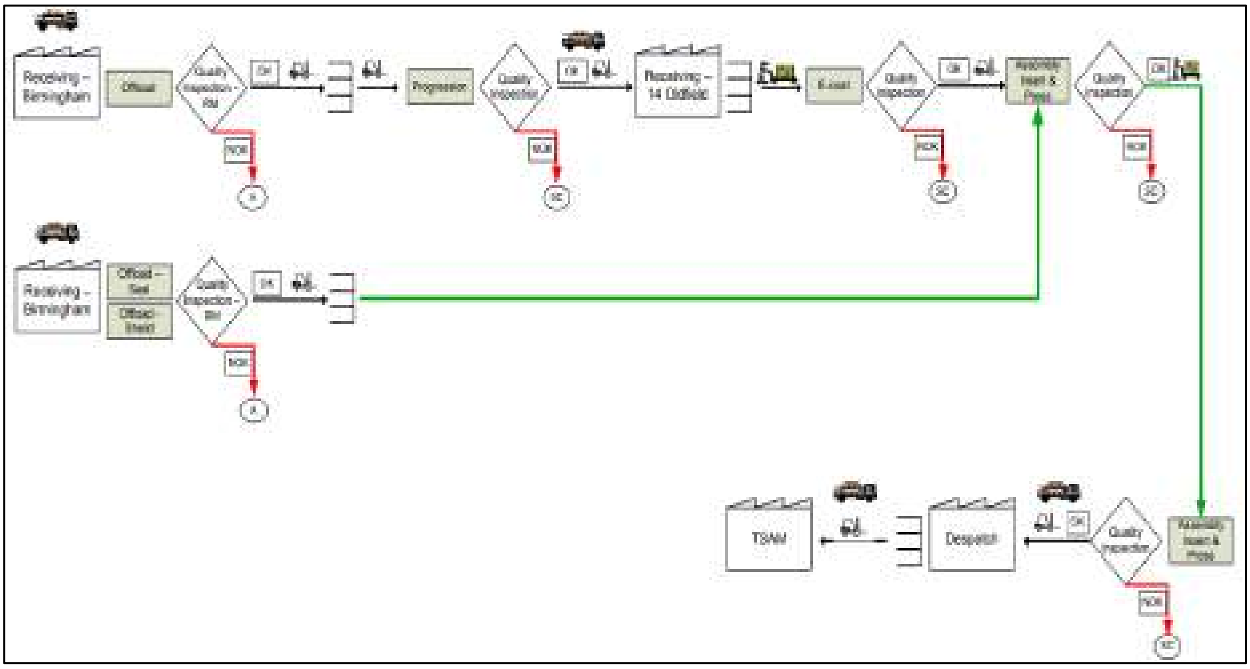


Figure 1: Process flow: Cover, Sub-Assembly Steering Column Hole RH & LH

The process flow displays the movement of the component from receiving until dispatch. This also shows all the quality inspection stages that the product is designed to pass through as per the process procedure. The main aim for the process flow is to show the area of focus for the problem and highlight the processes affected by the problem.

E-coating has 7 tanks for the process to complete:

- Tank 1 – Degreaser (Oil cleaning chemical tank)
- Tank 2 – Rinse tank (Cleaning degreaser to avoid chemical contamination)
- Tank 3 – Rinse tank (Cleaning degreaser to avoid chemical contamination)
- Tank 4 – D-ionized water
- Tank 5 – Primer Tank
- Tank 6 – Rinse tank (Preparing material for wet paint and removing excess primer)
- Tank 7 – Electronic coating

4.5 Investigation

The background scope of this study shows that the focus area is based on the process of the E-coating line. Under this process there's a number of difficulties faced as this is a chemical process which requires professional technicians.

Paint conformance: Testing of the paint is done only on Mondays at the end of the process. During the whole week all the parts run through the line based on the Monday's test results.

When the part's paint non-conformances to the specification than the whole batch is recycled on the conveyor but there are adjustments to the line as recycling only skips the other tanks and goes through tank 5, 6 and 7.

Falling of parts: During the e-coating process some parts may fall from the conveyor. If the components are small, the conveyor continues, however if it is large components fall then the line is stopped since it may damage the tanks.

Gaps on a conveyor: The conveyer speed is constant throughout the whole production time. The loading of parts is a manual process which requires that an operator ensures that all the hooks are loaded with the components.

This becomes a problem when there's a lot of components to load and the small items come in batches of 200 or more and thus to load the parts becomes difficult as the operator has to try and keep up with the speed.

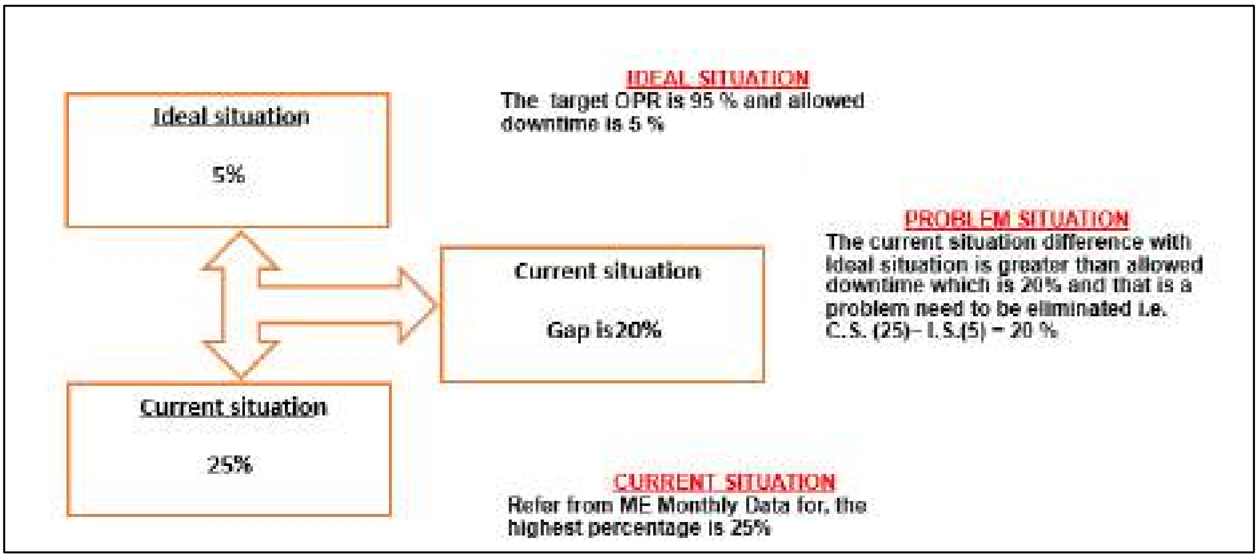


Figure 2: Current/Ideal situation

4.6 Root cause

Analysis of downtime

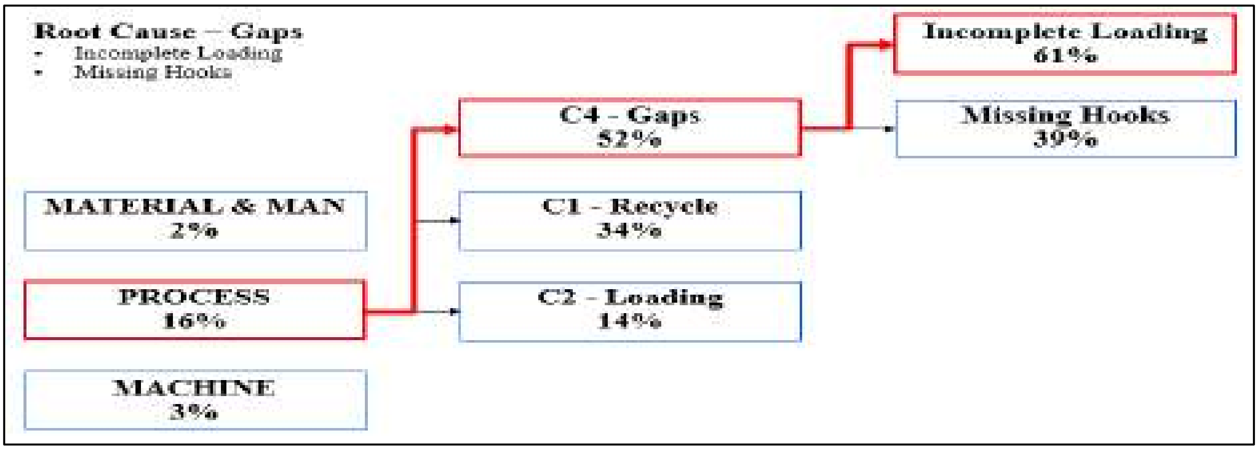


Figure 3: Identification of Gaps

4.7 Clarify the problem

In clarification of a problem, this step allows for an opportunity to analyse sub-problems and evaluate how to tackle each problem in order to find the solution.

1. Paint testing
2. Gaps on a conveyor
3. Parts falling of the conveyor
4. Product loading orientation

4.8 Investigation

The investigation phase involves interviewing production operators to solicit information regarding the sub-problems.

Table 10: Investigating sub-problems

Sub-problems	Investigation
Paint testing	Testing of the paint conformance at E-coating plant is one of the processes that require attention. This process occurs once a week during the weekly maintenance schedule. There is a two day lead-time for the results which are provided by a company located in Ballito. While the company waits for the results, the production can only hold-on to the parts until the tests are complete and approved.
Gaps on a conveyor	Investigation phase
Parts falling of the conveyor	Investigation phase
Product loading orientation	The loading procedure requires that each product has an identified hook for loading as per the standard operating procedure. Some of the large parts are loaded separately from the other small parts since they require human labour when loading. This means that they take a lot of space on the conveyor.

4.9 Set the target

In motivating for the study, the sub-problems aim for investigating possible solutions to the main problem as they highlight or prove to be possible root-causes.

Table 11: Set the target

SET THE TARGET	
1	Develop an efficient process for Paint Test.
2	Review the cycle times for the loading process to clearly identify the process capacity and purchase more hooks to keep as spare.
3	Review the quality of the hooks as they also require maintenance. Sanding off the paint is necessary since they are thickened during the process which enables the parts to sit flush and not fall off.
4	Continuous skill levelling is required to ensure that the standard is maintained. Reviewing of the loading orientation at least once a week and displaying of the standard on the notice board is necessary.

5 RECOMMENDATION AND CONCLUSION

The data collected provides an indication of the challenges experienced in the e-coating plant. This leads to low operator and machines performance. The data also shows the possible root-cause in the process of the production line for further investigation.

The methods used to approach this study were effective on terms of the application of industrial engineering principles. It is recommended that investments be made on the continuous development of operatives to enable them to function effectively in such an environment. Health and safety, ergonomics, protective clothing would assist operators in understanding their environment while meeting governmental policies. Constant monitoring of the production area in imperative to manage challenges that arise on a regular basis. Material handling and layout of materials are important for easy flow of work. Effective management, together with a trained team, will enable the continuous improvement of the E-coating plant with regular monitoring on the production environment.

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APPLYING LEAN PRINCIPLES TO AIRCRAFT MAINTENANCE

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ABSTRACT

Aviation in South Africa is experiencing numerous challenges, especially in the area of maintenance planning. Maintenance turnaround time at an aviation organisation increased by 40% between 2019 and 2021, which influenced the organisation's entire supply chain. The application of industrial engineering principles in the form of lean techniques was found to be the most suitable tool in this instance since it is a tried and tested technique. The objective of the study was to investigate aircraft maintenance procedures to promote process optimisation. Lean methods assist in optimising quality and delivering performance while reducing maintenance turnaround time. A qualitative methodology in the form of a case study was used for purposes of the study. The recommendations made based on the results and the findings of the study were welcomed by the organisation's management team for implementation.

Keywords: lean thinking, aircraft maintenance, industrial engineering, process optimisation

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1. INTRODUCTION AND BACKGROUND

South African Airways Technical (SAAT) is a maintenance, repair and overhaul organisation (MRO) that services both local and international customers. SAAT's acquisition of a new Airbus fleet implied that the organisation added a full Airbus maintenance capability to its existing capability on the Boeing fleet. Aircraft maintenance entails arranging planned maintenance, choosing which aircraft registration to bring in at what time and determining which maintenance tasks to complete. Even for a relatively modest airline on a global scale, scheduling planned aircraft maintenance cost-effectively is a challenging task. It is estimated that aircraft maintenance organisations (AMOs) handle 54% of global airframe heavy repair, 78% of engine maintenance and 16% of line maintenance [1]. The most important objective is to pick up higher line performance, higher efficiency and, in the long run, a lower cost price, while keeping up the quality of the maintenance that is performed.

An aircraft manufacturer specifies in a maintenance planning document (MPD) how frequently various components of an aircraft need to be maintained. Compliance with MPDs is overseen by government officials. There is no doubt that maintenance planning will keep on changing because of the worldwide shift towards new automation systems and the fourth industrial revolution (4IR). These changes will affect the way in which people, technology and machines interact in the aviation industry to improve production. AMOs have highlighted the adoption of lean concepts from the management level to the shop floor in a determined effort to remain competitive in a changing marketplace in response to growing competition in places such as Europe [2]. Certain work processes in SAAT's production department have been identified as being redundant since they consume unnecessary time and effort and increase the cost of the organisation's product. Furthermore, these processes cause worker fatigue, which has hampered growth in productivity.

Heavy maintenance is carried out on an aircraft every 24 months. Heavy maintenance is described as the performance of maintenance tasks covered by C and D checks that involve accessing panels and access doors, as well as disassembly for a more thorough inspection and eventual repair. Heavy maintenance coincides with lengthy downtime periods and large maintenance packages measured in man-hours. An enhanced method is required for analysing aircraft usage requirements on a yearly, monthly and daily basis. In such a method, maintenance item intervals are combined with simulated aircraft utilisation situations (high, average and low usage) and maintenance scenarios in the system. From there, the maintenance demand can be determined (in terms of numerous trips and maintenance man-hours). Thanks to computers and other technological equipment, employees can accomplish most jobs automatically rather than manually [3].

2. LITERATURE REVIEW

Lean management is the process of helping a business to develop the quality of its product or service, its productivity and its efficiency. The adoption of lean methods has been cited by businesses as having a major positive impact on productivity and effectiveness across their individual companies. Many organisations that provide aircraft maintenance have also acknowledged the importance of implementing lean methods to improve their ability to compete in the industry [4]. The keys to maintenance scheduling are what to maintain, when to maintain it and how to maintain it. A system was developed for operators, manufacturers and regulatory bodies to share their experience and knowledge of these issues in relation to new aircraft being developed [5]. Flight service disruption occurs as a result of unplanned maintenance downtime, resulting in a loss of customer satisfaction regarding on-time performance [6]. Planning for aircraft inspections, or when an aircraft should be stopped and what inspection must be completed during its upcoming inspection, is a key component of optimising aircraft maintenance.

Lean tools and methods were first used in the Toyota Production System in Japan. Lean successes should be clear, particularly within a global aircraft maintenance organisation. A case can be made for lean management in the South African AMO industry in the light of the industry-specific evidence of its effectiveness, specifically the reduction in turnaround time (TAT) that results from the implementation of lean methods. While the financial benefits of lean methods may not be immediately apparent to an AMO, the customer benefits from the shorter lead times, giving the AMO a competitive advantage to keep and grow its business [7]. It is also much simpler to identify and address quality-related issues quickly through lean management [8]. Lean methods must be applied to aircraft maintenance, which necessitates implementing ongoing changes and streamlining the maintenance procedure [9]. Lean thinking offers systematic methods for identifying and eliminating waste through a pull strategy, enabling an organisation to stay competitive in the global market [10]. Manufacturers of aerospace products looked to the automotive sector for inspiration and started learning about the principles of lean manufacturing [11].

Using the five lean principles of value, value streaming, flow, pull and perfection as the framework for an organisation to understand the strategic approach of lean transformation, Womack and Jones [12] provide instructions on how to set up rules and deal with the difficulties that arise when a non-lean industrial organisation tries to transform itself into a lean organisation. Value-adding activities (VAAs) transform material and/or information in the interest of meeting the client's needs, whereas non-value-adding activities (NVAAs) are linked to the consumption of time, resources or space that does not add value to the product and/or the service that must be delivered to the client [9]. Lean tools and principles must be adapted to an MRO. The objective is to raise the organisation's performance on operational metrics by encouraging staff to look for ways to cut costs, which helps it stand out from its competition [9]. Prior to implementing lean thinking, the organisation should assess its readiness for the integration of lean methods into its current processes [13].

Two fundamental components of lean thinking are creating value and understanding value from the viewpoint of the ultimate customer [14]. Value can only be determined by the final consumer, and it only makes sense when it is expressed in terms of a particular product [7]. Lean manufacturing is the process of removing waste from all aspects of production, including supplier networks, production flows, maintenance, engineering, quality assurance and factory management. Value Stream Mapping (VSM) is a comprehensive tool that produces an overall picture of a production process, including both value-adding and non-value-adding activities. It provides a visual representation of every action, task or activity involved in a process and records the progression of every action, task or activity from beginning to end. In order to apply the appropriate lean techniques where they are needed to secure a greater and more lasting impact, mapping can be used as an aid in understanding the resources that create waste within the value stream. Instead of focusing on isolated process improvements, mapping makes it possible to see improvements in the entire process. The mass production method known as batch and queue involves producing a part in large quantities and then sending the batch to wait in line before the next step in the production process commences [7]. A product must flow from conception to launch, from order to delivery and from raw materials to delivery into the hands of the customer without any stoppage, scrap or backflow. This is accomplished by completing tasks in a progressive manner along the value chain [12]. Time reduction needs to be continuously monitored because improvement signifies improved process flow. Takt time is a crucial tool for implementing flow because it precisely synchronises the rate of production with the rate of customer demand [7]. A Japanese tool for cleaning and organising a workshop is the 5S system. In this system, visual controls are used to organise the workplace and to improve safety and efficiency while eliminating waste. Work in progress (WIP) can be managed using a pull system. Raw materials or WIP is only released by a pull system after the current WIP has been finished by the previous process steps. An example of such a system is the kanban inventory replenishment system that was invented by

Toyota. For inventory of raw materials or WIP to be moved forward into the following stages, the system generates a visual demand signal. Tasks and operations related to aircraft maintenance enable the forecasting of AMO demands. According to a maintenance schedule approved by the Civil Aviation Authority (CAA), an AMO schedules maintenance tasks based on the operating hours, the landings and the time in service of aircraft. A flight schedule, which changes depending on anticipated customer demand, is a requirement for aircraft operations. It has been necessary to see the value stream, the flow of value, and the value being pulled by customer at every lean principle. A company must set goals and share them with everyone to achieve perfection. The goal of a kaizen workshop is to eliminate waste through the identification and implementation of significant process improvements. There are other methods besides lean methods that AMOs can use to increase their productivity. To increase productivity in AMOs, lean methods are often combined with Six Sigma. Six Sigma is based on a strict and structured investigation methodology and emphasises the reduction of variation while being problem focused.

3. RESEARCH METHODOLOGY

The research questions were designed to generate words rather than numbers, a qualitative approach was adopted for the study. A qualitative research design is appropriate for gathering opinions on a particular subject or when studying human and machine behaviour. Data were gathered through a secondary systematic review, which involved searching for articles on the internet [15]. To achieve the goals of the study, exploratory research was used in this study to define the topic's breadth and scope.

3.1. Data collection

The researcher chose to use the method of questionnaires to collect data. Questions were asked on the education level and years of experience of the candidates. Knowledge on lean terminology and methods were in the questionnaire. Data was collected on the impact of lean in the aircraft industry and the questionnaire was designed accordingly. The following questions were addressed:

a) Department and years of experience in the company.
b) Number of participants per department.
c) Education level of participants.
d) Participants knowledge of lean terminology.
e) Status of the implementation of lean tools.
f) Effectiveness of lean methods in each department.
g) Opportunities and challenges of implementing lean methods/tools.

Furthermore, the researcher chose to observe the current system in use at the organisation. The targeted population consisted of selected maintenance technicians, maintenance planners, engineering analysts, scheduling analysts, production planners and quality assurers at SAAT because they are direct stakeholders in maintenance planning and scheduling. Four different methods were used to gather data: interviews, observations, documentation and archival records. During this study, the observer/researcher analysed data from a C check that was done on a Boeing B737-800 work package, which contained tasks completed on an aircraft, man-hours, material used and duration.

3.2. Data analysis

Thematic content analysis was chosen as the method of analysis for this study. Thematic analysis is a structured, inductive method for extracting and analysing themes from textual information in a transparent and reliable manner[16]. Tables, graphs, percentages and frequency distribution tables were used to demonstrate findings.

4. RESULTS AND DISCUSSION

A total of 68 employees contributed to the research study from an initial number of 74 participants who were chosen to participate in it. The response rate was 92%. The remaining 8% of employees did not complete the questionnaire because they were on leave. Management was willing to let the employees participate in the survey because they believe that using lean methods can improve productivity and profit while reducing costs. The chart below indicates the respective departments to which the participants were attached and the years of experience of the participants.

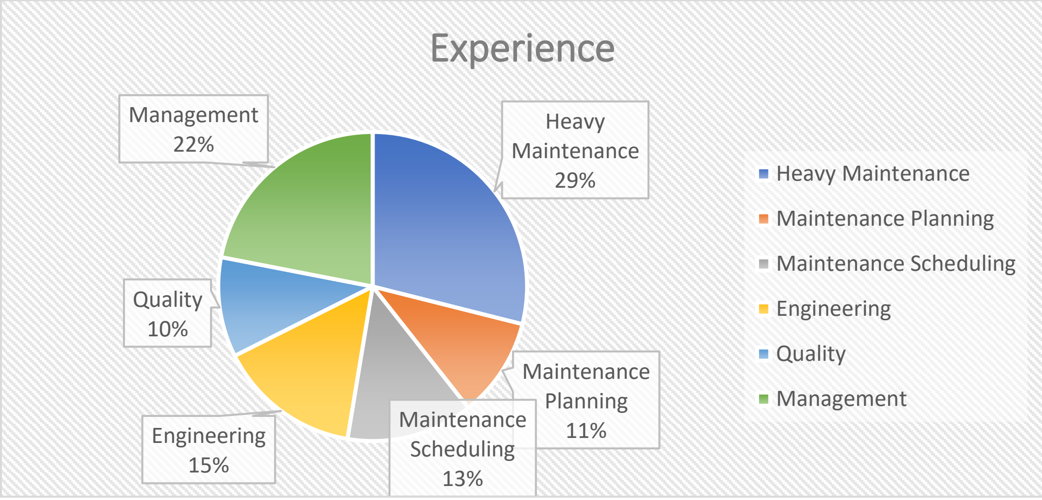

Figure 1: Participants: departments and years of experience

The total number of participants in this research was 68 of whom.

- 63% were artisans with experience of between 1 and 25 years.
- 8.5% were planners with experience of between 5 and 10 years.
- 7.5% were schedulers with experience of between 8 and 12 years.
- 7% were engineers with experience of between 5 and 15 years.
- 10% were quality controllers with experience of between 4 and 10 years.
- 4% were managers with experience of between 10 and 20 years.

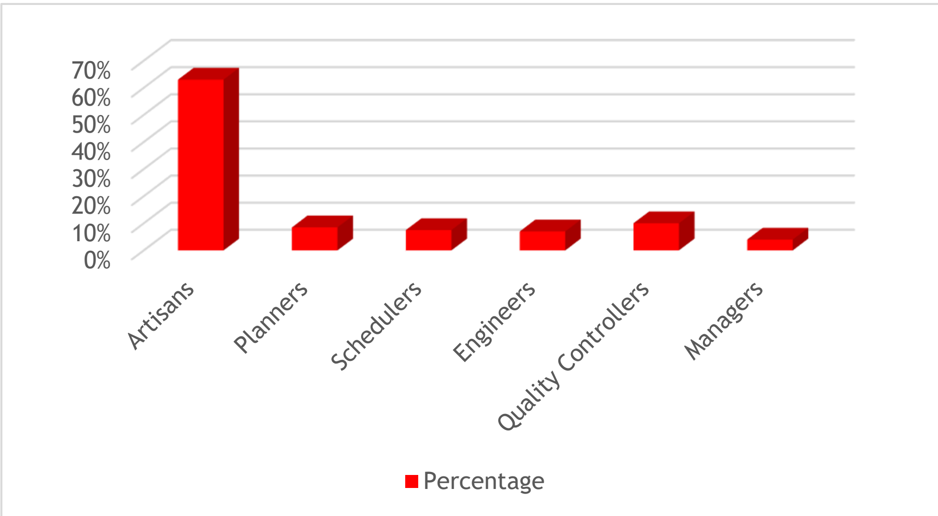

Figure 2: Participants per department

Based on the above overview of the participants, the researcher concluded that the experience that one has in the industry does not have an impact on one's contribution towards finding ways of improving aircraft availability by integrating planning and scheduling using lean methods. The participants involved in heavy maintenance were key people because they were faced with day-to-day challenges related to processes that were flawed because of the poor planning and scheduling of tasks. The chart below depicts the level of education of the participants.

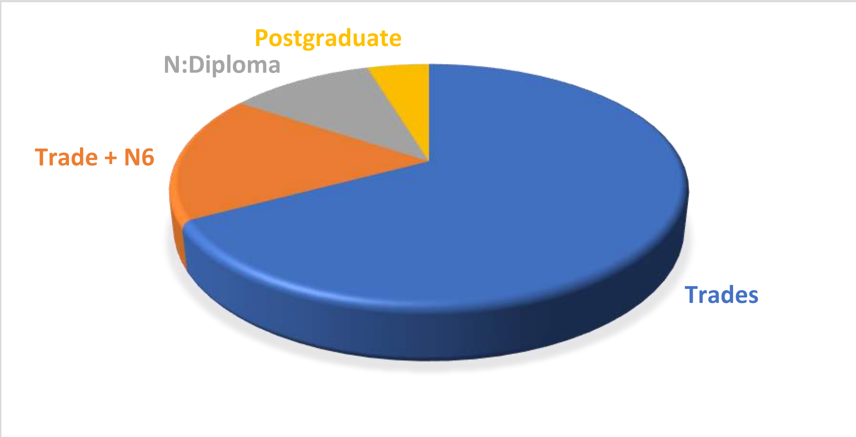

Figure 3: Participants' educational level

A total of 4% of the participants had a postgraduate qualification, 7% had degrees, 10% had N diplomas, 16% had trade certificates plus N6 and 63% had trade certificates only. Considering that the aviation industry requires knowledge of lean manufacturing and qualifications to integrate planning and scheduling using lean methods, the results paint a worrisome picture of the status of skills development in the industry. The proposed integration of planning and scheduling using lean methods requires certain knowledge of value streaming and kaizen. Employees of aviation companies require training and skills development to keep up with the global aviation industry.

4.1. Knowledge of lean terminology

A set of questions on lean methods was drawn up and used to test the participants' knowledge of lean methods.

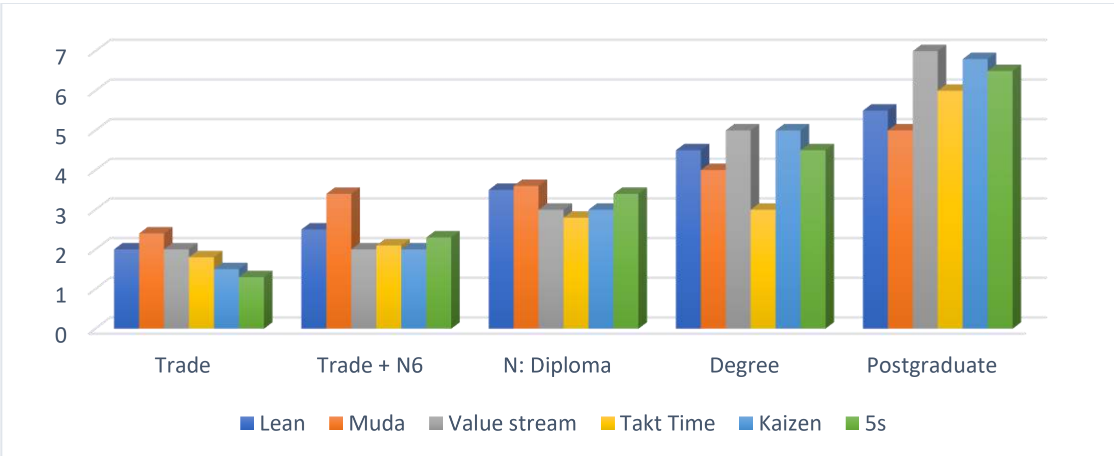

Figure 4: Participants' knowledge of lean terminology

The above figure shows that artisans who worked in heavy maintenance and whose highest qualifications were trade certificates had little knowledge of lean terminology. Likewise, participants involved in maintenance planning and scheduling had little knowledge of lean terminology. The company could invest in skills development to improve their skills, thereby bringing them on par with employees who have university qualifications and knowledge of lean manufacturing for the seamless integration of lean methods.

4.2. Status of the implementation of lean methods

The figure below indicates the status and experience participants encountered during lean implementation. Between 23% and 29% of engineering and quality departments, participants had a better understanding of lean methods implemented. The remaining departments ranged between 14% and 17%, which clearly shows that the participants had a moderate experience when lean methods were implemented in their perspective departments.

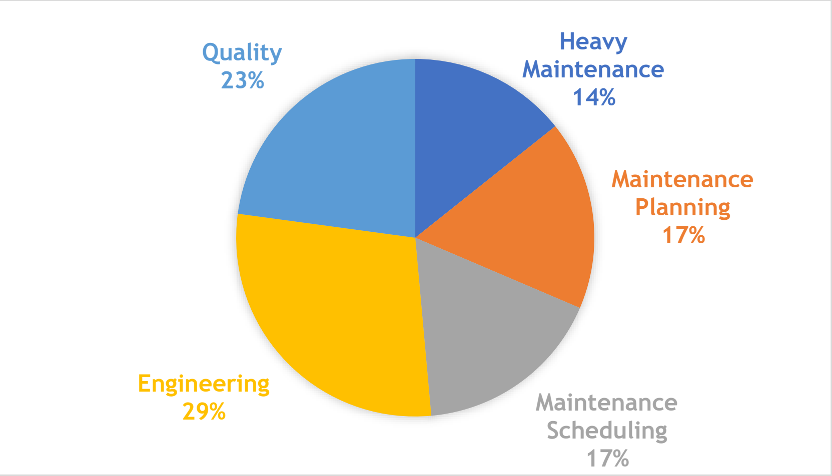

Figure 5: Status of the implementation of lean methods

4.3. Effectiveness of lean methods at South African Airways Technical

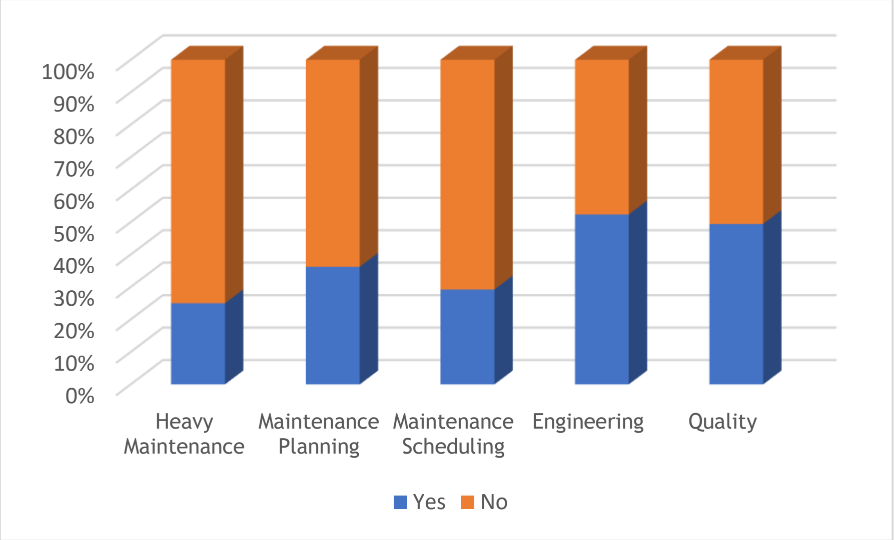

Figure 6: Effectiveness of lean methods in each department

The participants were asked if the implementation of lean methods had improved planned and scheduled maintenance. The figure above shows that the implementation of lean methods at SAAT is a work in progress and that most of the departments do not recognise the importance of adopting lean methods. Management should invest in improving the knowledge of employees working in heavy maintenance, planning and scheduling as far as the introduction of lean methods is concerned.

4.4. Opportunities and challenges encountered in implementing lean methods.

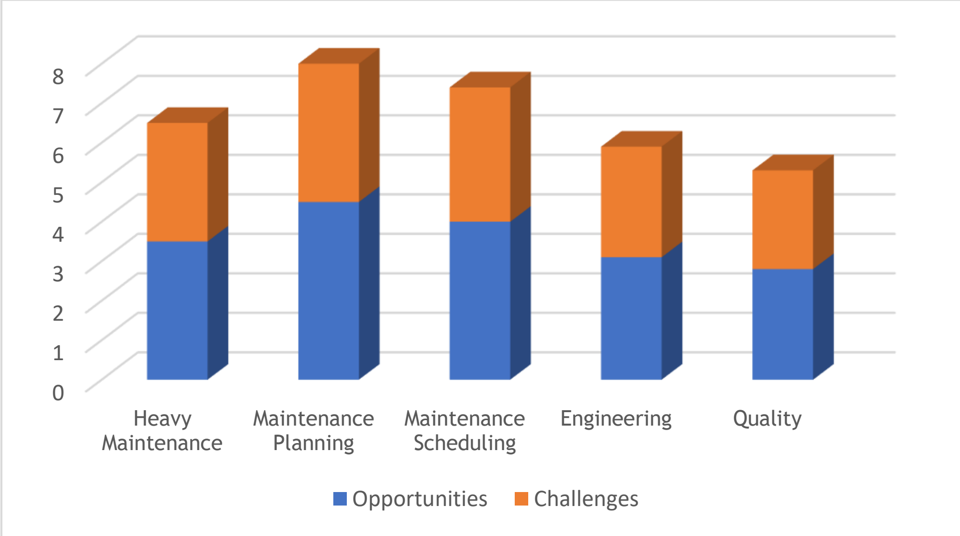

Figure 7: Opportunities and challenges

A questionnaire was used to determine which opportunities and challenges the participants had encountered during the implementation of lean methods in their perspective departments. A questionnaire was also used to assess the degree to which lean methods had been implemented.

Participants involved in heavy maintenance, planning and scheduling had an opportunity to outline what their departments needed to improve the movement of task cards. All the participants from different departments had equal and fair opportunities when it came to the implementation of lean methods with fewer challenges encountered.

4.5. Limitations of the study

The findings of this study are limited because the data that were used were sourced from international sources rather than local ones, which indicates that more research needs to be done in South Africa within the aviation industry. With respect the sample, only the heavy maintenance, maintenance planning, maintenance scheduling, engineering/quality departments and managers of SAAT were requested to complete questionnaires.

5. RECOMMENDATIONS AND CONCLUSION

The important initial step is for the management of SAAT to develop a strategy that is aligned with the company's operation and that has a clear measurement plan. Fundamentally, management are responsible for ensuring that employees are informed of and educated about the significance of lean methods. All targets that are set by SAAT management should be communicated to the entire organisation. The training and upskilling of workers must take centre stage to ensure that SAAT remains competitive in the global market. Management needs to invest in new technology and innovations to ensure the company's relevance and effectiveness.

Based on the data collected through interviews and system observation, it was concluded that the implementation of lean methods in the integration of planning and scheduling in an aircraft maintenance organisation can lead to an improvement in profitability and a reduction in grounded aircraft. Although the participants emphasised the importance of improving production, they were also concerned about their personal growth and how they would fit into the system. The introduction of a new system or new technology into the structure or the culture that already exists requires the full commitment of management so that employees will not feel left out. Furthermore, participants identified a lack of training, coaching, mentoring and skills development. This framework is explored and linked to the research results.

5.1. Future work

Companies which aim to remain competitive are striving to improve their levels of productivity, quality, and services. Lean management principles is a well-researched and successfully applied managerial strategy. Therefore, combining Industry 4.0 and Lean methods appears to be a critical evolutionary step for raising the bar on operational excellence. As is recognized from Lean methods, an increasing number of Industry 4.0 technologies are being employed to cut waste and reduce costs. In the process of continuous improvement, it's crucial to keep the client in mind and take into account how employees contribute to the value of the delivered goods and services.

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THE APPLICATION OF INDUSTRIAL ENGINEERING PRINCIPLES IN THE LEATHER-PROCESSING ENVIRONMENT

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ABSTRACT

The study was conducted at a plant that processes cowhide parts to manufacture leather parts for car brands. The cutting plant was not meeting the desired target per hour and only averaging only 4,1 m^2 per head/hour while the required performance was 5 m^2 per head/hour in order to meet the new demand. This resulted in a 0,9 m^2/head/hour gap in achieving the desire output, thus creating a bottle neck at the lamination process, which resulted in an inventory build-up of 18%. The main objective was to determine measures that can be implemented to improve productivity at the organisation's lamination process. The investigation through the use of industrial engineering tools, led to an improvement of at least 20% in productivity, as well as a workforce that has a greater understanding of the importance of conducting a cost-benefit analysis.

Keywords: lean thinking, industrial engineering, process optimisation

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1. INTRODUCTION AND BACKGROUND

The lamination operation of the cutting plant of a leather-processing company was not meeting the desired target per hour and was not achieving good productivity. This coincided with the launch of the new car model, which had increased demand, and led to poor performance at the cutting plant. The lamination operation averaged only 4,1 square metres per head per hour (m^2/head/hour) for the period being studied. The launch of a new car model led to an increase in leather needed for the car parts. The new targets were now revised 5 m^2/head/hour. Consequently, there was a shortfall of 0,9 m^2/head/hour in achieving the desired output, thus creating a bottleneck in the lamination process. This bottleneck resulted in a build-up of 18% in inventory.

The cutting plant of the organisation is divided into two main operations, namely, a cutting operation and an enrichment operation. The enrichment operation is based on customer-driven requirements. Lamination forms part of the enrichment operation leather panels are laminated because the cut leather parts have to be married to foam cut-outs. Leather panels are fused to foam cut-outs by aligning the two components on top of each other and then feeding the panels through a lamination machine. The lamination machine uses heat technology to activate and melt the glue adhesive surface found on the foam cut-outs, which then stick to the leather panels. The process is further summarised in Figure 1 below.

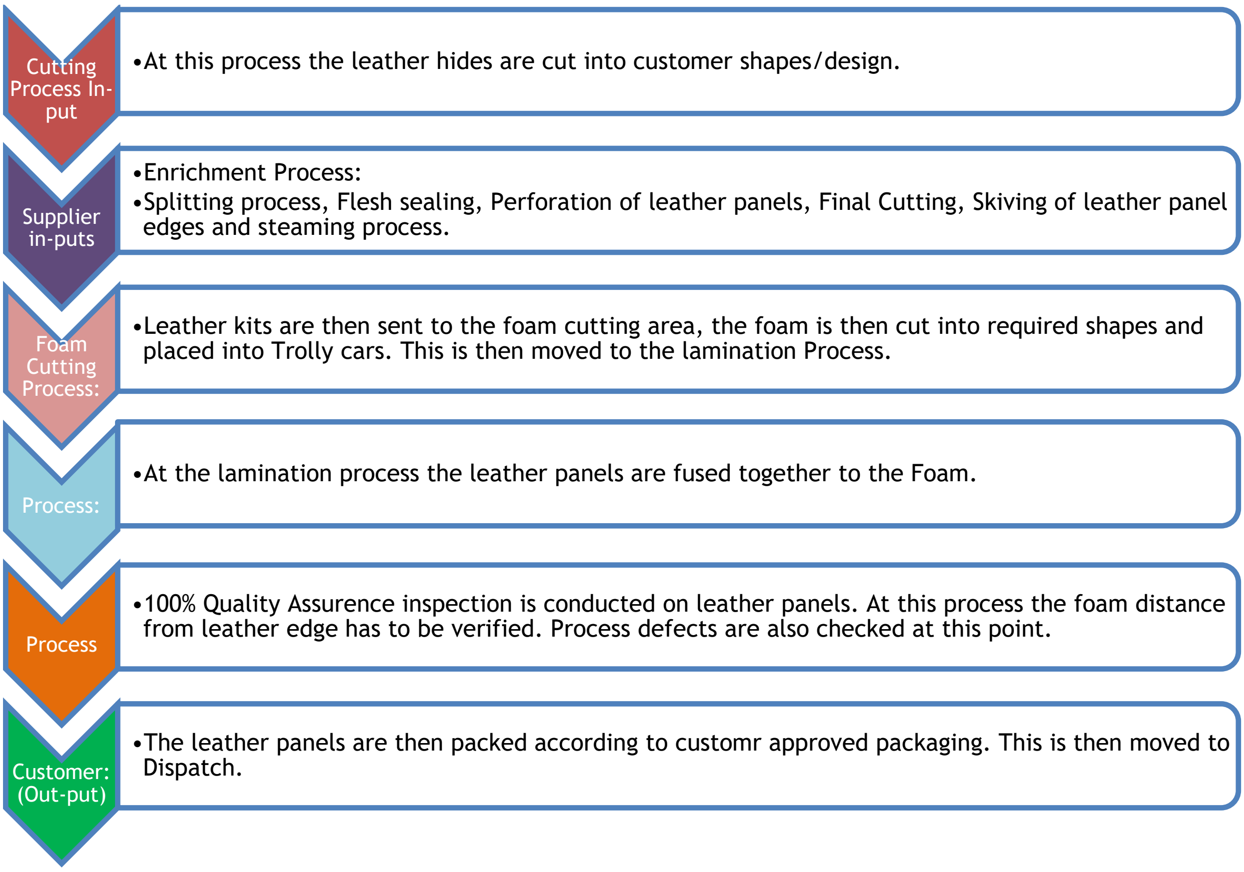

Figure 1: Lamination Process Steps summarized

Figure 2 below is a Suppliers-Inputs-Process-Outputs- Customers (SIPOC) diagram that maps the lamination process. It assists in analysing and visualising the lamination operation and ensuring that all key elements, such as suppliers, inputs, process, outputs, productivity and customers. Both external and internal suppliers and customers need to be considered when analysing the lamination process of the cutting plant.

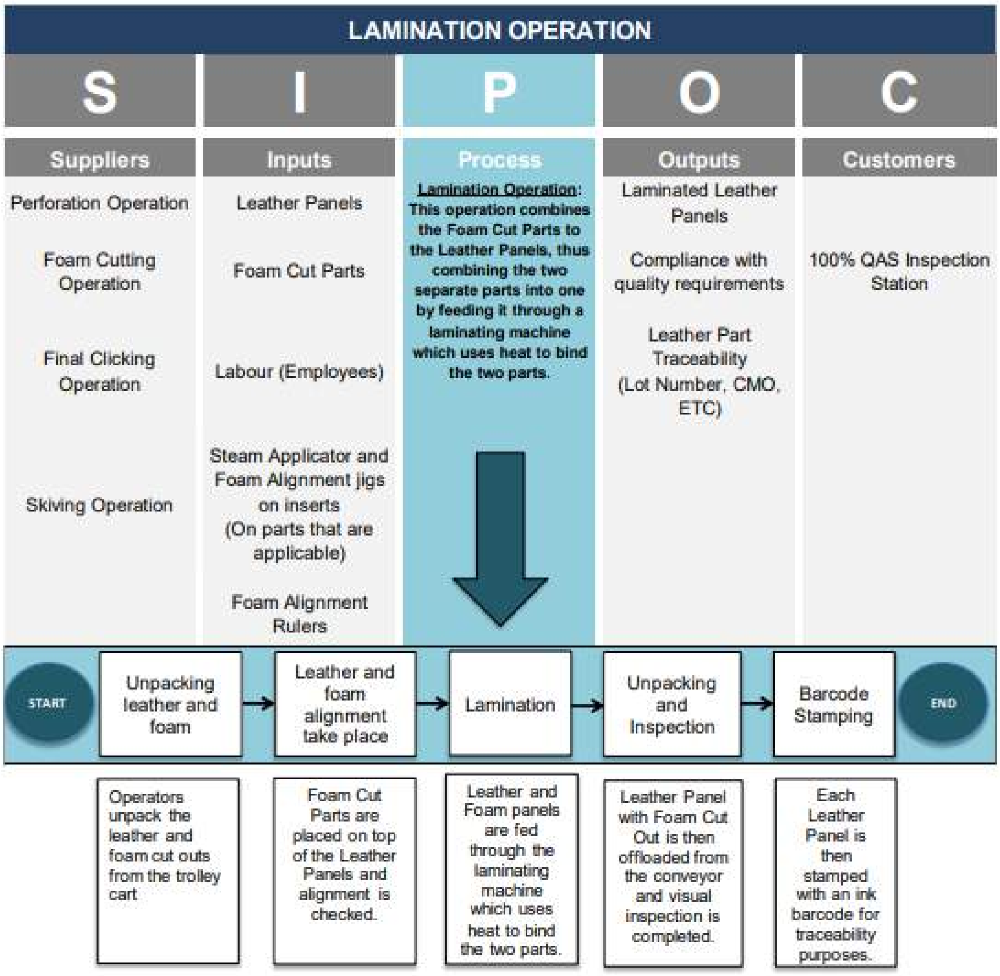

Figure 2: SIPOC diagram for Lamination Process

During the first quarter of 2022 the leather-processing company experienced an increase in demand for its products necessitating improvements in the enrichment process to ensure that products are processed in the shortest lead time. A target of 3 000 m² per day is required. The productivity of the current lamination process is 2 280 m², leaving a shortfall of 160 m² per day. This shortfall created delays in customer deliveries. At this stage, the reasons for shortfalls had not been identified. This process has many customer-driven requirements. In the lamination process, foam is fused to leather. When foam is fused to leather, customer tolerance needs to be taken into consideration. Outer nicks guide employees on correct positioning. Before the lamination process starts, an adhesion test has to be performed to determine if the leather and the foam bond well.

The main objectives which were to:

- Investigate the causes for not achieving the targeted output at the lamination operation from an average of 4.1 m²/head/hour to the desired target of 5 m²/head/hour by the end
- improve the productivity at lamination operation using lean principles
- To ultimately eliminate the bottleneck at the operation

2. LITERATURE REVIEW

Productivity is normally defined as the ratio between the output of production and the input of production factor [1]. Krueger [2] defined productivity a measure of efficiency in which resources are utilized to achieve desired outcomes and can drive economic growth and higher living standards by increasing output per unit of input. In the context of this study, it is therefore important for the company to measure and improve productivity to achieve the goals of research. This literature review focuses on the techniques and methodologies that can be implemented to improve productivity in this leather processing plant.

2.1. Lean Production and tools

Lean production can be traced to 1980's as reserachers depict the Japanese manufacturing industry's sucess, especially the Toyota Production System [3]. It can also be defined as a set of tools and technqied that assist improving customer value by focus on the reduction of wated generating activities[4]. Lean production and its principles is now widely used in many service sectors, rather than being only implemented in production. Fercoq et al. [5] defines the categories of wastes as:

- overproduction,
- waiting,
- excessive transporting,
- over production,
- unnecessary inventory,
- excess motion and
- defects

2.1.1. Plan-Do-Check-Act (PDCA) Cycle

The strategy utilized in this venture is execution of conceptualizing procedure in the organization. Under arranging period of PDCA CYCLE given by Deming the conceptualizing is finished and any remaining Len producing apparatuses recorded beneath. The PDCA cycle implies [6]

- PLAN: Design or modify business process parts to further develop results
- DO: Implement the arrangement and measure its exhibition
- CHECK: Assess the estimations and report the outcomes to chiefs
- ACT: Decide on changes expected to work on the interaction

2.1.2. Gemba walks

McClam Liebengood [7], describes gemba wallks as workplace walkthroughs which aims to examine operators, query about their tasks, and identify productivity gains. This usedful toolwas also used in this study. In this study, the study team walked the floor, made the operators understand the important and purpose of Gemba walk at lamination plant. The objective was to identify areas of improvement and achieve the targets, not to monitor or spy on the employess. The employees were informed in advance to prepare for the Gemba walk and questions that will be sked. Caution was taken to instill trasparancey.

2.1.3. 5 Why's

Melton [8] states that there is a practice of asking why five times whenever a problem was found and this way the root cause was solved rather than the symptom. During the gemba walk that was conducted, questions about the different activities that took place at lamination operation were asked. The 5 why's provide a great basis and valuable insight for the questions that were being asked. Employee input was seriously being taken into consideration. All employees shared their ideas and identified areas that needed improvement at lamination operations. Several observations were made during the walk; Managers from different departments were invited for the walk to get different points of view and fresh ideas.

2.1.4. 5S

Melton [8] further defines 5's as five activities used to create a workplace suited for visual control and lean practices and 5S is a straightforward useful methodology that conveys reasonable continuous improvement by driving responsibility to the cutting edge in your business. For this study it was explored.

3. RESEARCH METHODOLOGY

A combination of quantitative and qualitative methods was employed in the study. The researcher found it appropriate to conduct a qualitative investigation to gain a deeper understanding of the problem under investigation and to compare key factors. A quantitative study was also required since financial impacts and production processes had to be calculated.

A qualitative approach helped the researcher to grasp the problem quickly and to develop knowledge of the applicable field. A quantitative approach was followed to transform the information into relevant measurable data. Therefore, the researcher used qualitative and quantitative methods in combination by first gaining knowledge of the applicable field and then compiling and transforming the information into computable data. This methodology enabled the researcher to analyse the current process under investigation and to determine the set-up of the future process. A qualitative research design is appropriate for gathering opinions on a particular subject or when studying human and machine behaviour. The literature review section research data in this study were gathered through a secondary systematic review, which involved searching for articles on the internet. To achieve the goals of the study, exploratory research was done to define the breadth and scope of the topic.

The data collection method used at the lamination operation is semi-automated, that is to say, it is partially manual and partially automated. The data collection system at the lamination operation is considered manual because an employee has to scan the side-label barcode of each new batch for the system to collect data. The data collection system is also considered automated because information is automatically updated and converted into a square metre measurement, simply by scanning a side-label barcode. The system then calculates the square metres per net lettable area (sqm/NLA) based on formulas that have been fed into the data system. When an employee scans a side-label barcode, information is transmitted to a database and loaded into the automated Lamination Productivity Tracking System, as well as onto the company's Enterprise Resource System (ERP). The side label contains information such as the customer's name, as well as information on the applicable model, part number, packing quantities, parts and so on. The Lamination Productivity Tracking System is a database that was developed by the finance department to assist with the tracking of sqm/NLA in the lamination operation.

Before the introduction of the Lamination Productivity Tracking System, there was no defined way of tracking sqm/NLA because the ERP system proved to have limitations in providing this real-time data. In many instances, sqm/NLA could only be tracked using the ERP system once a batch reached the despatching area and was scanned into the despatching warehouse. This procedure was not beneficial for tracking progress at the lamination operation since the operators at this operation did not know if they were hitting the target until it was much too late. The introduction of the Lamination Productivity Tracking System was essential since it provides real-time data of sqm/NLA processed, simply by scanning in a side-label barcode and refreshing the system every time an update is needed. This helps employees by giving them access to real-time data, which indicates if they are behind or ahead in meeting the hourly target.

4. RESULTS AND DISCUSSION

The part of the research paper focusses on the results of the study

4.1. Performance vs expectation

A time series plot was developed in order to understand the current performance of the lamination process. This graph depicts data samples that were collected over 5 weeks, as well as the applicable customer specifications, which are represented by means of upper and lower specification limits. The graph shows whether the NLA per head per hour (NLA/H/H) falls within or outside the customer specifications as specified in Figure 3.

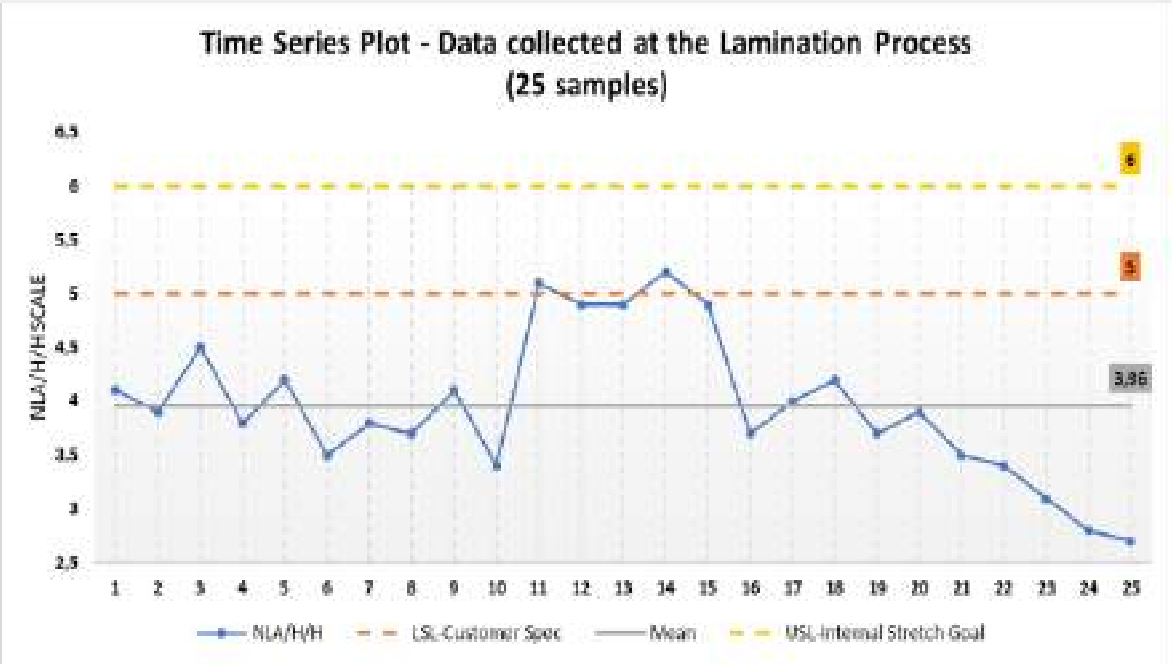

Figure 3: Time series plot for the data collected at the lamination process

An observation that can be made when looking at the time series plot is that only 2 data samples out of the 25 samples fall within the desired target range of 5-6 NLA/H/H.

In calculating the z-score on Excel, it was estimated that the lamination operation will achieve the desired target of 5 NLA/H/H only about 7% of the time. This is also depicted in the time series plot, where approximately 93% of the data samples fall below the desired target range.

Table 1: Summary of the challenges experienced in the lamination process

Lamination Operation - Cause and Effect Matrix (Key Input and Output Variables)					
		(Y) Statement: Lamination operation is not consistently meeting the average 5 NLA/H/H			
Number	Category	Root Causes Identified (X's)	Impact Score	Implementation Score	Total Score
1	Method	Production Delay- Shortage/ Extra foam parts (Only discovered once on the line)	9	3	27
2	Method	Production Delay- Wrong cuts on the foam panels (Only identified or detected once on the line)	9	3	27
3	Method	Production Delay- Mixed parts (Only identified once it is already on the line)	9	3	27
4	Method	Poor planning and scheduling at the lamination operation	3	3	9
5	Method	No defined method followed by each operator regarding task completion	9	3	27
6	Method	Misalignment reworks that cause delays during the lamination process (Currently make use of Prints for some leather inserts)	1	3	3
7	Machinery	Changeover times vary between different customer models. Different temperature settings are required on the machine	3	3	9
8	Measurement	Downtimes at the lamination operation not sufficiently being recorded	9	3	27
9	Measurement	Lamination Productivity Tracking System is temporary down due to IT complications	1	3	3
10	Manpower	Resistance towards change from how they use to doing work	3	1	3
11	Manpower	Team leaders are not effectively utilizing the Lamination Productivity Tracking system to check process performance during the shift	3	9	27
12	Manpower	Absenteeism	3	1	3
13	Manpower	Correct manning requirement for the operation	9	1	9
14	Environment	Poor 5S practiced at the lamination stations, resulting in unorganised and cluttered work stations and build up of leather panels on the lamination tables	3	9	27
15	Material	Delamination that takes place, results in panels having to be reworked	3	1	3
16	Material	Panels that are rejected at the QAS Inspection Station that have to be reworked.	1	3	3

4.2. Drivers and requirements

Based on the critical-to-quality tree (CTQ) analysis, delivery and quality play a vital role in meeting customers' needs, in this case, the quality assurance inspectors' needs. The focus is placed on the delivery function (5 m^2/head/hour) since the lamination operation is currently not meeting the customer demand.

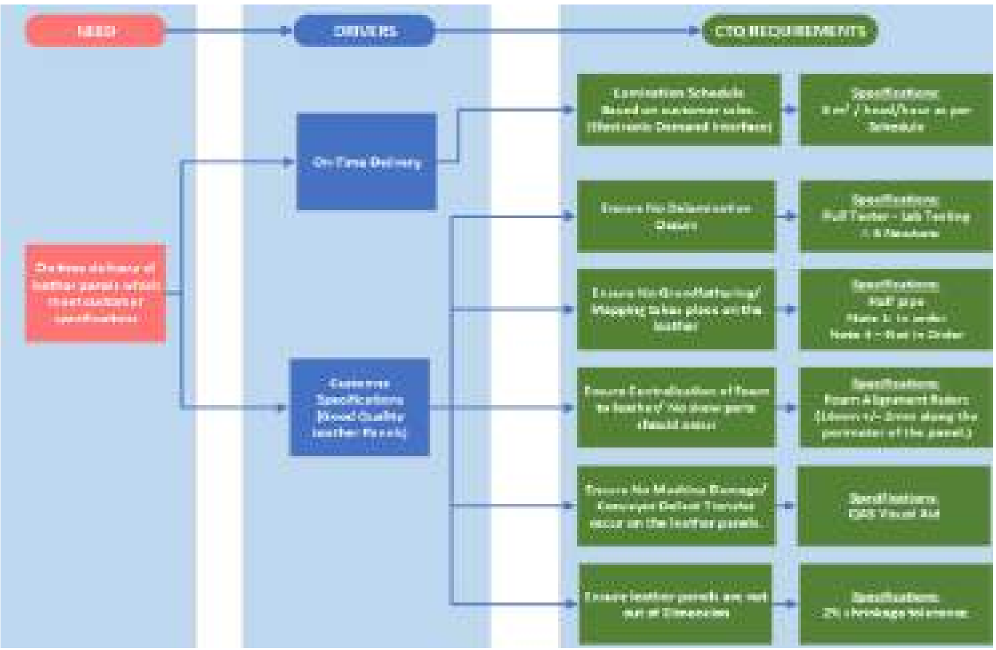

Figure 4: Driver and CTQ Requirements Analysis

4.3. Lamination productivity

Figure 5 below shows the performance (productivity) of the lamination operation at the beginning of the year. It started out well and then went down to below the target. The decline in productivity was the result of an increase in W206 lamination machine. Data thus far show that with an increase in W206 NLA, productivity decreases (scatterplot and regression analysis).

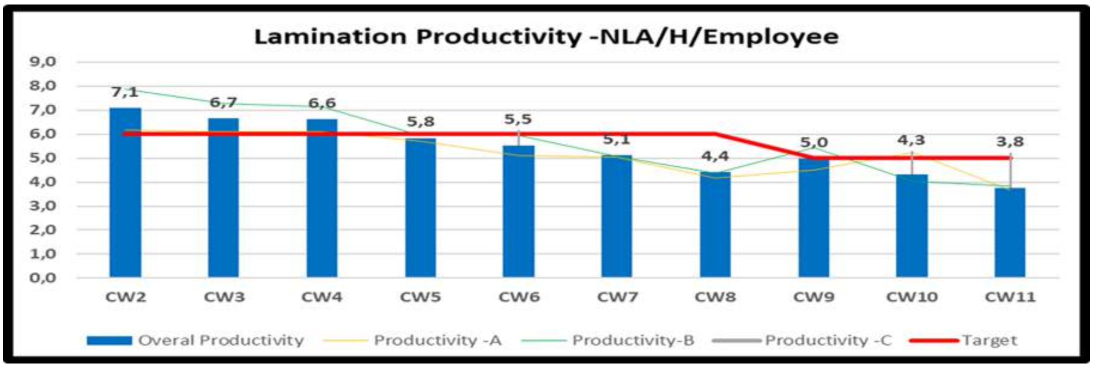

Figure 5: Lamination productivity per employee

4.4. Cause and Effect analysis

The cause and effect diagram presents the possible causes of not meeting the targets in the lamination process

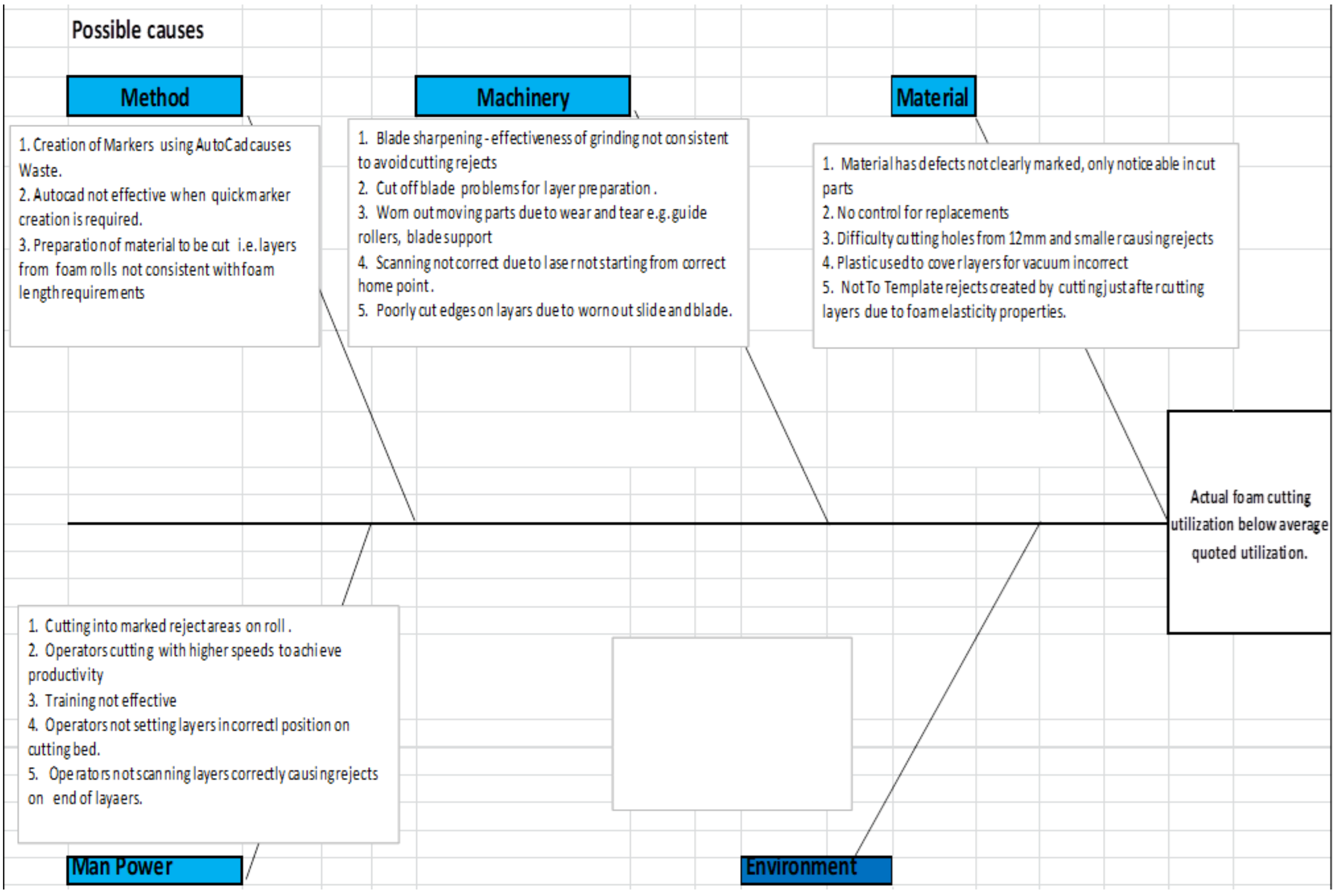

Figure 6: Root Cause Analysis

In summary, the causes and effects are summarised in Table 2 below.

Table 2: Summary of Causes and effects

Cause	Effect
Poor method of creating markers used	Low utilization causing waste
Wrong marker measurements used to cut layers	Miss-cut at the end of the roll
Cutting Speed to high	Rejects due to pieces being not to template
Layers poor aligned to the cutting bed	Miss-cuts on the far end of layers
Cutting blade not sharpened	Not to template, miss-cuts rejects cut.

4.5. Issues detected during Gemba walk

- Continuous change to the planning schedule, therefore making some makers unusable on a daily basis.
- Availability of time to change markers daily due to headcount restriction to employ a dedicated person to create markers.
- Machine related rejects such as miss-cuts can cause reduction in utilization achievement.
- Operator errors in when aligning layers can cause unwanted rejects.
- Excessive undeclared reject sections on roll by customer can affect utilization achievement.

4.6. Summary of Solutions proposed after using tools

The proposed solutions are summarised in the points below.

- Use offsite marker making software to improve markers making turnaround times.
- Train operators to improve the handling of material
- Improves and instil best practice methods to achieve the desired results.
- Combine different shapes using similar material with better interlocking shapes that leave smaller gaps between panels.
- Increase sharpening frequency by reducing distance between each between each point to reduce rejects.

4.7. Solution Selection

- Marker making using external software remotely at no cost was done.
- This helps with quick marker making process, improved utilization and cost reduction due to reduced waste.

4.8. Process performance (improved)

Once all the required solutions had been implemented, it was important for the team to determine if there was any progress towards achieving the desired goal of 5 NLA/H/H. Once all the necessary changes had been implemented and the relevant training had been completed at the lamination operation, it was time for the team to determine if any measurable improvements had taken place at the lamination operation and to quantify those improvements. The team collected data regarding the NLA/H/H achieved over a 3-week period (CW 28 to CW 30) at the operation after all improvement measures had been implemented. The diagram below shows the performance (productivity) of the lamination operation after the implementation of these measures. The productivity of the operation ended very well, reaching the target of 5 NLA/H/H.

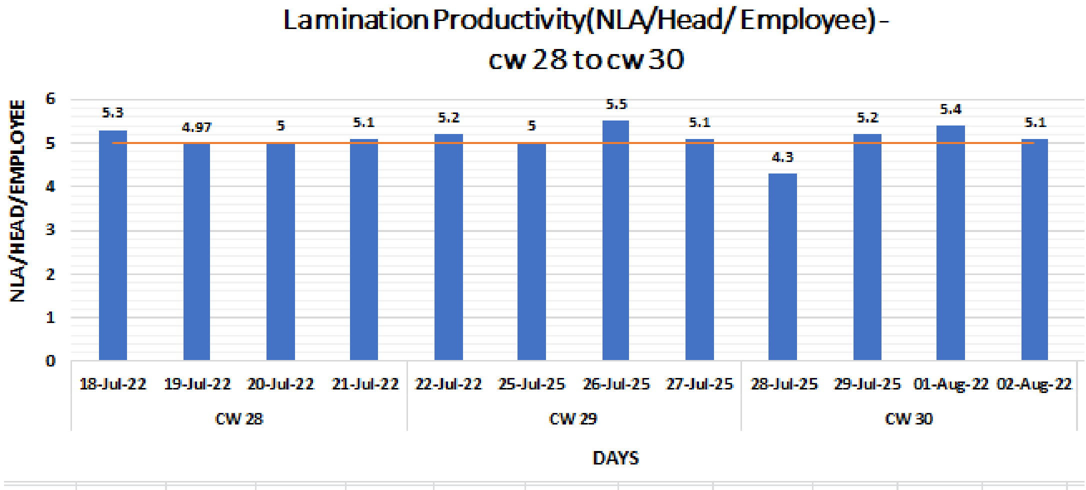

Figure 7: Lamination productivity

Figure 7 presents the results of the data collected over the period CW 25 to CW 30. The team noticed a significant improvement towards achieving the target of 5 NLA/H/H. When the team initiated the productivity improvement project at the lamination operation, the operation averaged 4,1 NLA/H/H for May. Based on the 3 weeks monitored in July, the operation averaged 5,21 NLA/H/H, which is above the desired target of 5 NLA/H/H. This was a great achievement for the operators working at the lamination operation since many of them were initially hesitant about the changes that were implemented in the work area.

5. RECOMMENDATIONS

The results of the study gave rise to the following recommendations:

5.1. Retrain employees in downtime

As identified in the cause and effect analysis, one of the major issues were operator errors in when aligning layers can cause unwanted rejects. This warranted refresher training and coaching specific topic/process that they have already encountered with the aim of jogging their memory and boosting their knowledge of the topic. This type of training is also useful for ensuring that employees have the most up-to-date information at their disposal. Refresher training is a great way to ensure that employees follow company best practices and adhere to important procedures, especially when it comes to compliance with regulations. A lack of compliance can lead to mistakes by employees and, in more serious cases, sanctions or penalties from external regulators [9].

Operators and team leaders at the lamination operation were given refresher training in downtime tracking and the importance of effectively recording any downtime that may occur at the operation. The refresher training was conducted in small groups during each shift at the lamination production boards. Downtime trackers are located at each of the production boards so that employees can update the trackers when any downtime occurs. The training was conducted by the cutting-process engineer and the researcher. The team wanted to ensure that all team leaders and operators gained a clear understanding of downtime tracking and how it affects the productivity metric for measuring NLA/H/H at the end of each shift.

Retrain team leaders and employees of the lamination operation to ensure they know how to effectively utilise the Lamination Productivity Tracking System. The production supervisors trained the team leaders in the use of the Lamination Productivity Tracking System so that they can monitor the NLA/H/H to determine if the team falls behind or is on target in meeting the hourly target throughout a shift. This training was vital because prior to the introduction of the system, the team leaders had no access to real-time data that could provide them with progress updates throughout a shift. The system gives the team leaders the opportunity and the time to implement corrective actions if the team starts to fall behind.

The final observation made during the implementation and testing phase of the improvement project was that following the introduction of a pre-lamination station and specified job tasks for each of the operators, the operator who was stationed at the pre-lamination station could not maintain the same pace as the operators who simply had to feed the line and no longer had to align leather and foam panels. Owing to a limited headcount, the team could not place additional operators at the pre-lamination station, which proved to be a challenge since the pre-lamination station created a new bottleneck. The team then came up with the idea of building buffer stock into the process in order to assist the operator stationed at the pre-lamination station. The team decided that one full packing quantity must be prepped for lamination prior to the end of a shift. This will ensure that the incoming shift will have buffer stock available and ready to be placed on the conveyor and fed through the machine.

This idea proved successful. If the operator who aligns panels at the pre-lamination station starts to fall behind and the buffer stock becomes depleted, the designated lamination team leader will temporarily step in and assist the operator to pre-align the foam and leather panels, just enough to replenish the buffer stock. During the last 15 minutes of a shift, when the operators perform housekeeping, 3 operators will start to align foam and leather panels at the pre-lamination station, thereby ensuring that buffer stock is available between the pre-lamination station and the lamination conveyor for the incoming shift; the rest of the lamination team will, during this time, continue to carry out housekeeping activities [10].

5.2. Hold daily production meetings

The cause and effect also found that there were issues with the availability of time to change markers daily due to headcount restriction and a need to employ a dedicated person to create markers. Furthermore, machine related rejects such as miss-cuts can cause reduction in utilization achievement. The daily production meetings can assist in this regard. It is important to hold a production meeting every day to discuss the day before and any issues that may need attention and to explain the targets for the day. It can be a very brief ‘stand-up meeting’ on the production floor at the start of a shift.

i. Communicate the ‘why’

It is important to communicate the ‘why’ – why it is important to work at a more efficient rate or why productivity improvements are essential for the longevity of the business – to workers and to inform them of the important role that they play in this respect.

ii. Use visual management techniques

The use of visual management techniques such as display boards with production targets and output data enables workers to track their progress against targets on an hourly/half-daily basis. Visual aids also enable different lines or sections to track progress in relation to one another. If the workers of a line or a section see that they are falling behind the other lines, they will increase their productivity to catch up, which could create healthy competition on the floor.

5.3. Changeover conducted twice within the same component owing to different lamination types

Each product type has two different foam types that require different lamination machine settings. The lamination machine setting has to be changed for the different foam types. This changeover normally takes about 4 to 5 minutes. The team decided to change the process as follows: the operator will start laminating with the first foam type and continue until the entire trolley car of this foam type is finished. At this point, the lamination machine setting will be changed to allow lamination with the other foam type. On average, the operators lose about 1 hour per shift if they change the machine setting after each foam type. There are three lamination machines, so the models are allocated to each machine. The new method gives the operators approximately 30 minutes per machine to increase their productivity.

5.4. Introduce a pre-lamination station for the foam-cutting process and start-up for success

The idea to introduce a pre-lamination station for foam cutting was based on the observation that the Q time of leather kits during this process was overlooked, reason being the time taken to complete the foam cutting of the entire trolley, the steamer can start working on the first completed trolley and if the is any (mixed parts, wrong cuts, and shortage of panels), foam concerns this can be addressed at the same time. If the steaming process takes place at the lamination machine, the operator feeding the line has to stop and rectify the error. Often, rectifying the error entails walking to the foam-cutting area to retrieve what is called a replacement foam panel. A replacement foam panel is an extra foam panel that is used to replace wrong cuts or that is used when the incorrect foam panel was supplied. Depending on how long the delay may be, the lamination operation will be idle while it waits for the outstanding foam panel to arrive. All panels that make up a kit have to be processed since the trolley cart cannot proceed to the next operation until all panels have been laminated.

Identifying these issues before the process reaches the line will resolve many of the production delays experienced at the lamination operation. Based on this observation, the team came up with the idea to relocate the pre-lamination station to the foam-cutting area. The pre-lamination station is a table that is placed before the lamination machine and that is used to pack and align leather and foam panels so that operators no longer have to do the alignment on the conveyor – all the parts are prepped at the pre-lamination station and fed directly onto the conveyor. With the introduction of a pre-lamination station, only one person is needed to feed the cut panels through the lamination machine, thus improving the 5Swithin the lamination area significantly. The additional 2 employees per machine can be moved to the steaming area, which improves the availability of material awaiting to be laminated, also allowed for the setup for success to be introduced.

5.5. Material availability at each process not defined

During the Kaizen event it was noted that not all process which feeds into the lamination process started , At the same time, this was due to availability of leather kits. Taking into consideration each process Takt time .The Q time, the team introduced a 25% availability of leather kits per process.

5.6. Rearrange the lamination work area to improve the flow at the workstation

A layout improvement was also implemented at the lamination operation to improve flow within the work area. During the brainstorming session one of the team members suggested that the pre-lamination stations be moved closer to the lamination conveyors. Placing the pre-lamination stations next to the machines eliminates the distance the operators have to walk to fetch leather and foam panels. This simple improvement allows operators to grab pre-aligned leather and foam panels and to place them directly onto the conveyors.

5.7. Redefine job tasks for operators at the lamination operation

Once pre-lamination stations were placed alongside the lamination machines and the employees received all the necessary training regarding the new changes, the new pre-lamination process was in place and the flow within the workstation was improved through 5S. With all the new changes in place, the team could start defining and outlining specific job tasks for operators at the lamination stations. This idea emerged during the Gemba walk conducted by the team.

During the Gemba walk, it was observed that there was a lot of movement within the work area. Through further observation it was noted that operators performed various job tasks/roles and that a standard job task per operator was not defined. This led to a lot of movement and chaos within the lamination area. For example, when a trolley cart had to be unpacked for a new batch, it was observed that all 3 operators would start unpacking the trolley cart simultaneously. Any operator would then scan the side label and all 3 operators would then move to the lamination machine and start aligning the foam and leather panels on the conveyor. Employees did not have specified roles, so they would perform different roles and job tasks throughout a shift. This prompted the idea to redefine the job tasks and roles of the lamination operators. It was important that the team bring structure back to the job tasks that needed to be performed. To do this, the team outlined specific job tasks and delegated these tasks to specific employees.

The team decided that 2 operators should be stationed at each lamination conveyor and 1 operator should be stationed at each pre-lamination station. The only job function of the 2 operators at the lamination conveyor would be to feed the line. The operator stationed at the pre-lamination station would unpack the trolley cart, scan the side label and pre-align and prep the leather and foam panels for the line. For the trial, an additional operator was stationed at the pre-lamination station to assist the third operator with the pre-alignment of foam and leather panels. The two operators stationed at the lamination conveyor would no longer align the foam and leather panels on the conveyor but continuously feed the pre-aligned panels.

6. CONCLUSION

The study showed that brainstorming is an effective tool if all members of a team are properly trained. Improvement of productivity and output are used to surpass sales turnover by utilising all available resources. In this study, PDCA, A3 a Gemba walk, 5S and a time study were used to improve the quality hence productivity. In this study, brainstorming led to the use of various techniques to improve productivity and reduce the cost of machining with quality control. Improving productivity and output does not mean that people should work harder; instead, it means that they should work smarter, use better tools, techniques, processes and resources and implement new ideas.

Moreover, everyone in a company is responsible for bringing about and maintaining an improvement in output and productivity. Productivity and output go hand in hand – they cannot be separated. Teams must work hard to improve productivity and output if they are to achieve positive results continuously. The study further showed that the PDCA cycle, coupled with the brainstorming technique, is an effective tool for improving productivity with quality control.

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STOCHASTIC TRAFFIC FLOW ANALYSIS THROUGH AN ARTERIAL ROAD JUNCTION

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ABSTRACT

Traffic flow is characteristically random. The traffic demand measured against the design capacity of a road section yields the efficiency of the respective section. Road section capacity and demand are random variables. Road capacity varies as prevailing driving environmental conditions subject to the maximum design limits. Demand is a function of time and associated economic activity. The quantitative performance analysis of key road traffic junctions is important for planning and decision support purposes. We apply stochastic modelling techniques to measure and analyze the traffic flow characteristics of a problematic junction in order to determine the quality of traffic flow. The delay costs associated with the junction are determined. The results form the basis for subsequent interventions on junction long term use and/or redesign.

Keywords: Stochastic Modelling, Traffic flow, Transport Systems, Traffic Congestion

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1 INTRODUCTION

Road vehicle transport networks facilitate communication, trade and global supply chains. Economic activities are heavily reliant upon efficient road networks. In traffic network design, arterial roads bear the predominant, they connect important urban centers of activity and residential neighborhoods [2]. To facilitate traffic flow and enhance safety, it is necessary to control the interaction and sequence of vehicular traffic from different approaches. The inherent stop-and go movement pattern on traffic, results in significant bottleneck and possible congestion.

Intersections are an integral part of road network geometric designs [2]. Intersections arise when two or more roads merge at the same elevation. Opposing streams of traffic compete for space and time at an intersection, giving rise to a traffic bottleneck. Traffic control is necessarily a critical design factor on busy intersections. Intersection performance is determined by signal timing plan, turning movement traffic demands, traffic stream composition, pedestrian volumes, intersection geometry, temporal variation in traffic demands, driver behaviour, weather, road surface conditions, and visibility. To effect control and informed decisions, it is important to measure, estimate and monitor these parameters over time.

Traffic congestion may be considered as excess vehicles on a portion of roadway at a particular point in time resulting in reduced travelling speeds and extended traverse time [2]. Traffic congestion and consequent delays results in driver frustration, missed delivery due dates, compromised economic productivity, increased CO_2 emissions and higher fuel consumption [3]. Vehicular traffic volumes have increased considerably in and around Johannesburg. The road network infrastructure is under considerable strain, as evidenced by noticeable congestion on most arterial roads.

The lifespan of road network infrastructure may be considered indefinite. The use patterns of such infrastructure evolve significantly over time. Upgrades, re-designs, and possible re-purposing may become necessary over time. The respective decisions are a function of accurate data and information on prevailing and forecast use patterns. Traffic counts are critically important in this regard. We analyse the traffic flow patterns at an important road junction in South Africa in order to inform policy on current use state relative to original design capacity.

Traffic volumes through an intersection varies considerably with time of day. The stochastic variation of vehicle arrivals at an intersection assumes the Poisson distribution [4]. This is however regulated applying the peak-hour volume analysis method.

2 LITERATURE REVIEW

Three parameters namely, volume, speed and density describe traffic stream characteristics [5]. Volume is a count of vehicles that pass a point on a highway during a specified time interval [5]. Traffic volume is generally used to determine tally and classifications of roadway vehicles at a given location at a specific time. Accurate information on traffic volumes is vital for maintenance, design and capacity planning purposes. Rate of flow is defined as the rate at which vehicles travel through a particular point on the highway segment [6].

Traffic counts are carried out to determine the quantity, movements, and classifications of vehicles in a specific area [7]. These data can be used to detect crucial flow times, assess the impact of big vehicles or pedestrians on vehicular traffic flow, or track traffic volume changes [8]. The duration of the sample interval is determined by the type of count being performed and the intended use of the data captured [9].

Traffic volume study is performed to find the number of vehicles passing per hour, day, week, month, and year. It is generally used to determine the number of movements and classifications of roadway vehicles at a given location at a specific time and note other related traffic characteristics (composition, flow fluctuations etc.) [7]. Accurate information on the amount of traffic on the roads is vital for the planning of both road maintenance and improvement policies [7]. Traffic volume network analysis helps in deciding/planning if there is need for improvement, expansion in terms of construction missing links, by-pass, alternative road etc [7].

There are two main traffic counts methodologies, being manual and automatic count. The manual count method of collecting traffic flow data is the most prevalent, and it consists of assigning someone to record traffic as it passes [8]. This technique of data collection is labour-intensive, yet it is required in most circumstances when cars must be categorized with several moves recorded independently, such as at intersections. Traffic should be tallied and recorded individually for each movement at an intersection [8]. It is critical that traffic on roads with more than one lane be counted and categorized according to traffic flow direction [8]. Permanent traffic-counting teams are often established to do the counting at various places around the road network at predetermined intervals. The duration of the count is set prior to the start of traffic counting and is decided by the purpose of collecting data.

The automatic count method uses traffic detectors to count vehicles without any human involvement. The most commonly used detectors include inductive loops, pneumatic tubes, weigh-in-motion, and video camera [8]. The inductive loops and pneumatic tubes are placed on top of the road surfaces and when a car passes over the loop, the magnetic field changes, which activates the counting device. The automatic count approach allows for the collection of large volumes of traffic data. The traffic counts are taken at 1-hour intervals for each 24-hour period [8].

Performance of other road network service facilities can be evaluated using additional indicators e.g delay and queue length [5; 6]. Queue lengths are commonly found wherever customers arrive randomly for services [10]. Queue length affects quality of traffic flow and it is an important performance measure.

Traffic flow characteristics, specifically vehicle interweaving, frequent lane changing and the geometric deficiencies degrade traffic flow efficiency [11]. Gartner and Wegner [12] employ cellular automaton microsimulation model to study traffic flow behaviour on a signal-controlled arterial street. The model is used to analyze arterial traffic throughput and travel times for various densities and signal spacings. Ali et al. [13] evaluated the performance of traffic flow at a signalized intersection. The parameters used to assess the performance of the traffic flow included delays, operating cost, fuel consumption, and carbon dioxide emission The results showed that the level of service was low, resulting in low speeds and lots of delays during the evening and morning peak hours.

Gunes et al. [14] used the queuing theory to determine the characteristics of traffic flow. Arrival rate, traffic intensity, average number of cars in queue, and service rate were all determined using M/M/1 model Their results show that the new model results were found to be better and the mean tail length and lost time values were lower. Quan et al. [15] analysed traffic flow characteristics at a signalized intersection. The characteristics analyzed are speed, delay, and flow rate. It was found that traffic flow is normally large during evening peak hours.

Urban road junction traffic patterns are vital in traffic monitoring and accident prediction, and so play critical roles in urban traffic management [16]. Understanding traffic dynamics and diagnosing traffic congestion require the identification of spatiotemporal traffic patterns in urban road networks [17]. Such knowledge can help traffic management organizations enhance traffic control strategies, improve traffic infrastructure, and reduce congestion from a macro viewpoint [17]. Existing studies either assume static traffic patterns or a multi-variant distribution model for junction traffic levels [16].

3 METHODOLOGY

We seek to characterise traffic flow through a specific road traffic intersection in Johannesburg. The methodological approach adopted is descriptive quantitative research. Systematic traffic counts were conducted at the selected intersection, based on relative severity of congestion at the intersection. Secondary data is presented and analysed. The respective research output will offer an objective evaluation of intersection service level performance and ultimately feed into a grand traffic flow optimisation model.

3.1 Site Selection

The aim of this study is to analyse the traffic flow characteristics at a signalized intersection. The intersection under study is extremely busy, with a history of peak period congestions; and therefore viewed as problematic. It is a four-legged signalised one-way intersection with three lanes from each direction. The intersection is illustrated in figures 1 and 2 below.

Figure 1: William Nicol Drive and Leslie Avenue intersection

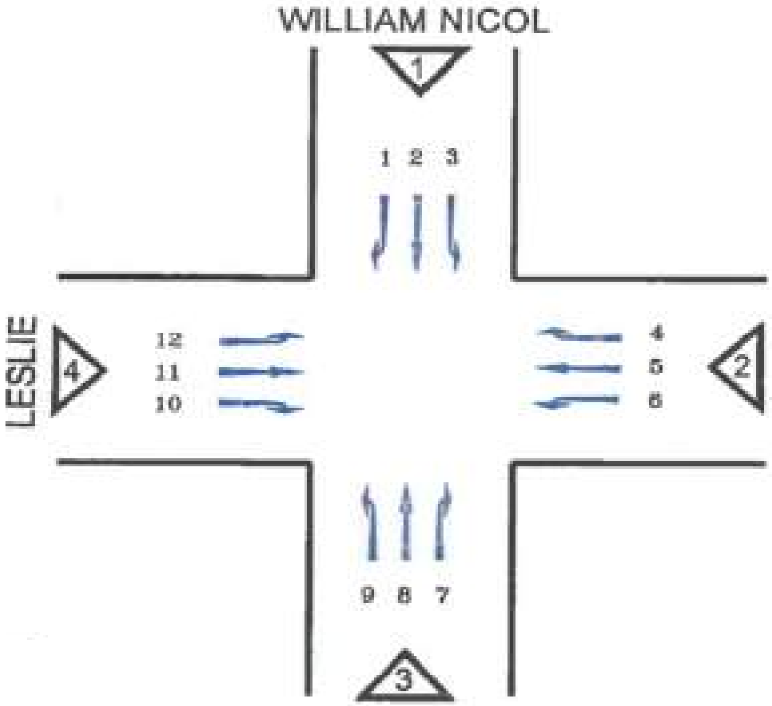

Figure 2: William Nicol and Leslie Avenue intersection

3.2 Data Sets

We apply secondary data to accomplish the objective of the study. Geometric properties were recorded on site.

The study was conducted under normal fair weather conditions. The tally reflected all vehicle types irrespective of class. Pedestrians and non-motorised cycles/vehicles are not included.

The pick hour traffic volume analysis methodology was adopted. The output data was statistically analysed. Traffic volume counts are typically stochastic, generally following the Poisson distribution. Ultimately, the estimation problem arises. To solve this problem, a hybrid of the two scenario generation methods, the sampling and deterministic methods, is applied.

There is a need to establish a finite number of scenarios. The estimation problem arises. Two scenario generation methods can be used: (i) the Sampling method and (ii) the Deterministic method. We integrate the two.

For modelling purposes, the expected value is given by:

$$g = E[(v)] = E\,[\,G(v_1 \ldots v_N)], \qquad (1)$$

Where;

g = a random variable, the volume of traffic recorded

The expected value is given by;

$$g_N = \frac{1}{N} \sum_j^N G\left(X^j\right), \quad \text{as } N \rightarrow \infty, \qquad (2)$$

Where

$X^j = \left(X_1^j .. .\, .X_N^j\right)$, is a vector of N independent identically distributed samples of v, As N approaches infinity,

$$lim_{N\to\infty}\, g_N \;=\; E\,[\,G(X)],\, with\; probability\; 1, \qquad \textbf{(3)}$$

Therefore,

$$E[g_N] \;=\; E\left[\frac{1}{N}\sum_j^N G\left(X^j\right)\right]$$

$$= \frac{1}{N}\sum_j^N E\;\left[G\left(X^j\right)\right] \qquad \textbf{(4)}$$

As sample size increases, the expected value of traffic volume in any direction approaches the mean value of the distribution in that direction.

With respect to the deterministic method, the distribution is approximated by a small number of discreet points. We select two discreet values to approximate the demand distribution, the expected value as determined above, and the highest recorded value.

4 RESULTS AND DISCUSSION

4.1 Summary of traffic counts

Table 1 below presents the summary of traffic counts. It shows the volume recorded during the peak hour for both morning and afternoon peak, for all movement directions. The peak hour factor (PHF) for each movement is presented.

Table 1: Summary of traffic counts

MOVEMENT		AM PEAK HOUR		PM PEAK HOUR		6 Hour Count
		Vol	PHF	Vol	PHF	Total Vol
North bound	NR	76	0.88	81	0.95	429
	NT	2457		2531		12101
	NL	99		55		499
East bound	ER	84	0.86	113	0.94	587
	ET	87		111		542
	6EL	427		251		1519
South bound	SR	192	0.88	264	0.94	1109
	ST	2608		1454		10871
	SL	120		708		1849
West bound	WR	682	0.97	123	0.77	2138
	WT	133		74		495
	WL	94		77		378
TOTAL		7059	0.94	5842	0.96	32517

The peak hour factor (PHF), which measures how steady traffic flows during peak hour and compares the total traffic volume during the peak hour with the traffic volume during the busiest 15-minutes of the peak hour is given by:

$$PHF = \frac{Peak\ Hour\ Volume}{4 \times Highest\ 15\ minute\ Volume} \quad (5)$$

4.2 Traffic counts

Manual Traffic counts are done by surveyor(s) who record traffic as it passes. Data is collected by using hand tally and/or manual counters. A tally sheet is designed with the first column allocated for selected time intervals. To minimize error, two or more surveyors are assigned per direction of movement. A vehicle is counted and recorded on a tally sheet as a tick as it approaches or passes the traffic signal. A stopwatch is used for measuring the count intervals.

The sample graphs presented below show the typical hourly traffic volume for morning peak, 06:00am – 09:00am and the afternoon peak, 15:00pm – 18:00 pm. in a specific direction. The graphs are produced for all traffic directions recorded.

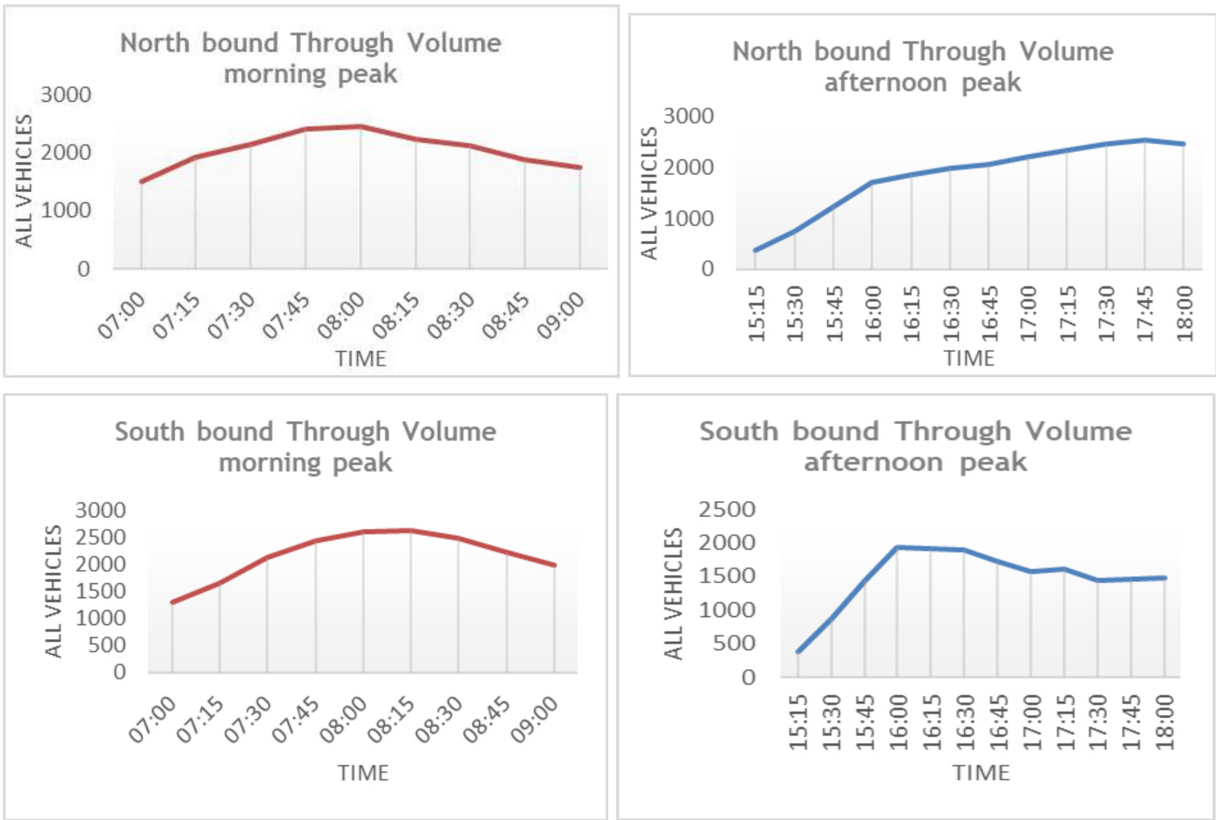

Figure 3: Traffic volumes

4.3 Descriptive statistics

Table 2: Descriptive statistics

Volume Count	Mean Veh/hr	Standard Deviation	Co-efficient of Variation	Observation	Maximum (Veh/hr)	Minimum (Veh/hr)	Number of Lanes
North bound (R)	71	21,46	0,3022535	21	104	30	3
North bound (T)	1925,048	568,3	0,2952134	21	2531	368	3
North bound (L)	80,86	26,27	0,3248825	21	112	16	3
East bound (R)	95,48	29,84	0,3125262	21	135	29	3
East bound (T)	91,24	32,79	0,3593819	21	132	21	3
East bound (L)	250,67	110,62	0,4412973	21	437	26	3
South bound (R)	185	65,91	0,3562703	21	276	44	3
South bound (T)	1768,09	557,72	0,3154364	21	2614	384	3
South bound (L)	297,43	257,12	0,8644723	21	719	44	3
West bound (R)	333,38	282,06	0,8460616	21	699	22	3
West bound (T)	81,43	29,03	0,3565025	21	133	16	3
West bound (L)	62,05	24,94	0,4019339	21	97	7	3
Overall Average	436,8065	167,1717	0,4313527		665,75	83,91667	

Table 2 shows the hourly traffic volume statistics for all directions evaluated. The North bound through traffic recorded a count of 1925,48 veh/h on average. The South bound through traffic recorded the highest maximum of 2614 veh/h. This correlates with the fact that major economic hubs are situated North of the intersection. The East bound and the West bound through movements are relatively low.

The North bound through direction has the highest standard deviation of 568,3 which indicates that the traffic volume traversing in this direction has wider spread. The turning movements (all directions) have a low standard deviation, indicating that the traffic volume is clustered around the mean.

There is variation in the peak hour volume that occurs at the intersection. The coefficient of variation (CV), which is calculated as the ratio of the standard deviation over the mean, can quantify this variance. The CV varies from a minimum of 30% to a maximum of 86% and on average is equal to 43%.

4.4 Determination of correlation between the direction of movement

Some correlation between movement directions was established. It is established that the South bound through movement has a high correlation with the north bound right turning movement. The higher the volume from both directions, the higher delay is experienced.

5 CONCLUSION

The objective of this study was to examine the traffic volume at the intersection under study. The aim was to establish traffic counts in different directions of movement and degree of congestion. This will assist in formulating demand management strategies and consequently reduce delay, queue lengths.

The results show that the demand is higher in the North bound and the South bound direction through movements. This means that more green time should be given to this direction by the traffic signal. This will allow more vehicles to pass in order to reduce the queue length and the waiting time for these motorists at the intersection.

The congestion and consequent delays negatively impact road users. Excess time is wasted in traffic, adversely affecting productivity, delivery due dates and generalised economic activity.

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TOWARDS SETTING A DIRECTION FOR DATA AND INFORMATION MANAGEMENT FOR THE ADOPTION AND IMPLEMENTATION OF THE FOURTH INDUSTRIAL REVOLUTION TECHNOLOGICAL INNOVATIONS

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ABSTRACT

The emergence of the Fourth Industrial Revolution (4IR) phenomenon has engendered a heavy dependency on integrated data & information systems and technologies by companies for effective day-by-day functioning of their operations. This is because 4IR phenomenon introduces intelligent networking of machines and processes for industries with the help of information and communication technologies, as it connects the physical, biological and the digital world. As a result, there arises a need for an alignment of Data & Information Management approaches with the organizational strategic plans for adoption and implementation of the 4IR technological innovations. The main objective of this paper is to outline data and information management in the context of 4IR phenomenon and exhibit the criticality and the influence of data and information management in 4IR technological innovations. The research methodology includes qualitative, exploratory, descriptive and integrative literature reviews. The study also proposes an information management model for the adoption and implementation of Fourth Industrial Revolution technological innovations.

Keywords: Information Management, Fourth Industrial Revolution (4IR), technological innovations, integrative literature review, technology adoption and implementation.

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1 INTRODUCTION

The advent of the Fourth Industrial Revolution (4IR) phenomenon has brought with many transformative technologies, which allow for the creation, generation, collection, analysis and dissemination of data and information to relevant stakeholders. These 4IR data and information enabling technologies include big data, analytics, cloud computing, 3D printing, drones, internet of things and others. However, these transformative 4IR technological innovations have created complexity in managerial decision making at the time when agility in decision making is critical.

The adoption and implementation of 4IR technological innovation involves elicitation, archiving and processing of very large data sets with the application of big data techniques [1]. It has been posited by [2] that one of the drivers of 4IR technological innovations is the large quantity of data that companies' need to process. According to [3] processing of large amounts of data, streamlining of operations and data transparency are some of the critical drivers of 4IR technological innovations.

According to [4], information management and information technologies are critical for the success of business as they directly affect the mechanism through which they create and capture value. It has been highlighted by [5] that data management is crucial for the creation of an environment where data can be useful across the entire organization.

Information flow is critical for 4IR technological innovations as the level of integration is relatively higher than in the preceding revolutions and 4IR phenomenon is characterized by data-based services. It has been postulated by [6] that 4IR technologies enable smarter and connected products that can generate, capture and share data.

As posited by [7] speed in sharing information that becomes the basis of decision-making, actions or other important activities taken by a customer, supplier or partner has become a major source of competitive advantage for many companies. It has been concluded by [8] that data resource in an organization is an essential asset that must be explicitly and professionally managed and requires a joint effort by both IS professionals and business managers.

According to [5], effective data and information management require business managers who are concerned about data, view it as an important asset and therefore establish a management system that treats it as such. It has been observed by [9] that businesses seeking to manage data and information effectively must understand how data information differ from other resources and what those difference imply.

There are various reasons that drive companies to embark on the 4IR technological innovations, amongst them is to reduce the cost of exchanging data and information and for executing various transactions [2], [10], [11], [12], [13], [14], [15], [16], [17].

Improved data and information and the need for shorter time delays have also been cited as one of the key drivers for adoption and implementation of 4IR technological innovations [18], [19], [20]. However, companies are faced with a challenge of having to process large amounts of data in order to improve / increase organizational competitiveness [2], [12], [21], [22], [23], [24].

One of the key aspects identified by many authors as a key driver for companies to adopt and implement 4IR technological innovations is acquisition of data for decision -making [25],[26]. It has also been established that one of the main challenges facing organizations when adopting and implementing 4IR technological innovations is data and information management [25], [27], [28]. Thus, it is critical for the organizations adopting and implementing 4IR technological innovations to have a tactical approach for data and information management.

As posited by [29], with the advent of 4IR technological innovations, it has become difficult to form organizational practices on how to use available data, who takes ownership, and how to set-up these workflows and governance structures. Secondly, the integration of several systems where data is stored is a challenge in many companies and the management of data and information across organizational and regional is generally unsatisfactory.

Due to the relative novelty of the 4IR technological innovation phenomenon, and complex integration of data and information amongst multiple information platforms, there is still emerging but inadequate scholarly work outlining data and information management approaches for 4IR technological innovations. Because all the previous studies related to the Data and Information Resource Management were conducted before the ubiquity of the 4IR technological innovations, a new domain specific model is required that can support data and information management planning for the 4IR epoch.

To fill this gap, this paper introduces a complementary domain specific Data and Information Management model for supporting adoption and implementation of Fourth Industrial Revolution technological innovations.

It is against this backdrop that this research paper considers setting a direction for data and information management by proposing a technology management-based approach for data and information management for the 4IR epoch.

The main objectives of this research study are to.

1. Understand and exhibit the importance and influence of information management on the adoption and implementation of 4IR technological innovations.
2. Highlight the strategic criticality of information management in the 4IR epoch.
3. Propose a data and information management resource planning approach for adoption and implementation of 4IR technological innovations.

This paper comprises a brief description of the research methodology used, integrative literature review, the findings and a discussion against the objectives and research questions, proposal of the data and information management model, conclusions and recommendations for future work.

2 RESEARCH METHODOLOGY

In line with the breadth of our research questions, the research methodology used for this study is a combination of an integrative literature review as well as an exploratory approach. These research methodologies were chosen in order to (i) provide a better understanding of the data and information management in Fourth Industrial Revolution epoch while highlighting the strategic criticality of data and information management, and (ii) propose a framework to be used for data and information management in 4IR technological innovations.

An integrative literature review as a non-experimental design in which objective critique, summary and conclusions on the selected subject is done through a systematic search, and analysis of both qualitative and quantitative means [30]. The integrative literature review focused mainly on peer-reviewed papers (both in research and practices) pertinent to 4IR / Industry 4.0 / digital transformation, using the following research databases, AIS Library, Business Source Complete, ScienceDirect, Scopus, Google Scholar, JSTOR, Web of Science, IEEE Xplore, EBSCO, Directory of Open Access Journals (DOAJ).

As postulated by [31] exploratory studies are useful where not enough is known about the subject of interest. It has also been highlighted by [32] that exploratory studies are valuable means of understanding what is happening, to seek new insights, to ask questions and to assess phenomenon in a new light.

To achieve the objectives of the study, the following research questions were addressed in the study.

1. What is information and data management in the context of Fourth Industrial Revolution?
2. Why should companies regard information management as a strategic element for the adoption and implementation of Fourth Industrial Revolution technological innovations?
3. What is the proposed approach for data and information management for the Fourth Industrial Revolution technological innovations?

3 INTEGRATIVE LITERATURE REVIEW

The integrative literature review focused on answering the two main research questions, data and information management in the context of 4IR technological innovations, and the strategic element of data and information management in 4IR technological innovations.

3.1 What is data & information management in the context of 4IR technological innovations?

The Fourth Industrial Revolution is described as a new industrial age characterized by the extensive use of advanced resources of data, information and communication technologies [33], [34]. Several authors view 4IR to be mainly about the technical integration of Cyber-Physical Systems (CPS) in the value chain [35], [36].

The 4IR phenomenon is being regarded as a data-driven paradigm because it makes better use of data to create more value hence many 4IR technologies are in some way related to data [37]. As postulated by [38], the fundamental approach in 4IR technological innovations is the real-time availability of all relevant information through the integration of all objects in the value chain and the capacity to determine the optimal value flow at any time from the data.

As postulated by [39], 4IR is the basis for data-based value creation, innovative business models, and agile forms of organization. However, the interpretation of these data sources still requires manual data analysis by human experts using various digital data visualizations and data and information management tools.

Data and information resource management has been defined as a comprehensive approach to planning, organising, budgeting, directing, monitoring and controlling the people, funding, technologies and activities associated with acquiring, storing, processing and distributing data to meet a business need for the benefit of the entire enterprise [40]. Important to note is that this definition came to the fore prior to 4IR phenomenon's ubiquity, thus its susceptibility to the 4IR epoch may require complementation.

The 4IR is about mechanisms that promote connectivity between machines, smart production and systems as well as integrated solutions [41], [42]. In other words, the essence of the 4IR is generation of large and complex amounts of data, usually referred to as Big Data.

According to [43] 4IR technologies foster the generation of data. As argued by [44], companies' connectivity, physical/ virtual joint functioning, interactivity, interoperability, self-organization, smart decision making, and others, are fundamental to fostering 4IR potential. The 4IR is about a Smart factory paradigm [45], [46], which essentially is the integration of physical and digital worlds through creation of smart products and processes capable of transforming the conventional value chains of cyber-physical systems [47].

According to [48], 4IR highlights the impact of IT on organizational structure, routines, information flow, and organizational capabilities to accommodate and adapt to IT. Essentially the technological root of IT and the alignment between IT and business become critical. It has been established that compatibility, integration and interoperability of ICT systems [21], integration between multiple information platforms [13], [21], [22] are some of the core context parameters for 4IR data and information performance characteristics.

It has been identified by [43] that availability of data is one of the building blocks of 4IR technological innovations. Data and information management in 4IR epoch, should fit with the SMACIT approach [49], which stands for social, mobile, analytics, cloud and internet of things.

Data and information management in the 4IR epoch means communication within the organizations whereby the organization's intention is to build networks for knowledge sharing and information sharing [50], [51], [52].

Other authors such as [53], view 4IR as a paradigm within ICT and proposed a conceptual framework based on business data exploitation. Digital security and compliance are part of the leading 4IR data and information management parameters [50], [51], [54], simply because companies operating in the 4IR epoch are excessively exposed to cyber-security threats and to protect their business are expected to take appropriate measures to counter the cyber-threats.

According to several authors [55], [56], data ownership and privacy (i.e., the rights and control over data) are highly relevant factors in determining competitive positioning and elements of an organization's data and information strategy.

Data and information management in the context of 4IR technological innovations encompasses at least, information environment, information context, information systems and information retrieval. Figure 1 exhibits that data and information management comprise of, amongst other parameters, data and information systems, data and information contexts, data and information environment and data and information retrieval. Data and information environment as applied in the 4IR technological innovation, refers to the distributed, complex and heterogeneity, end-to-end integrations of value chains concomitant with 4IR phenomenon.

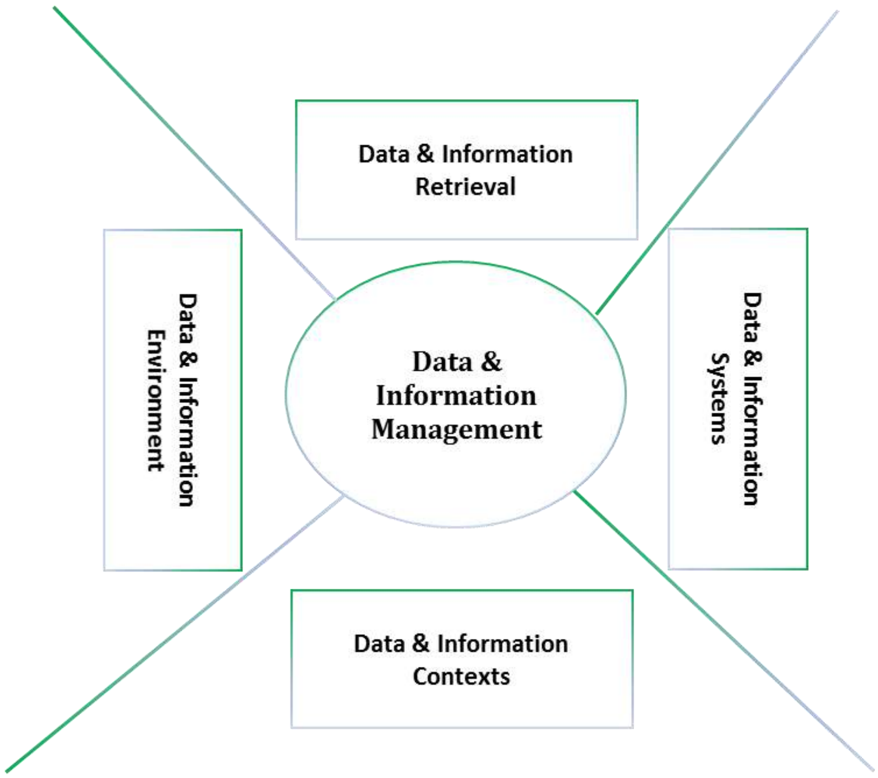

Figure 1: Data and Information Framework (Adapted from [92])

With regard to data and information retrieval, it refers to the effectiveness of retrieval performance characteristics. This is particularly important since data and information collected for 4IR technological innovations is used for agile decision making.

Data and information management systems refer to designs, implementation and usage of computer based data and information systems.

3.2 Why should companies regard data & information management as a strategic element for the adoption and implementation of 4IR technological innovations?

According to [95], strategic elements have some of the following dimensions (amongst others), require top management decision, require large amounts of company resources, affect long term prosperity of the company, has multifunctional consequences, and is affected by the company's external environment. These dimensions are fully applicable to the adoption and implementation of 4IR technological innovations, which are about the profound changes taking place in society and industries through the use of digital transformation [96], [97].

The emphasis on the criticality of data has been an issue of discussion by scholars and technology practitioners for some time. It has been concluded by [98] that the data and information revolution affects companies at least in three vital ways, namely:

- It changes the industry structure and ultimately alters the rules of the competition.
- It creates competitive advantage by giving companies new ways to outperform their needs.
- It spawns whole new business often from within a company's existing operations.

Data and information have unique properties which make them important resources for all industries, such as: Data & information are inexhaustible resource [37] and have extensive application [99]. While data and information are core resources, it is also important for companies to possess an infrastructure capable of storing, sharing, and analysing data [100].

Decision-making has become a key factor in global competition for all industries which has subsequently made the use of real-time analysis and large data processing (Big Data) capabilities a strategic issue for companies [101]. The strive for using data to make agile decisions has given rise to a need to leverage the full potential of the rapidly expanding data volume, velocity, and variety which has resulted in significant evolution of techniques and technologies for data storage, analysis, and visualization [100].

With the advent of the 4IR phenomenon, the volume of data has been expanding rapidly with many data types (structured, unstructured, semi-structured) and data sources available [60]. With the emergence of the 4IR technologies, companies have experienced rapid technological change [102], [103], exploding application and data [104], [105] agility in decision making [106], [107] frequent external shocks and growth in business management understanding of technology which result in data-based decision making.

According to [108]), with the 4IR technological innovations, the volume of data coming from sensors / internet sources has increased to the point that new data analysis techniques are required if organisations wish to integrate them in their business models to improve their performance.

It is posited by [109] that the company owns the data when it can fully control who can access the information and how it should be used. And [110], alert that in modern times, companies cannot afford to ignore information technologies.

It has been established that most critical systems and strategies rely on data, however, not enough investments have been made to ensure the reliability of data [111]. According to [112], in technological innovation management, data is critical for the following reasons: understanding of current and potential changes in the business environment, strategic and operational decisions are based on data and information, and data fosters strategic approach in organizations.

Other strategic issues brought about by the 4IR phenomenon include data security [113], [114], poor understanding of integration and systems architecture [115], and of some them have been identified as major barriers to the successful adoption and implementation of 4IR technological innovations. Other authors like [116], have identified data and information safety and security as one of the critical seven dimensions for implementation of 4IR technological innovations. That includes data storage, protection of data interfaces and use of services from ICT experts.

In the 4IR epoch, value chains within industries are interconnected and larger volumes of data are generated and the data is usually complex and heterogeneous. This increases the risk of data integrity and consistency [94], [117], [118], [119], [120].

According to [121] the functioning of the network and learning effects are heavily dependent on data. Network effects describe the value added by increasing the number of connections within and across networks, while learning effects are about capturing the value added by increasing the amount of data flowing through the same networks.

One of the critical sources of competitive advantage is speed-based strategies. Speed-based strategies are business strategies built around functional capabilities and activities that allow the organization to meet customer needs directly or indirectly more rapidly than its main competitors [95]. Data & information are key for speed –based competitive advantages as it result in optimal customer responsiveness, shorter product development cycles, reliable and speedy deliveries and distributions and most importantly quicker information sharing. According to [86], today's data & information technologies accelerate the speed at which enterprises make decisions, process information and collaborate to solve problems. It has been observed that 4IR technologies facilitate greater transparency and visibility throughout enterprise ecosystems [105].

The advent of 4IR technological innovations brought to the fore the essence of organizational agility [43], [111], [122], [123]. According to [124] time is at the core of technological innovations' success and timely executions, informed by timely data and information.

According to [125], the ability of organizations to analyse large sets of data using Big Data technologies / methodologies has become a critical basis of competition underpinning new waves of innovation. As noted by [126], data and information should be viewed by organizations as a new source of competitive advantage, and it has strategic implications for companies competing in the new age economy.

Studies by various authors [126], [127], [128], [129], indicate that data and information are new factors of production, in addition to the classical factors of production, which are land, labour and capital [130], [131].

A posited by [132], data has become a form of capital in the same way as financial capital due to its ability to generate new products and services. According to [133], data has become the underlying resource for business intelligence, and it has been the increasing availability of big data that has driven new forms of business model innovation.

As observed by [50], one of the drivers for adoption and implementation of the 4IR technological innovations is the inability to process large amount of data in the paper form, and the key success factors are compatibility, integration of information and communication systems and integration between multiple information model platforms.

Firstly, for the companies adopting and implementing 4IR technological innovation to achieve improved resource planning and improved information flow through their value chains [12], [21], [134] , they need to regard data and information resource management as a strategic issue. Secondly, process efficiencies and optimum productivities can only be achieved under shorter time delays [18], [20] and data and information is key for effecting it.

New and emerging technologies that are concomitant with 4IR technological innovations, trigger new needs and requirements for data and information, particularly processing of large amounts of data [23], [24] and pressure for data transparency [20]. The ability of companies to successfully respond to changes brought about by the emerging technologies concomitant with 4IR technological phenomenon, can only be achieved with the use of accurate and reliable data.

4 SUMMARY OF RESULTS AND DISCUSSION

4.1 Summary of Findings from Literature Review

Hereunder is a summary of the main findings from integrative literature review with respect to the research questions and objectives.

4.1.1 Data and Information Management in the 4IR Context

From the integrative literature review, many constructs pertaining to data and information management have been posited by various researchers and are summarized in Table 1. The main constructs include, data and information resource [57], [58], data interoperability [44], data and information transparency [76], data operational costs, data organising, data and information capabilities [66], [82], data and information privacy [77], [79], data and information usage [81], cyber-security [69], [73], efficient data and information management [68] , data collection [63], quantity of data and information [64], storage of data and information [61], connectivity [44], quality of data and information [88], data and information sources [58], accessibility of data and information [59].

The quality of data is important for predictive analysis. Predictive analysis is the application of skills, expertise, and algorithms on collected data to estimate the likelihood an event will take place in the future [89], [61], [90].

According to [91] with the increased connectivity and use of standard communications protocols concomitant with 4IR, the need to protect critical industrial systems and manufacturing lines and system data from cyber security threats increases dramatically.

It has been indicated by [93] that properties of data generated from 4IR technological innovations to be in large volumes, unstructured and in no direct relationship, generated and captured at a relatively high speed, and must be processed, structured and analysed within a shorter life cycle to create value.

Quality of data has at least four aspects, namely, competitiveness, accuracy, consistency and redundancy [94].

The above deliberations and discussion show that with advent of the 4IR phenomenon, the context of data and information management has changed significantly, having to encompass many parameters that were not critical in the preceding industrial revolutions. It is no longer simply about systems, context, retrieval and information environment, it now includes many additional aspects such as data transparency, interoperability, data privacy, cyber-security, reliability, high connectivity amongst others.

The 4IR epoch has made data and information management a vital component for companies adopting and implementing 4IR technological innovations. The context, scope, complexity and level of integration of data and information management have changed significantly from what it used to be. The integrated wireless network (IWN) in use needs to be aligned with 4IR data and information management to provide enough bandwidth for heavy communication and transfer of high volume of data.

Table 1: Data & Information in the 4IR technological innovation context

Data and Information Management in the Context of 4IR technological innovation	
Context Parameter	**Some Scholarly Publication**
Data and information as a resource	[57], [58]
Accessibility of data and information	[58], [59]
Data and information Sources	[58], [60]
Quality of data and information	[60], [61], [62]
Connectivity of data and information systems	[44]
Storage of data and information	[61], [63]
Volume / quantity of data and information	[60], [64], [65], [66]
Data collection	[63], [67]
Efficient data and information management	[68]
Cyber-security	[69], [70], [71], [72], [73], [74], [75], [76]
Data and information privacy	[65], [77], [78], [79], [80]
Data and information usage	[65], [81]
Communication / dissemination	[18], [51], [52]
Data and information availability	[82], [83]
Capability / resources for data and information	[66], [82]
Data and information organizing	[84], [85]
Data and information operational costs	[86], [87]
Data and information transparency	[76]
Interoperability of data and information systems	[44]

4.1.2 Criticality of Data and Information Management for 4IR Adoption and Implementation

Table 2 is a summary of attributes for criticality of data and information management when companies are adopting and implementing Fourth Industrial Revolution technological innovations. Attributes of criticality include, amongst others, the need for data transparency, compatibility, integration and interoperability of data and information systems, prevalence of inter-organizational data and information exchange, intra-organization data and information dissemination, cyber-security threats etc.

New business models that have emerged with the 4IR technological innovations can only be optimized with the use of reliable data and information. As postulated by [53], [54], [152], [154], companies must develop business models that maximize innovation and effectiveness in leveraging 4IR digital technologies.

Shaping of future business strategies is key for the sustainable competitiveness of the companies [51], [149], [154], [155], which can only be achieved with effective data and information approaches.

The above discussion affirms the criticality of data and information management for the adoption and implementation of 4IR technological innovations for the companies. The 4IR phenomenon is a data-driven paradigm because data and information are at the core of digitization [37]. It exhibits that data and information, particularly in the 4IR epoch, is an important lever that companies use to create competitive advantage.

Table 2: Key Data / Information Attributes for Criticality of Data and Information Management for 4IR Adoption and Implementation

Key Data / Information Management Citicality Attributes for 4IR Adoption and Implementation	
4IR Attributes	**Some Applicable Publication**
Data transparency	[12], [20]
Compatibility, integration and interoperability of data / information systems	[21], [50]
Integration amongst information platforms	[13], [21], [22]
Stakeholder/ ecosystems approach data management	[135], [136], [137], [138]
Inter-organizational data and information exchange	[18], [19], [61], [139]
Intra-organizational data / information dissemination	[16], [50], [51], [108], [134], [140], [141]
Inter-disciplinary collaborations	[43], [52], [61], [142]
Cyber-security threats/ regulatory requirements	[143], [144], [145]
Processing of Big Data / large amaounts of data	[2], [12], [21], [22], [23], [24]
Emerging 4IR technologies	[17], [122], [146], [147], [148], [149], [150], [151]

The findings also underline the complexity of the technological environment, exacerbated by the advent of the 4IR epoch, within which companies has to operate. According to [156], the annotations of the data entities are very diverse and it is an increasing challenge to incorporate diverse data repositories with different semantics for advanced data analytics. Moreover, this new reality is a strategic issue for companies as it has direct impact on technological innovation and performance of the companies, as well as on their sustainable competitive advantage.

4.2 What is the proposed approach for data and information management for the Fourth Industrial Revolution technological innovations?

According to [8], two key reasons for poor data and information quality are the rush to install new systems and the failure to take up an integrated view of the organization's data and information requirements.

It has been proposed by [9] that some critical points for organizations to consider when dealing with data and information resources, are, focused internal data management programs, honed data needs, identification and management of the most critical information chains, recognition of the proper role of technology, development , maintenance and availability of the inventory of data resources, terms and conditions under which data may be accessed, clear delineation of management accountability for data, leadership for data management programs.

Figure 2 shows the data and information resources planning process as posited by [8]. It also shows how the Data and Information planning processing could be aligned with the business direction. This is one of the Data and Information Resource Management Planning models that were compiled prior to the ubiquity of the Fourth Industrial Revolution phenomenon.

According to Figure 2 , the process starts with assessment of the company's information usage, data and information architecture, strategic plan and operational plan. As shown in Figure 2, feedback is only happening between Assessment of Information Use and Management "and "Vision of How the Business Should Use Information". This might not be adequate when dealing with data and information concomitant with complex 4IR technological innovations.

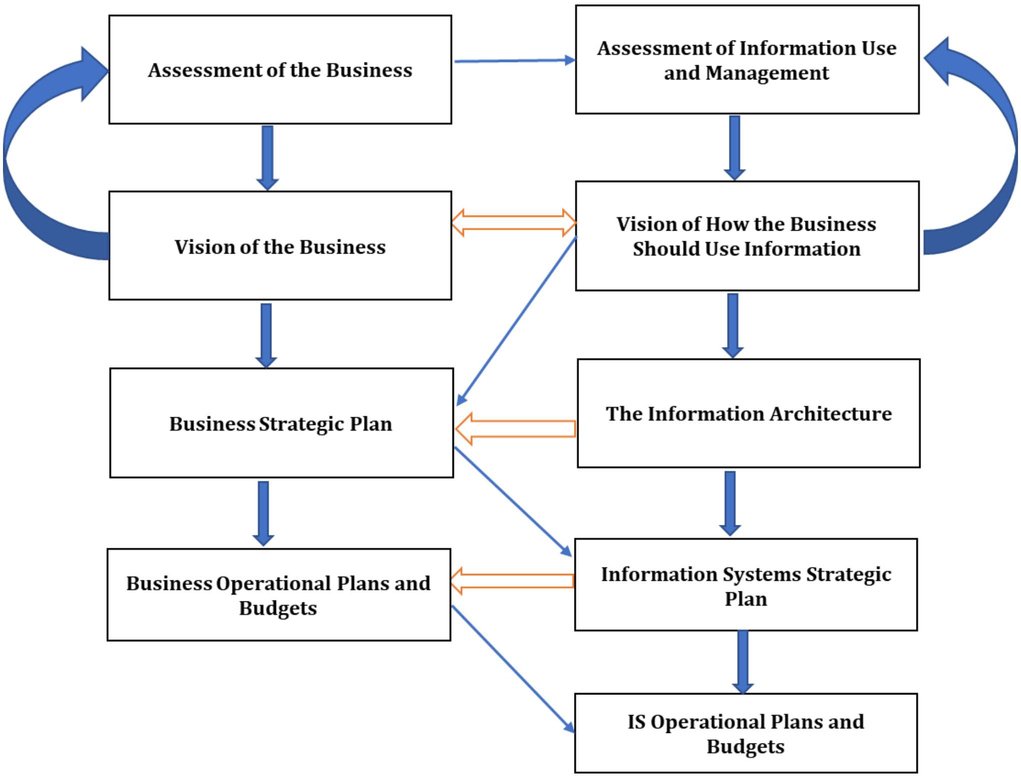

Figure 2: Information Resource Planning Process [8]

It has been reported by [157] that the emergence and diffusion of 4IR digital technologies have led to increased data and availability, which has subsequently increased the importance of data and information management. Considering the complexity , level integration and intelligence concomitant with Fourth Industrial Revolution technological innovations, Figure 2 needs to be complemented so that it incorporates the specific complexities associated with 4IR phenomenon, and Figure 3 does just that by proposing a complementary data and information planning model that can be used by companies when adopting and implementing 4IR technological innovations.

This proposed model encompasses the following key dimensions: fundamental complementary functions of general management functions (planning, organising, leading and control), PESTEL (drivers, enablers and constraints), Technology, and Innovation management process framework (identification, selection, acquisition, exploitation and protection), data & information planning process and performance characteristics & outputs.

When conducting data and information management and resource planning, it is important to understand the environment in which the organization operate, hence the need to have full appreciation of PESTEL constraints, enablers and constraints.

In contexts of data and information management for 4IR adoption and implementation, drivers and enablers can be seen as external or internal triggers for why organizations engage in data and information management.

The proposed model commences with the identification of 4IR data and information requirements. As posited by [158], identifying, and agreeing on the requirements for a new information technology (IT) application are two of the most difficult tasks in the information systems delivery (ISD) process.

This step is an integral part of the framework as it is about understanding data and information management's challenge that the company needs to attend to. It is in this step whereby a desired level of data and information management for 4IR technological innovation will be set. This step is particularly important as it has been established by many authors that large volume of data gathered through various technologies used in 4IR leads to difficulty in extracting the useful data [94], [117], [118], [119]. This step is meant to assist companies in generating data and information of value.

It has been alerted by [158] that not only are there multiple stakeholders whose various ways of understanding requirements must be taken into account and reconciled, but their ideas may change, particularly in long-term projects or if business conditions and key stakeholders change.

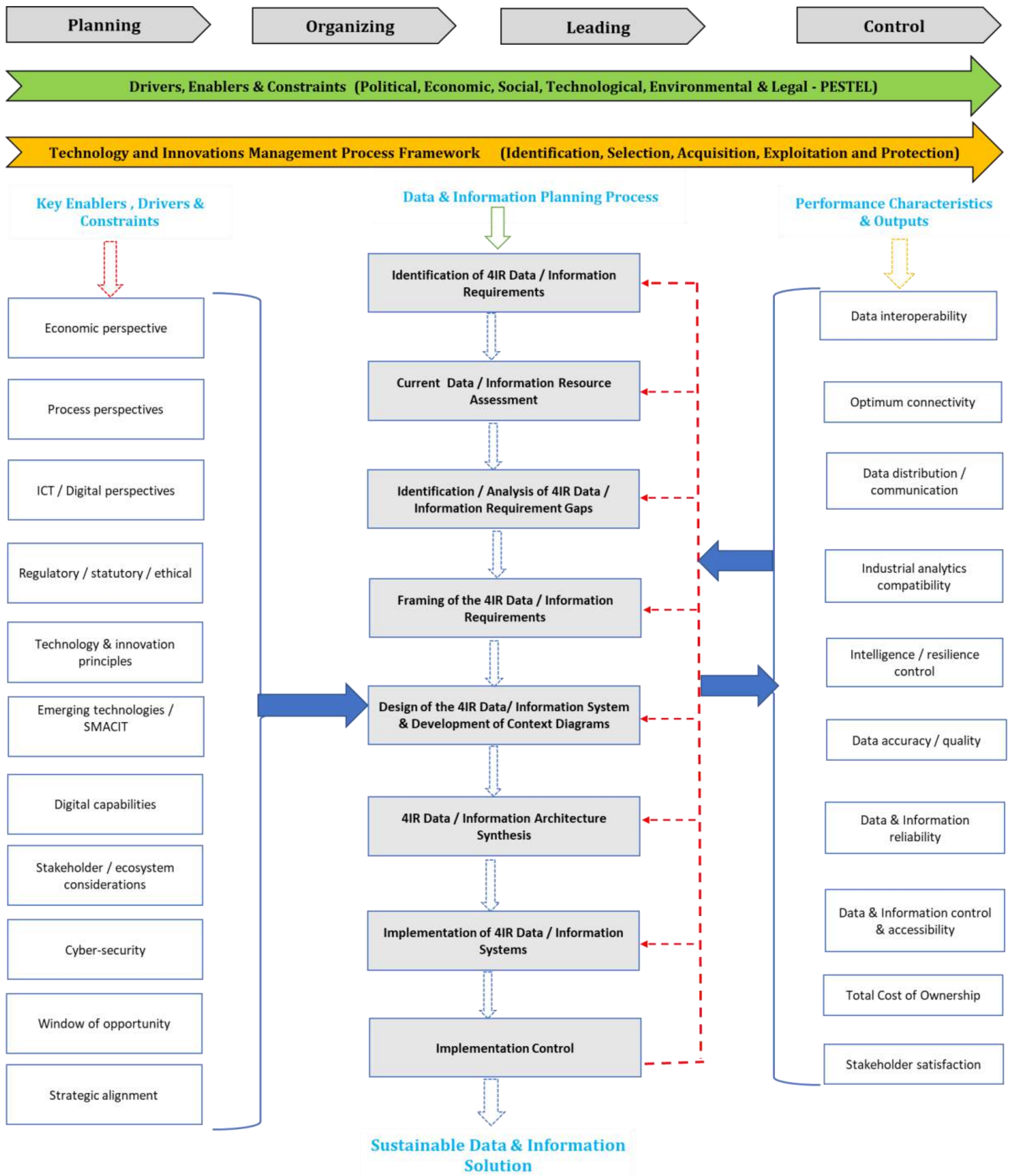

Figure 3: Proposed Data and Information Planning Model

The second step is to assess the current data and information resources status. This step is about determining the current status of data and information management which forms the basis for the gap analysis. It has been found that in some instances companies are not ready with all the technological infrastructure needed with every stakeholder in the value chain [35], [119], [159], thus creating a barrier for successful adoption and implementation of 4IR technological innovations.

The third step in the proposed model is about gap analysis of the 4IR data and information requirements and the current resources status. This step allows for analysis and prioritization of the gaps between the current and 4IR data and information requirements of each of the alignment components, and it is this step that provides the major content of the business. Understanding of the gaps will assist in ensuring that adequate focus is achieved, and effective prioritization is made.

The fourth step is the framing of the 4IR data and information requirements and is essentially about the important information applications and technologies. According to [160], the main objective of the framing process is to ensure that the right problem is tackled, from the right perspective, by the right people and it assist aligning the team towards success and reduce the probability of failure.

The fifth step in the proposed data and information planning process, is the design of the 4IR data and information system and development of context diagrams. [161] warns that infrastructures do not grow from scratch, but inherit the strengths and limitations from the existing base. According to [162] data and information infrastructure only creates value if it reflects a large and diverse user base and components, and most importantly data and information management system should be designed for direct usefulness. Emphasis has been made by [161] that design rules relate to a prioritization of immediate use value by being simple to implement and use, as well as to postpone scalability, extension, and completeness of the solution.

On completion of the design of the 4IR data and information system and development of context diagrams the next step is the synthesis of 4IR data and information architecture. The 4IR data and information architecture synthesis is about the data and information technology priorities, policies, and choices that allow applications, software, networks, hardware, and data management to be integrated into a cohesive platform. According to [8] data and information architecture specifies how the technology, human assets and the IS resources should be deployed to meet the companies' data and information needs and requirements. Elements of the architecture include, but not limited to, hardware, software, network, data, personnel, management etc.

Step number seven in the data and information planning process is about implementation. This step is the "doing" part of the proposed model where the organising and leading are critical to ensure that all that have been identified are implemented effectively and efficiently. It is at this step that alignment with respect to business and functions plans, leadership, culture and any necessary support systems must be ensured.

The last step in the data and information planning process is implementation control. According to [163] the controlling function involves monitoring the activity and measuring results against pre-established standards, analysing and correcting deviations as necessary and maintaining/ adapting the system.

In conclusion, the proposed model complements data and information resource planning models that were adequate for the industrial revolutions preceding 4IR. This proposed model will assist companies in honing their data and requirements as it gives some guidelines of how to approach data and information management and planning in the 4IR epoch. It will also help in alerting companies in understanding the importance of identification and management of most critical data and information chains that every company adopting and implementing 4IR technological innovations should take into account.

What is also unique about the proposed model is that it is not only about ICT / digital technologies, but it also renders full recognition to other complementary management disciplines such as general management, strategic management, and technology management. Thus, it is an inclusive data and information management framework and is integrative in its approach.

5 CONCLUSION AND RECOMMENDATIONS

This research paper highlights the criticality of data and information resources management and planning for adoption and implantation of 4IR technological innovations. It has brought into light that the pervasiveness of the 4IR technologies commands for new forms of data and information management and planning to effect and support 4IR technological innovations.

The motivation for this research stems from the lack of existing research focused specifically on data and information management and planning for industries adopting and implementing 4IR technological innovations. Data and information management approaches and strategies for industrial revolution preceding 4IR are not adequate as 4IR technologies brought with unprecedented complexity, levels of integration and co-ordination and unprecedented volumes of data & information.

As it would be the expectation with any technological innovation, it is critical to understand the mechanisms and processes through which data can be used to add business value to user companies, and to have a clear understanding of the concomitant elements and their interdependencies.

The study revealed that data and information in the context of 4IR technological innovation has a broader meaning and implications, which comprises data compatibility, integration and interoperability of ICT and systems, connectivity, cyber-security, data transparency amongst others. It also brought in the postulation that data and information management, particularly in the 4IR epoch, should be viewed to encompass data and information that the company utilizes as well as the broader spectrum of emerging, convergent and linked technological innovations concomitant with 4IR phenomenon.

This research paper proposes a framework with the following key action fields, fundamental complementary general management functions, PESTEL enablers, drivers and constraints, technology and innovation management process framework, data and information performance characteristics and outputs & data and information resource planning, that could assist with data and information approach when adopting and implementing 4IR technological innovations.

To ensure that data and information management systems are aligned to 4IR technological innovation, companies must engage in a pro-active, dynamic data and information resources planning as shown in the proposed model. The proposed model for data and information management for 4IR technological innovation is a critical base for inputs into the framework for adoption and implementation of the Fourth Industrial technologies.

Important to emphasize is that data and information management /resource planning model should be linked and aligned to the company's business plan and strategic goals.

This study contributes to the Fourth Industrial Revolution body of knowledge in twofold: firstly, it highlights and contextualize the criticality of data and information management and planning for adoption and implementation of 4IR technological innovations. Secondly, it proposes a framework that can be a useful input into business strategies, technology management frameworks and policy-making by scholars, practitioners and policy makers respectively. The study also enriches the body of knowledge in the field of technology management, general management and strategic management, ICT/ digital management by highlighting the complementary synergic possibilities.

Recommended future research work could include an in-depth case studies with quantitative and empirical approaches to offer an opportunity for the application and understanding of the proposed data and information management and planning framework.

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ASSESSMENT OF LEAN MANUFACTURING PRACTICES AND STRATEGIC SUSTAINABILITY IN THE AUTOMOTIVE SECTOR

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ABSTRACT

The popularity of lean manufacturing mostly stems from empirical evidence that it enhances a company's competitiveness and quality by reducing all forms of waste. The South African automotive manufacturing sector is in a state of despair with losses from Covid 19 and the April floods of 2022. When demand is high, lean and the Toyota Production System (TPS) methodologies are ignored and only volume is prioritized, which contributes to defects, scrap, and failure to meet operation targets and increase in vehicle recalls. The purpose of this study is to assess lean manufacturing practices (LMPs) and the extent to which the organisation utilizes innovative strategies to improve sustainability in a highly competitive manufacturing environment. The research methodology is mixed method in nature using qualitative and quantitative instruments for data collection.

Keywords: Lean, Quality, Sustainability

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1 INTRODUCTION AND BACKGROUND

"*South Africa's weak manufacturing growth has hurt growth in sub-Saharan Africa*" [1]. South Africans are concerned about de-industrialization over the past 20 years and that imported goods are increasingly replacing locally produced goods. As a result, South Africa's manufacturing future is being questioned and challenged. This is occurring against a backdrop of relentless government intervention aimed at stabalising the tide of de-industrialization while positioning the manufacturing sector in a more favorable and expansive position [2]. Manufacturing is the lifeblood of any country's economic growth and critical for job creation.

Between 2014 and the first quarter of 2020, the sector's contribution to GDP was less than 1 percent. Between the second and third quarters of 2020, the sector recovered and recorded a contribution of 10.8% and 16.2%, respectively. Aspects such as the easing of closure restrictions, improved production of food, beverages and motor vehicles contributed to this higher contribution. Be that as it may, the sector's activity level remains worrisome and is significantly below that of recent years. For example, annual manufacturing output at the end of the fourth quarter of 2020 was down by about 11%, due to declining steel demand and Covid-19-related production stoppages [3].

Currently, the main challenges in the this sector are the quality of the product that does not meet the global standard, defective products that affect the image of the organization, recalls, and the lead time, where customers do not receive their orders on time, which contributes more to customers opting to utilize alternatives. Given the fact that Toyota is highly rated in the utilization of lean, the study's purpose is to examine lean manufacturing practices (LMP) and the extent to which the automotive sector uses innovative strategies to enhance quality and its sustainability [4].

The automotive sector has introduced smart tools that can detect anomalies in use and stop the production line until the problem is fixed; by introducing the smart tools, the company is able to improve quality. Every product or service is judged by its quality, and the quality of the product improves the demand. TSAM invests more in quality through training and the latest facilities. Motorized sector has also introduced the Manufacturing Academy, whose main purpose is to recruit unskilled workers directly from high schools and train current employees in the sector's principles and tradition.

Currently in the automotive sector, when the demand is high, lean and Toyota Production System (TPS) methodologies are ignored and only volume is prioritized, which contributes to defect flow out of the process, a scrap rate that is too high, failure to meet operation ratio (OPR) and straight delivery rate (SDR) targets, and in some cases, recalls. Downtime on the production line, delay of parts, members not achieving target time, machine breakdown, and no feed from the lines behind are the factors that affect the daily target, resulting in a delay in the entire production line.

1 LITERATURE REVIEW

1.1 Introduction

To identify appropriate strategies that could be employed to meet the study's objectives; this section evaluates the literature on previous research projects based on lean manufacturing methods and quality measures. The section examines two topics: lean theory and quality measures.

1.2 Lean Theory

The studies find that despite numerous studies providing empirical evidence that lean improves quality and eliminates waste in the value chain, implementation of the benefits, application, and opportunities of lean manufacturing practice (LMP) is still slow, warranting further evaluation. Less than 30 percent of LMPs are successfully implemented. In addition, researchers have documented numerous cases of failed AMP implementations, even in companies in developed countries such as the U.S. and the U.K [5]. The literature focuses primarily on the benefits of implementing lean manufacturing principles in an organization, but researchers have acknowledged the amount of work required to critically evaluating a successful lean manufacturing program, and they note that little research addresses the challenges of sustaining lean manufacturing once it has been implemented in a production system [6]. Although many companies report great benefits from lean applications, there is still much uncertainty about the applicability of lean outside of the stable, high-volume manufacturing environment [7].

Many researchers have proven that lean can shorten lead time, improve quality and productivity, reduce inventory, and lower costs, while on the other hand, profit and competition increase. However, not all lean initiatives are successful; some fail due to inadequate plans to implement lean strategies. Lack of management support, lack of training, and unwillingness of employees to change are all factors that contribute to the failure of lean. It is impossible to manage lean without evaluating its results. By implementing a quantitative method to determine lean performance, decision makers can quickly review the efficiency of manufacturing processes and identify potential areas for improvement [8]. Lean principles can occasionally fail because business leaders often do not have a map of their own company [9]. Increasing globalization and rising customer demand are increasingly forcing manufacturing companies to seek effective and flexible means to overcome challenges in applying lean. Many academics have already contributed knowledge about lean manufacturing, but they have yet to distinguish the exact way in which lean tools are applied, making it difficult for scholars to grasp the practicality of lean. Companies, especially in the automotive industry, are finding it difficult to compete in the global marketplace. Therefore, they are turning to alternative tools and strategies to succeed, such as lean manufacturing, which aims to meet customer demand while reducing waste [10].

The success of manufacturing companies is generally determined by their ability to carry out daily operations using effective work methods and techniques. Several basic principles for production management in a company are part of lean manufacturing. Numerous companies have recognized the need to put lean principles into practice to increase productivity and gain a competitive advantage in the very turbulent global business environment. To gain insight into the elements that influence the sustainability of lean manufacturing, the factors that influence lean manufacturing principles in a production system were examined. A checklist is used to give some order to the observations on the different topics. Without neglecting the other topics of the study, the study concludes that operations meetings, training, and problem solving are the three most important topics that require attention from all the observed topics with different observable elements. If the way training is conducted is improved, many other problems could be solved as training has been found to be the main cause of other problems as shown in the study [11]. To understand the challenges and barriers of lean, we need to examine current technical management, leadership culture, organizational science, and employee development [12]. Lean practitioners have identified seven forms of waste: Transportation, Inventory, Movement, Waiting, Over processing, Overproduction, and Defects, which need to be clearly understood and well communicated in production [13]. The seven forms of waste are listed as follows [14]:

1.3 Defects

Customers place a high value on quality, and it is this factor that keeps any business afloat. Defects can be found not only in the manufacturing process but also in any other process, such as the maintenance process. For example, if a maintenance repair is performed and the fault returns quickly, this indicates a flaw in the repair process. Standardization of work procedures is an effective way to reduce the likelihood of failure and improve quality. Processes can be mapped, and potential quality issues can be displayed on charts. If a quality issue arises, the standard procedure should be reviewed and updated to avoid making the same mistake in the future [15].

1.4 Unnecessary inventory

Inventory is a type of waste that should be minimized. Lean inventory management is considered worthwhile inventory management. The following activities should be done to attain a lean inventory system [16]:

1. Production levelling is the lean strategy employed to remove overproduction and consequently decrease the inventory level.
2. Adoption of JIT and Kanban is an important activity to achieve lean inventory.
3. Total productive maintenance (TPM), statistical process controls (SPC), and total quality management (TQM) guarantees the accessibility of machines and aid managers in implementing inventory plans.

According to empirical research, lean production does, in fact, boost a company's competitiveness. Increased inventory waste will result in higher interest, space, record-keeping, and obsolescence expenses. [8].

1.5 Waiting

A backlog of materials is a waste. An operator who has no meaningful task to accomplish while waiting for supplies or instructions is wasting time.

1.6 Transportation

Materials must be transported further and at greater expense due to an unsatisfactory industrial layout. To shorten the moving distance, work canters should be close to one another. Someone might argue that WIP inventories have no room in close work canters. The material should be transported to the location where it will be used. The material must be carried directly from the vendor to the assembly line area where it will be used. The term for this technique is point-of-use storage (POUS) [17].

1.7 Inappropriate processing

Over-processing is unintentionally doing more processing work than the customer requires in terms of product quality or features, such as polishing or applying finishing in some areas of the product that will not be seen by the customer. Over-processing occurs in situations where overly complex solutions are found to be simple procedures [18].

1.8 Overproduction

Overproduction results in more material handling, poor quality, and irrational inventories. Consuming resources for things that aren't necessary could result in a lack of resources for products that are. Never overproduce goods just to keep workers and equipment occupied. Leave it alone if the needed load is less than the capacity. Labour can be transferred to other departments, used for machine cleaning or maintenance, accepted for training and education, etc.

1.9 Unnecessary motions

To avoid running and handling losses, the operator must have his tools handy and must be handed the required parts or materials in the correct orientation. The operator should never leave his workstation to look for spare parts or tools. 5S is a good technique to eliminate the problem of looking for tools. Access to tools is greatly improved by keeping them organized and placed in a visible location [15]. Takshi Osada invented 5S in the 1980s as a management tool or approach to create and maintain higher quality, productivity, and a safe work environment in an organization. 5S not only streamlines the work environment and reduces waste, but also helps improve workplace safety [19]. The main problem is that management often lacks an organizational chart, which occasionally causes lean concepts to fail. Recent research shows that only 55 percent of middle managers can accurately identify even one of their company's top five strategic priorities, and more than half of them fail when it comes to explaining strategy to their employees. Not only are strategic goals poorly understood, but they also seem disconnected from the company's larger business plan [20].

2 QUALITY MEASURES

The cost of quality is more than twice the cost of error-free execution. All resources and costs spent to produce the defective product are lost and spent again to compensate for that defect [5]. Quality principles use simple and clear methods that must be followed if the company wants to achieve world-class quality [21]. The company should understand that these methods will not work without a strong corporate culture. Training, technology, management support, poor planning, and employee attitude are some of the many factors that affect the quality of the product produced by a company [22].

Quality is considered one of the most difficult problems that manufacturers must solve in the era of globalization as they seek low-cost distribution channels for their goods. Companies need to maintain quality at marginal cost and apply total quality concepts as the best approach to solve this problem. One possible cause of the recalls was Toyota's inability to keep pace with its recent aggressive growth. A requirement that leads the company to ignore Lean or TPS methodology and focus on chasing demand. This study has provided a systematic framework of Crosby's 14 quality principles for manufacturing challenges and contributes to the body of knowledge by recognizing a hierarchy model of variables used in an ISM-MICMAC strategy for successful TQM implementation. Up to 85 percent of all inefficiencies are the result of a company's systems [23]. The TQM methodology extends the traditional manufacturing process to the entire organization and all of its functional areas. According to the findings, the stated principles of "take action to effect change," "introduce training," "encourage employees to learn," and "introduce leadership" are strategic requirements, while "reduce fear," "break down barriers between personnel areas," and "eliminate number quotas" are tactical requirements. Operational requirements for TQM applications include adopting the new philosophy, creating consistency in improving products and services, and ending reliance on mass audits. TQM is a set of management principles for continuously improving product quality and operational efficiency to satisfy customers. It is now widely used in the management jargon of companies on a global scale [21]. TQM is the main manufacturing strategy that plays an important role in strengthening the competitiveness of companies in the market, and the popularity of lean manufacturing is largely due to empirical evidence that it increases a company's competitiveness [8].

The TQM principle is illustrated in the figure below:

2.1 Total Quality Management

The theory of total quality management (TQM) places a strong emphasis on employee engagement, customer happiness, and continual development. The overall goal of an organization is to meet the expectations of the client or customer. For every organization or firm to be resilient and competitive, the business world has prioritized quality [24].

The figure below (Figure 3.1) illustrates the concept of TQM.

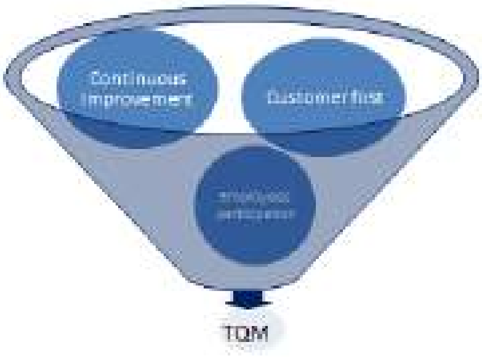

Figure 3.1: Total quality management

The figure above (Figure 3.1) is showing TQM concept. To achieve TQM the customer comes first and to meet the needs of the customers there must be employee participation in the continuous improvements.

The study goes on to state that several studies have been conducted on TQM, but no study has examined the relationships among Deming's 14 quality principles. The study concludes, "*Top management should promote employee education and institute leadership to successfully implement TQM in service and manufacturing companies*". TQM is a philosophy that emphasizes customer satisfaction, employee involvement, and continuous improvement [25].

The seven quality control (7QC) tools can be of great help in improving quality in a company. Control sheets, Pareto charts, cause-effect diagrams, flow charts, histograms, scatter diagrams, and control charts are examples of graphs for improving product quality and competitiveness. Companies' main goals are to improve quality and reduce costs and lead times. They achieve this by putting the ideas of lean manufacturing and quality measures into practice [26].

The quality of goods and services is largely determined by the competence of the people who provide them. In commerce, products are tangible items that are exchanged for other goods or services [27]. Services, on the other hand, are activities provided by others, such as teachers, doctors, hairdressers, dentists, and even Internet services. According to economic theory, the end consumer is rewarded with satisfaction and utility through the consumption of products and services. Businesses consume products and services as part of the process of producing other goods and services. Marketing theory, on the other hand, uses the goods-services model [28]. Employees' work experience has a significant impact on how customers perceive the quality of goods and services. Consumer satisfaction is determined by receiving the goods and services that the customer expects. If an organization's employees promise a good or service that the operation cannot deliver, the customer's expectations are not met, the consumer is disappointed, and the quality of goods and services is not perceived. Operations and production do not determine the quality of goods and services. Customer expectations, the actual goods or services received, and the manner in which the service is delivered [29].

The ability to achieve higher productivity standards without compromising quality is an important goal of a manufacturing company [19]. Quality has a cost that is more than double the cost of doing things well the first time. All the resources and expenses used to produce the defective product have been lost, and new expenses are incurred to make up for that defect. In addition, there are other costs associated with implementing changes, root cause analysis, and process improvement. Defects, rework, and additional requirements or adjustments are added together to form the cost of quality. Some examples of lean manufacturing techniques include cellular manufacturing, multifunctional workforces, lot size reduction, just-in-time (JIT), labour delegation, TPM, setup time reduction, TQM, continuous flow manufacturing, agile manufacturing strategies, safety improvement programs, process capability measurements, and human resource management (HRM)[16].

The fierce competition that exists today on a global scale in all industries is forcing companies everywhere to constantly strive to improve their goods, services, and operations. Toyota Motor Corporation is one of several companies in the automotive sector that have distinguished themselves by placing quality at the heart of their production process. The Toyota Production System, which promoted the formation of business excellence models, has been continuously developed, applied and refined to improve their goods, services and operations [30]. The factors that affect product quality in Kenyan printers are training, technology, management support, poor planning and employee attitude. These are just some of the many factors that affect the quality of the product produced by a company [31]. Motor sector defines quality as a product that meets and exceeds customer expectations. To ensure good quality at motor sector, the company has implemented various quality measures, such as quality cycles, kaizen, cause-and-effect diagrams, problem-solving procedures, Group-by-Off (GBO), Poka-Yoke systems, suggestion system, the 5Tei system, system check sheet, Andon system, My Problem and Countermeasure Sheet, system check sheet, defect tracking sheet, and the use of smart tools TSAM includes Hoshin Kanri (policy management) and Nichijo Kanri (daily management) by management and supervisors [32].

2.2 Cause-and-effect analysis

The cause-and-effect diagram (Figure 3.2) illustrates the problem-solving technique that motorized sector employs to get to the root cause of the problem. The diagram shows one of the functional a defects that was picked up at group-by-off (GBO).

In this diagram (Figure 3.2), it is easy to pick up what was the cause of this defect (pinch bolt loss). The first noticeable thing is that under "*machine*", the poka-yoke tool was faulty. A poka-yoke is a tool that detects if there is a problem and stops the line, but in this instance, it did not detect the problem. It is also noticeable under "*material*" that the scanner was not working and the bolt was cross-threaded, which caused the bolt to not be fully tightened. The bolt was not pre-fitted, which caused the cross threads. Under "*man*," it shows that the operator did report that he was experiencing a problem with the poka-yoke tool. The finding from the analysis shows that the problem occurred under "*method*", "*machine*" and "*material*", which led to "*pinch bolt loss*". After the root cause has been found, a countermeasure needs to be implemented to ensure this defect does not flow out again.

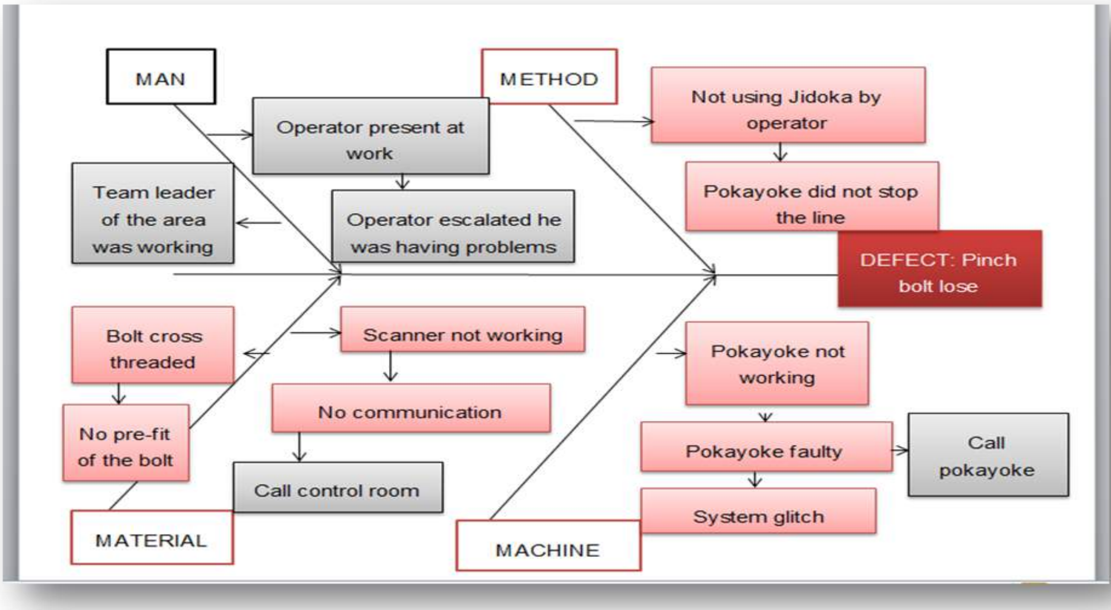

Figure 3.2: Cause-and-effect analysis

2.3 Group-by-Off (GBO)

The GBO diagram below (Figure 3.3) illustrates the system that the automotive sector employs to pick up the defects that occurred during the process.

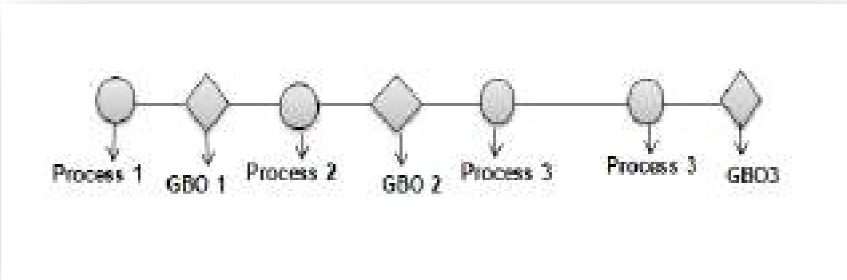

Figure 3.3: Group-by-Off

Each production line has a quality gate, also known as a group-by-off (GBO), where double quality assurance checks are performed. The sector has established a culture in which the customer is a part of the production line; process number one sells the product to process number two, and so on until the product reaches a consumer who has paid for it, all while adhering to quality standards. The quality management system and standardized work are considered the organization's culture, which is followed by all of TSAM's affiliates.

3 RESEARCH METHODOLOGY

This section presents and justifies the methodology adopted for this study, and the approaches that were used to collect database on the research questions formulated. It also includes data collection methods and instruments, instrument construction (questionnaire), survey questionnaire development, and scale construction.

3.1 Research design

The mixed method design was used to examine and analyse data. The importance of mixed method research is that it provides the time, place, and tools for the researcher to describe, analyse, interpret, and clarify experience as it is lived and constituted in awareness. It aids researchers in comprehending the views, intricacies, and under-researched areas of participants. Because the study's focus was on examining lean manufacturing techniques and strategic sustainability in manufacturing sector to enhance quality, competitiveness and sustainability, it was based on an exploratory research paradigm to allow a complete review of the causes of not attaining the aforementioned targets [33]. To find fresh insights into phenomena, exploratory investigations often take an open, flexible, and inductive approach to study. Forty-four (44) questionnaires were sent out to various respondents in the organisation. Of the fifty (50) that were send out only 35 of them were returned representing a response rate of 80%.

3.2 Target population

In this study, the target population was fifty (50) top management staff in four departments at TSAM. The study focused only on TSAM, and survey questionnaires were distributed via email among the sample group.

3.3 Sampling method

The probability sampling method was employed by the researcher, where individual components are selected through a logical, technical, or mechanical process, similar to the lottery approach, rather than being consciously or thoughtfully chosen from a set of components [33].

3.4 Measuring instrument

For the proposed research, a survey questionnaire was constructed that is in line with the identified objectives of this study. Relevant questions in the data collection instrument were also constructed uniquely and originally.

3.5 Data analysis

Statistics Package for Social Scientists (SPSS) is the best application for evaluating data. For this reason, the researcher divided the qualitative data analysis process into five stages and used SPSS version 27 for the quantitative data. To create graphs, tables, and correlations for descriptive analysis, SPSS version 27 was specially employed.

4 RESULTS AND DISCUSSION

4.1 Factors that affect the quality

The figure below (Figure 4.1) shows the factors that affect quality in motor sector. This figure also indicates where the company must focus on improving in order to achieve high quality.

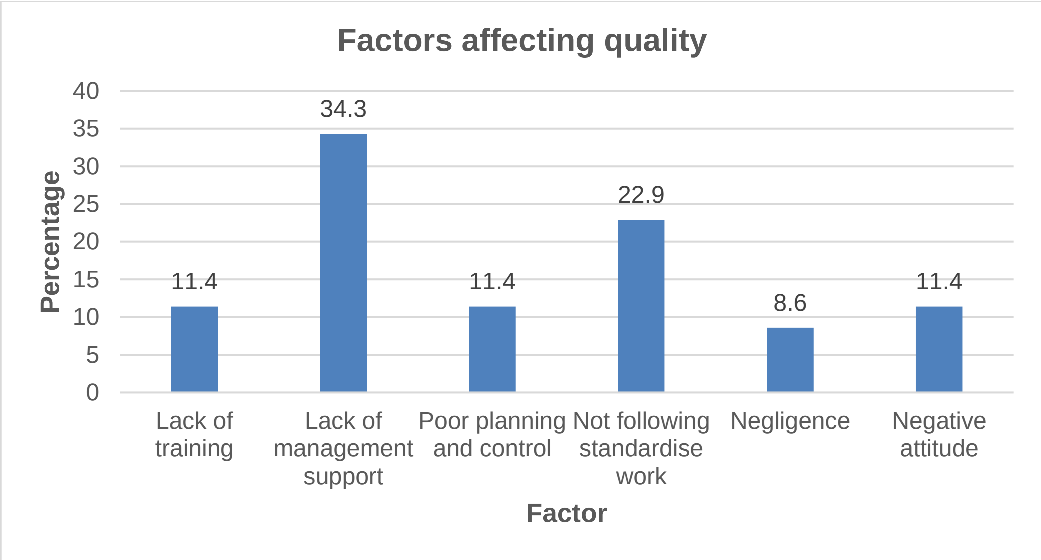

Figure 4.1: Factors affecting quality

Management support refers to managers' willingness to adapt to employees' schedules and tasks and provide support that can help employees better manage and complete their tasks. This is confirmed by the results of the study, which show that about 34.3 percent of TSAM employees believe that lack of management support is the biggest factor affecting the quality of work. However, not all lean initiatives are successful; some fail due to inadequate plans to implement lean strategies. Lack of management support, lack of training, and unwillingness of employees to change are all factors that contribute to the failure of lean, which also leads to poor product quality. Customers place a high value on quality and that this factor keeps any company afloat. Defects can occur not only in the manufacturing process but also in any other process such as maintenance process. For example, if a repair is made and the defect quickly reappears, this indicates a defect in the repair process. Standardizing workflows is an effective way to reduce the likelihood of errors and improve quality [15].

4.2 Quality measures

The figure below (Figure 4.2) represents the quality measures that are in place in TSAM and also shows which quality measure is the most effective.

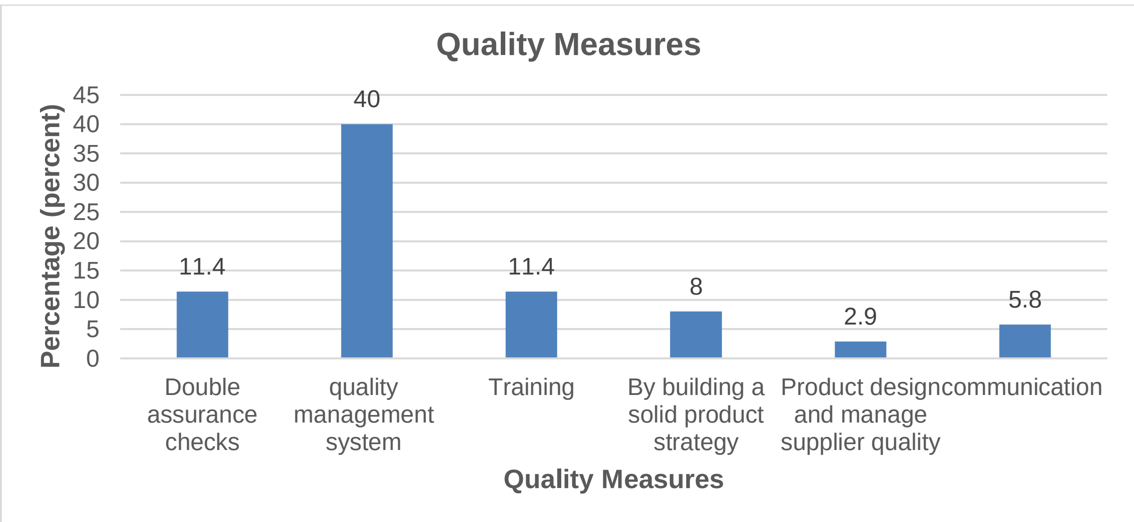

Figure 4.2: Quality measures

The main challenges in the motor sector are product quality that is not up to global standards, defective products that affect the image of the company, and lead times where customers do not receive their orders on time, which contributes to customers being more likely to use alternatives. This assertion is also supported by the results of this study, which show that 40 percent of the respondents believe that the company has implemented some quality management systems [4]. This is also supported by the study that defines quality as only suitable for the intended purpose. The study further reveals that quality in the manufacturing sector is determined by how closely the product meets the specified product requirements. This ultimately leads to improved organizational productivity, which translates to a better work environment for employees and leads to business expansion. This ultimately leads to improved organizational productivity, which impacts a better work environment for employees and leads to the expansion of the company. Seven quality control (QC) tools are very helpful in improving quality within an organization to achieve higher quality. Inspection sheets, Pareto charts, cause and effect diagrams, flow charts, histograms, scatter plots, and control charts are the seven basic QC tools. To increase profit, quality is a critical aspect in the manufacturing industry [26].

4.3 Perception of lean

The perception of lean as understood by motor sector is depicted in figure 4.3 below.

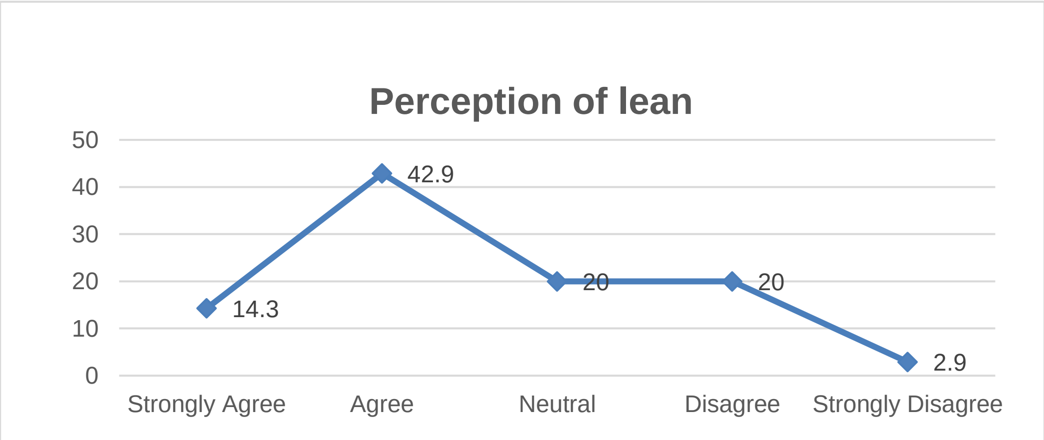

Figure 4.3: Perception of lean

The results show that about 42.9 percent of the respondents agreed that they had a better understanding or perception of lean. The respondents in this study were employees, department managers, senior executives, and directors who indicated they had a better understanding or perception of Lean. However, the main problem is that management often lacks an organizational chart, which causes lean concepts to occasionally fail. Recent research shows that only 55 percent of middle managers can accurately identify even one of their company's top five strategic priorities, and more than half of them fail when it comes to explaining strategy to their employees. Not only are strategic goals poorly understood, but they also seem disconnected from the company's larger business plan. The sobering reality is that most business leaders are unable to articulate their company's strategy in a simple and compelling way [20].

4.4 Good lean practices (continue practicing)

The figure below (Figure 4.4) represents the elements that motor sector must continue to practice.

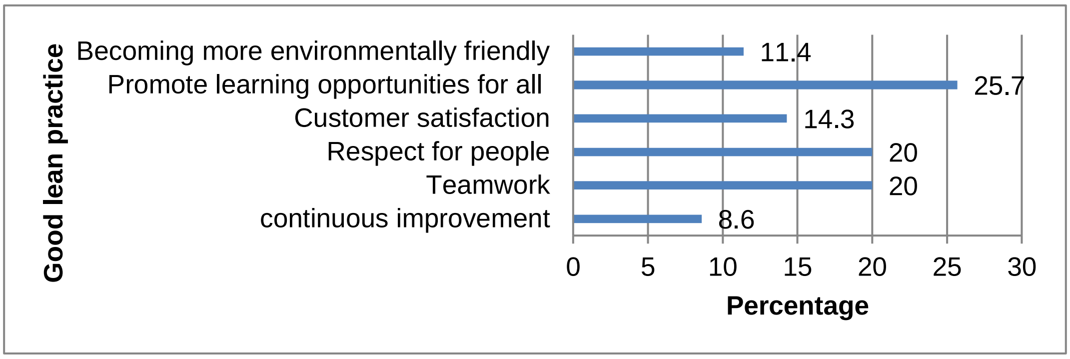

Figure 4.4: Good lean practices (continue practicing)

During the study, respondents were asked about the good practices they would like to see the organization continue practicing. About 25.7 percent recommended that the organization carry on promoting learning for everyone. About 20 percent of the respondents encouraged the organization to carry on promoting teamwork amongst employees, while the other 20 percent emphasized the aspect of respect for employees no matter their position in the organization. About 14.3 percent indicated that the organization should keep focusing on customer satisfaction; on the other hand, 11.4 percent indicated that the organization should become more environmentally friendly. The remaining 8.6 percent emphasized that the organization should continue focusing on continuous improvement.

4.5 Not good practices (stop practicing)

Figure 4.5: Stop practicing

The researcher asked the employees in motor sector about the practices that the organization should stop practicing, and the results indicated that 22.9 percent of the respondents highlighted that the organization should stop treating employees as numbers but rather as assets. Furthermore, 20 percent of the employees indicated that the organization should stop compromising on the quality of products over volume, while 14.3 percent said that the organization should stop prioritizing profit over employee well-being. About 11.4 percent of the employees emphasized that the organization must stop hiring or employing unskilled people in positions of influence. The other 11.4 percent said that the organization should stop setting unrealistic goals and practicing poor planning and control. The remaining 8.6 percent said that the organization should stop micro-managing employees.

The majority of employees believe that training and management support can improve quality. It was interesting to see that the majority of the respondents indicated that the level of communication was very good in the automotive sector; however, there was still room for improvement in downward communication.

There were some good practices that the respondents would like to see the organization continue practicing, such as promoting learning opportunities for all, continuous improvement, respect for people, teamwork, customer satisfaction, and becoming more environmentally friendly.

5 RECOMMENDATIONS AND CONCLUSION

5.1 Introduction

This section concludes the study by summarizing the key findings in relation to the research objectives

Objective 1:

What limitations, challenges and good practices of lean that can be identified in the automotive sector?

From the data in this study, it appears that the organization should stop treating employees as numbers, but rather as assets, and that the organization should stop compromising on the quality of products versus quantity. In addition, organizations should stop hiring or employing unskilled employees in positions of influence. This is consistent with literature highlighting that Lean and TPS methods are not prioritized when demand is high, which contributes to defects flowing out of the process, which later leads to a high scrap rate, excess parts from inventory, failure to timelines, or even recalls because the standard is not met. The daily target is always affected by downtime caused by stoppages on the production line, machine breakdowns, parts shortages, and lack of replenishment from downstream lines, resulting in a delay on the line [32].

5.2 Objective 2:

What are the quality measures that the automotive sector has implemented to improve product quality and competitiveness?

From the survey data, 40 percent of respondents indicated that quality management systems should be used in practice to ensure good quality. Literature indicates that the automotive manufacturing industry is the most important industrial sector in South Africa. The major challenges in the manufacturing sector are product quality that is not up to global standards, defective products that affect the image of the company, and lead times where customers do not receive their orders on time, which contributes to customers being more likely to use alternatives. This assertion is also supported by the results of this study, where 40 percent of respondents believe that the company has implemented some quality management systems to improve quality and competitiveness [4]

5.3 Objective 3:

What can the automotive sector recommend as best lean/TPS practices and strategic sustainability in other small and large manufacturing sector?

Various data collected suggest that the organization should stop setting unrealistic goals and poor planning and control, promote learning for all, invest in training and development, and improve communication. This is supported by the literature that suggests that training, technology, management support, poor planning, and employee attitudes are some of the many factors that affect the quality of the product produced by an organization [22].

6 CONCLUSION BASED ON THE STUDY

The main objective of this research paper was to assess lean manufacturing practices and the extent to which the automotive sector uses state-of-the-art facilities to improve quality and sustainability. Based on the results of the study, the following conclusions were drawn:

- In terms of lean implementation, the study concludes that the most important aspect of the organization is training. This is supported by the results of the study, with (50.8 percent) of respondents indicating that training is the most important aspect of the organization.
- The study concludes that the factors that impact quality are lack of management support and failure to follow standardized work procedures. The study also suggests that a negative attitude is the cause of many problems in the company and in the outside world. The responses show that (34.3 percent) believe that lack of management support is the main factor affecting quality, while (22.9 percent) believe that standardized work is the main factor.
- Regarding the perception of lean in terms of understanding, the study concludes that there is an understanding of lean production, as respondents can understand the issues related to the process of lean production. About (42.9 percent) of the respondents support the study's findings.
- In terms of perceptions of lean as it relates to lean practices, the study concludes that companies need to build a culture that emphasizes quality improvement and ensures that employees are satisfied with their work environment. The study also concludes that managers should increase job satisfaction and encourage personal development. Respondents (14 percent) support the study's findings.
- According to the research findings, the study can conclude that the vast majority (82.9 percent) of respondents want to satisfy customers, which indicates that respondents are willing to go the extra mile to satisfy customers.
- Based on the research findings on quality measures, the study concludes that quality management systems should be used in practice to achieve good quality. (40 percent) of respondents believe this is the best quality measure that can be implemented.

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HOW SYSTEMS THINKING CAN HARNESS CORPORATE ENTREPRENEURSHIP: A CASE STUDY

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ABSTRACT

This study investigates how Systems Thinking can help organisation function better through proven Systems Thinking philosophies. The research is built around the current mode of thinking (traditional linear thinking) by means of assessing the organisational complexities, linear thinking philosophy, organisational policies, and the contributors to innovation challenges. The study was carried out using mixed methods, first the quantitative and thereafter qualitative method. Managers from different divisions and departments responded through the anonymous questionnaires and ten managers were sampled for in-depth follow-up interviews. The results showed that there are complex challenges that are experienced in the everyday business within the organisation due to a lack of Systems Thinking within the corporate. These challenges range from hindrances to achieving departmental goals which ultimately lead to not realising the main goal of the organisation, challenges with the written policies, synchronisation amongst different teams, etc. The study showed that linear thinking within an organisation hinders the organisation's chances of remaining competitive in the external environment (market).

Keywords: Systems Thinking, Corporate Entrepreneurship, Linear Thinking, Systems Thinking Tools, Competitive Advantage.

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1 INTRODUCTION

Systems thinking focuses on addressing complex systems and diverges from conventional linear thinking that isolates observations of phenomena [1]. Numerous corporations face challenges and find it difficult to thrive in highly competitive environments. One of the factors contributing to these struggles is the prevalent perception of entrepreneurship as a linear process, rather than recognising it as a complex system with interconnected stakeholders and activities influenced by feedback loops. To unlock the full potential of businesses and corporations, establish a sustainable advantage, address the needs of the natural ecosystem, and maximise profits, it is essential to comprehend the application of systems thinking in corporate entrepreneurship [1].

Corporate Entrepreneurship is a term used to describe entrepreneurial behaviour within mid-sized and large organisations. Systems Thinking offers a framework for identifying and addressing future challenges by proactively developing solutions. It allows for the possibility of adapting or completely abandoning a concept based on the insights gained from a systems perspective or systems foresight, indicating whether the concept would be advantageous or not.

Businesses are dominated by feedback loops, coincidental consequences of business decisions concomitant structures, mental models, and wavering of inventory and staff levels, all these are all suited to systems thinking tools and concepts [2], [3]. Systems Thinking offers a meniscus for instituting and examining purpose, structure, and conduct in the context of a largely complex and dynamic environment [4], [5], [6].

In this study, Systems Thinking is employed effectively in the context of a local organisation by using the deductive method to understand how the traditional linear thinking philosophy is detrimental to business. Linear thinking can be defined as static in nature focusing on particular events, viewing behaviour generated by a system as driven by external forces and viewing causality as one-way with each cause independent of all other causes [18]. Taking into consideration the latter definition, the study's objectives were derived:

1. The challenges experienced with lack of Systems Thinking within the organisation,
2. Systems Thinking practices and its effectiveness in remaining competitive and relevant in the external environment, and
3. challenges that are faced within the organisation during the process of innovation.

The article commences by introducing the theoretical foundation and the conceptual model, which addresses the three research questions of the study. This is then followed by an explanation of the research design and methodology. The paper concludes with a discussion of the study's main findings and their implications within the organisation and lastly, the research limitations are provided.

2 THEORETICAL BACKGROUND

Meadows [7] stated that despite the technical brilliance that has been meant to diminish the various challenges that face society, such as poverty, environmental degradation, unemployment, and drug addiction, these issues continue to exist. The concept of systems thinking is a framework that aims to help society think critically about its complex problems and develop effective solutions. It was developed to address the limitations of traditional linear methods of problem analysis and thinking. According to this concept, it is not enough to study all parts of a system in isolation but rather when solving the problem, it is necessary to consider the various interactions of components [8]. This study explores how systems thinking and Entrepreneurship can be combined to create a more effective and efficient corporate environment.

Systems thinking is described as the collection of techniques, methods and concepts that are utilised to comprehend a phenomenon where there are powerful interactions between the various parts that together form complex systems like those in entrepreneurship and sustainable development [9]. Classic Systems Thinking literature focuses on the balance of forces and counter forces to maintain equilibrium. This helps explain how current social issues are perceived, and how and where these issues are at present. Cabrera et al. [10] have pointed toward an enlightened understanding of the models' complexity and the development of more upgraded mental models. Mental models can be explained as extremely held internal images of how the world operates [3]. One of the most challenging phenomena which is at the forefront is that it is difficult to predict the effects that will be because of changes made. This is because a single change can influence flow, leading to the second, third, and umpteenth sequential consequences [11]. This phenomenon is not widely discussed in entrepreneurship literature, and it means that entrepreneurs' mental models are not fully equipped with the skills to anticipate the consequences of a new product or service when it is launched [1].

Entrepreneurship is often regarded as a system or network of interlinked actors that is related to the complex issues such as sustainability and this topic is rarely discussed in the academic research environment [1]. A system outlook on entrepreneurship is required to consider the various factors that affect the development and operation of a business and also requires the entrepreneur to explore and consider the effects of the system that is being targeted [13], [14].

Morris *et al*. [15] stated that advantage derives in Corporate Entrepreneurship from five crucial organisation capabilities namely adaptability, flexibility, speed, aggression and innovativeness. Organisations that are more flexible, aggressive, fast, adaptable, innovative, and aggressive enough are well positioned not only to adjust to a threatening, dynamic and the complex external environment, but they have the ability to create change in such an environment [16].

3 RESEARCH DESIGN AND METHODOLOGY

Corporate entrepreneurship has various segments, and is considered complex as it involves all divisions within the corporate which contribute to the business functionality.

To study Systems Thinking in this particular corporate, the conceptual model outlined on Figure 1 links the main concepts namely Systems Thinking; Complexity Management; Innovation Dynamics and Managers Thinking Style and the associated research questions were formulated:

1. What are some of the organisational complexities caused by lack of Systems Thinking practices within the organisation's corporate business/entrepreneurship?
2. How are managers affected by maintaining the traditional linear thinking philosophy in the corporate place?
3. Which challenges do the organisation faces with respect to innovation, stakeholders and inter-departmental participation during the innovation process?

Figure 1: Conceptual model for Systems Thinking on Corporate Entrepreneurship.

Research design can be described as the logical sequence that links the empirical data to study's research questions and eventually towards the conclusion [17]. Triangulation method was used to obtain data and the conceptual model was created to answer the research questions.

The research was set and conducted in one of South Africa's largest logistics organisations which has various branches and operating divisions throughout the country. The organisation has assets worth more than R350 billion. It is an organisation with a strong chain of corporate entrepreneurial activities between its six divisions. This organisation made it possible to study the impacts that systems thinking has on corporate entrepreneurship because of its vast operations in the country.

Data gathering was carried out through a survey questionnaire (25 questions) which was sent to different managers within the organisation in different departments and divisions, and 60 valid responses were received (70% response rate). After the results were interpreted from the survey questionnaire, 10 managers from different departments and divisions were sampled for in-depth follow-up interviews using the purposeful sampling technique. Purposeful sampling technique affords one an opportunity to focus more in-depth on a phenomenon and therefore allows one to explore cases rich in information from which one can learn greatly on issues of central or principal importance to the research [12]. The interview respondents were selected on the basis of the departments they represent. Some of the sampled departments were Welding Co-ordination, R&D, Operations Department, Mechanical Design Office just to name a few. These departments were selected to get a broader view from different branches of the corporate so that a broader perspective can be drawn.

Statistical Package for the Social Sciences (SPSS) was used for descriptive statistics for quantitative data and Atlas.ti was used to analyse the qualitative data. The quantitative data paved the way for the collection of qualitative data. The empirical results of the primary qualitative data were linked to the research questions being studied. This was achieved by capturing qualitative data with Atlas.ti, followed by coding and therefore deducing themes from the coded data using thematic analysis.

Due to the reason that this was a case study research, only descriptive statics was used to analyse the quantitative data. The quantitative approach was undertaken to guide what questions should be most focussed on to attain in-depth qualitative data. Construct viability was enhanced by comparing the various interview responses where possible. The authenticity of the results was guaranteed by sternly adhering to the comments and answers given by the participants during the interview process.

Formal ethical clearance from the ethics committee of the university was obtained on 08 August 2022.

4 RESULTS

4.1 Quantitative results

The survey results indicated that there is little trust between management and employees. The command control structure is the kind of structure that aims to control employees and could lead to little trust between the two forces. There is a division on whether management recognises strong job performance (meaning the reward feedback system is not as strong as explained by [3] with over 90% of the respondents having stated that they understand how their work impacts the organisation's business goals. According to the survey results, most managers are not convinced that their leaders/superiors inspire them to seek more of the company vision and this has a negative impact on the organisational performance because leaders are meant to construct, architect and design the systems in the organisation [18].

Most managers agreed that they consider part of their responsibilities as ensuring that they maintain the existing corporate order which is the linear thinking philosophy and maintaining the current functioning system and thereafter letting the system live naturally. This prevents managers from thinking systematically and seeing the bigger picture which results in challenges within the corporate business and therefore hinders the entity's competitive advantage in the external environment

4.2 *Qualitative results*

From the quantitative results, managers were sampled for in-depth interviews of which thematic analysis was used to analyse the data and four themes emerged thereafter. These themes are presented in Figure 2 namely: complexities within organisation, linear thinking philosophy drawbacks, organisational policies, and innovation challenges contributors

- **Theme 1: Complexities within organisation**

This theme is built on sub-themes of trust, strong job performance, and synergy. Trust is one of the most important factors in relationships and this is no different between management and employees. Trust can be eroded by a variety of factors including lack of transparency between two parties, underlying mental models, and even lack of communication.

Lack of trust has been noted to be due to so many dynamics, i.e., employees do not have a sense of transparency from managers and lately, "there has been no communication from management regarding the direction the organisation is taking". When asked if there is trust between employees and managers, one respondent answered:

"I don't think there's any trust, maybe at some levels, there might be some form of trust because of the instability but I think it's in small pockets. At this current stage with restructuring as it is, I don't think anybody can even go to their managers and ask them to explain where they will be five months down the line." (Participant 4, Manager: Welding Engineering, 25/08/2022).

When there is a lack of trust between management and employees, one of the two parties tends to execute the job religiously, simply because they have to, and it's always a matter of 'one needs to cover themselves if something is to happen and with the unions of the workers not as strong as they used to be, there is less trust and as a result, there is more of the disinterest and the indifference behaviour from employees, as one of the respondents said:

"I think in general, there's mistrust. I think it's very subdued because, you know, in the past, in this company, the unions were very strong and that has changed since. And because of that, you know everything is quiet, even though there's mistrust, it's more of a don't care attitude based on there not being sufficient trust." (Participant 1, Manager: Locomotives Business, 31/08/2022).

There also seems to be an issue with how there is a breakdown in communication from the Executive management. It was said that one of the many reasons why there is a lack of trust between management and employees is that there is no alignment. Information gets lost in the communication chain, from the Executives to the senior managers, to the middle managers and finally down to the supervisors. Top management may understand the strategy and the business plan but when the message is passed down, it gets lost in the translation and this creates misalignments and mistrust between the two parties.

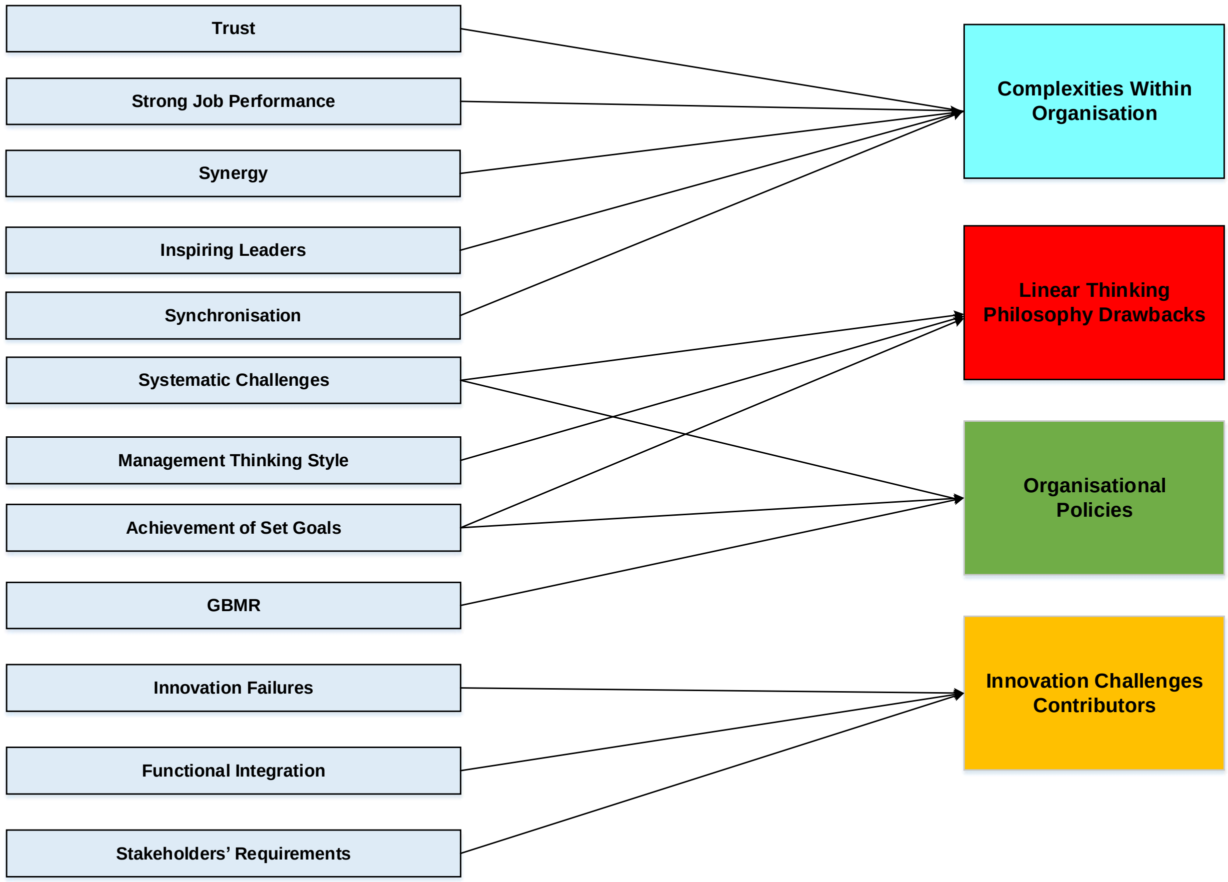

Figure 2: Analysis outcome: Coded data and corresponding themes.

Another pillar that forms part of the organisational complexities is the recognition of strong job performance. Employees tend to thrive when their good performances are recognised and when the opposite happens, the departments and organisation at large start to experience less creativity, intrinsic motivation, and good performance diminishes, short-term thinking arises, and crowding out of good behaviour can also result. From the interviews carried out, it was noted that the organisation has not been practicing such a feedback system for a few years this has demoralised many. One respondent stated that:

"There is no recognition to be honest. A good example is the KPI system that has been implemented over the years. I mean that system is not effective because at the end of the day, even if you score 5/5 on your KPI, you get nothing at the end of the financial year." (Participant 5, Senior Manager: Mechanical Design Office, 01/09/2022).

- **Theme 2: Linear thinking philosophy drawbacks**

This theme is built on three sub-themes namely systematic challenges, management thinking style, and achievement of set goals. Linear thinking has been widely practiced in the industry for a number of decades and it is only in recent decades that Systems Thinking has gained ground in the corporate world. The survey questionnaire for the quantitative data revealed patterns in terms of the maintenance of linear thinking philosophy within the organisation, where most respondents agreed that they consider part of their responsibilities as ensuring they maintain the existing corporate order which is the linear thinking style. One of the challenges with linear thinking is that failures could result, and all the interviewees agreed that keeping to such a thinking style could be detrimental. These failures could be attributed to, but not limited to; the failure to resolve or adapt to a new thinking style, the failure to recognise and resolve systematic challenges.

When the sampled managers were questioned if they experience systematic challenges within their departments, they all agreed with the first respondent sighting that 75% of the challenges being systematic in nature is basically the minimum. These challenges are a huge hindrance to operations resulting in less production and declining profit margins. One respondent stated:

"Even if there is work to do, you don't have spares. You have other issues that stop you today, for example, the whitings are not working, if the whitings work, then we can't do shunting because shunters don't have valid certification." (Participant 1, Manager: Locomotives Business, 31/08/2022).

- **Theme 3: Organisational policies**

This theme was aimed at investigating if the organisation practices the feedback systems; Goals Behaviour Metric Rewards and how the systematically structured policies contribute towards departments not achieving goals. This theme is built on three major sub-themes namely systematic challenges, achievement of set goals, and the Goals Behaviour Metric Rewards.

The metric reward system is a system that influences behaviour of employees. The Goals Behaviour Metric Rewards is a feedback system that reinforces employees positively for profitable behaviour and negatively reinforces the employees for undesirable behaviour. Employees are said to perform better when they feel appreciated, recognised, and even rewarded for good performances. Only two interviewees agreed that the organisation does practice such a system, two respondents stated that the organisation does and does not reward its employees and six respondents disagreed that the organisation practices such a system.

These organisational policies are said to be more high level and though there are those which cater for departmental rewards and these policies are not effectively implemented as far as the hierarchy descends, this was attested by one of the respondents who stated *"The policies are there, more for formalities' sake, they are rarely used and there might be some people who actually use these somewhere in the organisation, but maybe in other operational divisions not here. I actually don't know where these policies are used"*. (Participant 4, Manager: Welding Engineering, 25/08/2022). The reality that these policies are not well implemented or even practiced (for the last 4-5 years) has resulted in so much despondency amongst different teams.

- **Theme 4: Innovation challenges contributors**

This theme is critical in assessing the challenges and hindrances that the organisation is faced with as far as the innovation implementation process is concerned, both radical and incremental. The sub-themes to be explained which have been found critical for this assessment are the innovation failures, functional integration, and the synchronisation of the stakeholders. While investigating the challenges that hinder innovation within the organisation, trends related to the previous themes emerged and all these were understood to be systematic in nature.

During the quantitative data collection, just under 80% of the respondents agreed to be aware of innovation failures that the organisation has experienced. The interviews also revealed that

80% of the respondents know of various innovation failures that have happened due to the silo mentality, lack of synergy, etc as one of the respondents stated:

"Yes, there is one I can vividly think of, the XXX project is a perfect example. The stakeholders in that project did not agree on a whole lot of things, so what made that project fail from the beginning was the planning, giving the project to people who didn't know what they were doing…." (Participant 2, Manager: Welding Technology, 25/08/2022)

One innovation failure one of the respondents spoke about was the failure of XXX project that was designed a year ago. All the work, the design, and the drawings were completed. The design process was completed and commissioned, and it was in 2022 when the project was supposed to be on the prototype stage that there was an announcement of a lack of finances to fund that project. This is due to a lack of synergy and unsynchronised stakeholders between engineering and other departments because there is no understating of the organisation's position. One respondent stated that *"the design was commissioned and completed, but the project still had not come to fruition due to finances, that lack of synergy to understand where we are as a business and if there can be an implementation of this project."* (Participant 5, Senior Manager: Mechanical Design Office, 01/09/2022). This example is one of many which were explained during the interviews and one of the respondents emphasised on the issue of linear thinking being the cause of such failures.

5 DISCUSSION

Data analysis resulted in four different themes which aimed at answering the research questions namely complexities within organisation, linear thinking philosophy drawbacks, organisational policies, and the innovation challenges contributors presented in Table 1 with the research question(s) they address. Each of the themes will be discussed in more detail hereunder.

Table 1: Research questions related to themes.

Research Question	Theme
1. What are some of the organisational complexities caused by a lack of Systems Thinking practices within the organisation's corporate business/entrepreneurship?	1-Complexities within the organisation 3-Organisational Policies
2. How are managers affected by maintaining the traditional linear thinking philosophy in the corporate place?	2-Linear Thinking Philosophy Drawbacks
3. What are the challenges that the organisation faces with respect to innovation, stakeholders, and inter-departmental participation during the innovation process?	4-Innovation Challenges Contributors

5.1 Complexities within Organisation and Organisational Policies

Research question number one was addressed by themes (1) and (3); one of the challenges that the organisation is faced with is the lack of trust between management and employees. This is said exacerbated by the restructuring that is currently underway where no one is confident of the outcome. It was also observed that every time new Executive Management is appointed, there is a reshuffling of individuals which filters down creating instability and mistrust. Systems Thinking comprises of different factors in the workplace and mental models are part of them. Everyone has a mental model based on intuition and this is usually established subconsciously as a result of what is discerned to be the circumstance and cause of a certain event [19]. Good mental models yield positive structures and bad mental models yield negative structures [1], [2]. Based on these statements, there are mental models that have been developed by the employees/managers over time and have resulted in a lack of trust. Employees are reacting to events that they are faced with within the organisation and this lack of trust is an emerging pattern that is characterising the nature of the system problem. When business' KPIs are not as per expectation, managers should embark on reviewing their own mental models to determine if they require modification. Recognition of strong job performance was also one of the factors that have been found to be adding to the organisational complexities. Individuals thrive when they are recognised for good performance, behaviour, and character and the opposite is also true.

According to the interviewed managers, 60% of the respondents agreed that the organisation does not recognise strong job performance and as well as practices the Goals Behaviour Metric Rewards. Rewards form part of systematic anatomy and these are tools that motivate the desired behaviour. Rewards must also be factored within the financial constraints and should be distinctly linked to the behaviour that gave the reward as per Maslow's hierarchy of needs [2]. The lack of recognition of good performance and the reward systems causes unintended consequences such as crowding out of good behaviour, performance decline, and demotivation as shown on Figure 3. To avoid unintended consequences, the organisation should identify the structures and feedback loops that cause such consequences [4].

The organisation is said to have policies that cater to the reward and the recognition system, but these policies are more for formalities as one of the respondents mentioned. Policies should be implemented and if there are hindrances to implementing them, they should be reviewed and revised leading to Rube Goldberg structures as argued [11] as well. Monat *et al.* [2] stated that situations change and when these situations change, the policies become outdated or invalid, so it becomes prudent to review company rules, procedures, policies, incentives, and structures regularly and map out corresponding Causal Loop Diagrams to ensure that intended behaviours are yielded.

Figure 3: Employee Manager Feedback Loop, negatively reinforced because of no recognition and reward (Adopted from [2]).

Fifty percent (50%) of the interviewees disagreed that there is synergy amongst different departments within the organisation with forty percent having agreed that there is synergy. Synergy within an organisation denotes wholeness and the systems approach permits the connecting of objects at various types to a single whole and to organise various types of activities into one complete whole [18]. Synergy requires holistic thinking, centered on system logic and process orientation.

It was also observed during the analysis phase of this research that 60% of the interview respondents disagreed that their leaders inspire them, with some mentioning that some of their leaders are not aware of what the goals and vision of the organisation are. The organisational goals must be well defined because, without the proper definition of the organisational goal(s), the pathway to the future is disorganised. Organisational goals are hierarchical and start at the pinnacle of the organisation such as the Board of Directors, CEO, and President, and filter down through the company [20]. Goals should engage and support each other at all ends. The leader's new role in the organisation is to be its constructor and the systems approach regarding the organisation structurally alters the role a leader plays within an organisation. This was not found to be the case from the analysed qualitative results, and with the quantitative analysis where only 36.07% agreed that their leaders inspire them to seek the company vision. An organisation requires leaders who are charismatic and inspirational toward their followers to seek the vision, and plan the strategy, politics, and structure of the organisation [18]. A manager requires a multi-systematic approach to be able to systematically restructure the old system into a new one. However, according to the survey results that were obtained, 68.85% of the sampled managers agreed that they consider part of their responsibility as ensuring they maintain the existing linear thinking philosophy.

5.2 Linear Thinking Philosophy Drawbacks

The findings on the theme drive towards answering research question 2 which focuses on the management thinking style, systematic challenges, and the achievement of set goals. The management team in this organisation is still focused more on the traditional way of thinking (linear philosophy). This was observed from the quantitative survey results where 68.85% of the sampled managers agreed that they consider part of their responsibility as ensuring they maintain the existing linear thinking philosophy, with over 60% having agreed that they orient themselves to the maintenance of the system and therefore let it live naturally. According to [18], managers orient themselves in such a way because of lack of time, the inability to develop a holistic perspective and because of traditional ways of reasoning.

All the sampled managers for interviews agreed that they are capable of developing a holistic perspective and some attributed such ability to the fact that they have been with the organisation for a long time, and they have learned to create and understand the bigger picture. It's worth noting that even though the managers have got the capability to develop the holistic view, most managers are still linear philosophy minded as was observed during the survey data collection. Organisations are created to accomplish certain results and if such results do not ensure then structures, operational processes, information flow, and interrelations must change to meet the needs [21]. Linear thinking focuses on certain events, it views behaviour generated by a system as driven by external forces, searching for perfectly measured data and seeking to prove models to be true by validating with historical data [22].

All ten sampled managers agreed that linear thinking philosophy could result in failures within an organisation because problems are not fully defined, there is little to no information that is gathered for the problem's solution, there is no formulation of the hypotheses, presumptions, and correctness of the findings are not examined in order to create a solution of the challenges that might be expected during the course of the project [18]. The organisation has suffered so many losses due to its linear thinking style, such as lucrative contracts with competitors and costly resources.

The linear thinking philosophy also results in systematic challenges. All sampled managers agreed that their departments are plagued with systematic challenges and that they do not reach their goals due to low morale amongst different teams, late design changes or changes in User Requirements, etc. An organisation should exercise operational thinking or dynamic thinking that will assist with the evaluation of the multi-loop feedback systems, and the identification and recognition of the delay effect and growth barriers [18].

5.3 Innovation Challenges Contributors

Theme 3 was identified to be critical in assessing the challenges that the organisation faces when they are embarking on an innovative project. Most of the findings that were observed under this theme link back to the linear thinking philosophy that the organisation is more accustomed to. This philosophy results in inherent systematic challenges that have already been discussed and therefore the hindrances in achieving the set goals as all the sampled managers alluded to during the interviews.

Eighty percent (80%) of the managers agreed to be aware of the innovation failures due to various factors such as lack of synergy, lack of effective communication, the practice of linear thinking that does not allow for a complete definition of the problem, etc. Linear thinking does not utilise the system called interactive design. Interactive design is the design of the desired and intended future coupled with implementation procedures, where it is a requirement to define the problem, identify and gathering of information for the problem solution, hypotheses formulation, observation of presumptions, and correctness of findings, and thereafter create a solution [23]. Interactivists are different from proactive and reactive players because Interactivists mainly put focus on the problem, the definition of the problem, its formulation, and the search for its solution. This becomes a critical assessment as it affords the stakeholders an intuitive skill that allows for better creativity which in turn results in a distinctive competitive advantage in the external environment. It is stated that system perspectives on innovation's focal point are the nature and influence of the collaborative character of innovation [24], [25].

6 CONCLUSION

The objective of the research was to determine and study the challenges that are caused by a lack of systems thinking philosophy within the organisation and its daily business activities. The lack of this practice leads to various organisational complexities such as lack of trust due to developed mental models between employees and management, demotivation, and despondency due to lack of good performance recognition and even lack of inspiration from leaders. This calls for managers and the organisation to stop thinking in a linear manner but a Systems Thinking way.

Four themes were identified, and these were aimed at dissecting and answering the research questions. Through the qualitative approach, different challenges were observed that the organisation is experiencing, and these challenges were observed to be mainly because of the linear thinking philosophy. Linear thinking philosophy is static in nature and does not allow for a dynamic approach towards daily activities. This thinking as the name describes (linear) is a straight-line thinking, which views causality as moving one way with each cause self-standing from all other causes [22].

Systems thinking is defined as a language, a set of tools, a perspective that has the ability to usher a holistic view that relationships observed on system components, between such components and the environment are as important as the components themselves [2], [26]. Not only does the external environment requires dynamicity, but the internal environment requires such a thinking style to annihilate various organisational complexities within the organisation. This study proved that there are various challenges within the organisations such as different mental models, and systematic challenges that hinder the departments from achieving their set goals and ultimately the goal of the organisation [3], [9], [10]. Morris *et al.* [15] stated that firms cannot remain static and so they must continually adapt, adjust and redefine themselves as this remains to be the basic principle in a free market economy.

It was found that organisational complexities are exacerbated by linear thinking philosophy because this thinking does not consider the systems methodology in holistic thinking, operational thinking, interactive design and self-organisation as explained by [23] and [26]. Static thinking focuses on certain events and views behaviour created by a system as driven by external forces and this also manifests in innovation failures that have been encountered within the organisation. Systems Thinking places the responsibility for behaviour on internal actors who craft and manage policies and plumbing of the system (i.e., organisational policies) unlike the system being thought of as driven by external factors.

7 LIMITATIONS AND FUTURE WORK

The study targeted a certain corporate organisation in South Africa. Participants in the study were selected using the purposeful technique and various managers from different departments and divisions were selected for different perspectives therefore findings of this study are limited to such an organisation. One other limitation is that the study only targeted managers and not employees and should therefore be used in such context as employees could bring a different perspective from that of managers This was a case study investigation and the case study method by design does not provide generalisation to the population. Further research could try and explore other organisations and industries at large on the effect of Systems thinking on Corporate Entrepreneurship. It is worth noting that other organisations can apply the findings of this study by adhering to the principles of Systems Thinking and as well taking into account how linear philosophy can be detrimental to entrepreneurial activities as seen in this study.

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A SYSTEMS ENGINEERING AND MANAGEMENT APPROACH TO ESTABLISHING A FLEET MANAGEMENT SYSTEM IN AN UNDERGROUND UG2 BOARD AND PILLAR PLATINUM MINE IN SOUTH AFRICA

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ABSTRACT

South Africa is a world-leading Platinum producer. Most of this mining takes place in an underground narrow tabular setting. Mines are heading for challenging times in the coming years because mines are becoming deeper and more expensive to extract. Technology must be implemented to ensure long-term optimal extraction in these underground mines. The literature indicates that surface mines have seen major production increases where fleet management technology has been implemented and that underground mines were trailing in this technology due to the harsh environment. The author, therefore, investigated how data and fleet management technology could be implemented to improve productivity in underground narrow reef board and pillar mines. The research objective was to develop and define a fleet management system using the systems engineering approach to improve productivity at the Two Rivers Platinum mine and to determine all the aspects to be considered. This mixed methods research used the literature, stakeholder interviews, and tests to design and establish the fleet management system. A case study compared the newly developed fleet management system to the current fleet management processes. The results were encouraging, indicating that cost savings and production increases could be realised.

Keywords: Board and Pillar mining, Systems Engineering, Fleet management system, Underground data network, Condition Monitoring

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1 INTRODUCTION

The Platinum Group Elements (PGE) is a scarce commodity and essential in modern advanced technologies and chemistry. The PGE comprise the following metals: Platinum, Palladium, Rhodium, Iridium, Ruthenium and Osmium.

South Africa is a world-leading producer of Platinum (92%) and Rhodium (80%) [1] and all these PGEs are mined from the Bushveld Igneous Complex. Mines must improve efficiencies and reduce costs to ensure that mines can mine at the lowest possible dollar per ounce prices and stay salient and profitable.

The mining industry is heading for challenging times in the coming years [2]: High-grade ore is more problematic to obtain because mines are becoming deeper and more difficult and expensive to extract. Mining companies need to shift to a more technological approach to ensure that long-term, cost-effective production is possible [2].

Two Rivers Platinum Mine is situated in the Steelpoort Valley on the eastern side of the Bushveld Igneous Complex and mines the UG2 (underground two chromite layers) with TM3 (Trackless Mobile Mining Machinery) using the fully mechanised board and pillar mining method. The board and pillar mining method best suit a reasonably vast, flat dipping reef. Optimal results are achieved with a reef at least 2m high [3].

The mine has 153 TM3 mobile machines currently working in the underground mining environment. These machines have intelligent capabilities and can provide valuable information and communicate information to a central data system.

These intelligent capabilities can transfer vast amounts of information remotely from an independent mobile platform to an existing data collection system such as Wi-Fi. This allows the user of the telemetry system the opportunity to receive real-time data from this separate device, as well as the ability to have remote control over this system [4].

This information could improve fleet management, maintenance, overall availability, and the utilisation of trackless machinery. The study will use systems engineering processes and more specific requirements engineering processes to define an optimal underground data collecting and management system and propose an architectural framework (AF) that any low-profile board and pillar mine can use to obtain the most optimal and efficient system. Some verification and validation processes will also be performed on the proposed system to determine if the needs of the stakeholders are satisfied. The system can ultimately ensure that machines can be operated autonomously, but this will not be explored in this study.

The data received from the machines and the proper management of this data could lead to a more efficient and effective mine. The productivity of 10 surface mines increased by between 10 and 20% when intelligent scheduling for underground mobile machinery was applied [5].

No wireless underground data system exists at Two Rivers Platinum to convey the data from the machines to a central point. Wireless networks can facilitate communication and data transfer in underground mines [6]. Still in the current underground environment, communication methods are trailing behind what is available in surface mining applications [7]. This is not solely due to a lack of effort in the underground environment but also the harsh and hazardous environment.

There are also currently no theoretical wireless models available for board and pillar mines with tunnel heights lower than 6m, and this area is not well researched [6]. This is the reason for an investigation in how technology – specifically, data and fleet management technology underground, could be used to reduce costs underground to improve the efficiency and effectiveness of the production machines generating the platinum ore.

1.1 Systems Engineering

The wireless backbone underground, the data sending capability of the machines and the data receiving, analysing and management tool can each be described as separate sub-systems. It can be described as a system. A system is an assembly of different elements that, if put together, achieves results that cannot be produced by the elements alone [8].

Systems engineering and system management is a growing trend in project environments. It changes the management principles from "project-based" to "system based" and improves the rate of overall success in a multitude of industries, including mining [9] [10].

In using a top-down and bottom-up approach when designing a system and by proper assessment of the risks and opportunities, you can ensure that the system performs more effectively and efficiently than a system created on an ad-hoc basis [10].

Various promising technologies and products failed to be implemented successfully [11]. Aerospace and defence manage to accomplish ever more challenging missions and endeavours successfully and remain at the cutting edge of technology through their use of the systems engineering approach [11].

From the literature cited above, it can be concluded that a proper way to introduce wireless technology and a fleet management system underground can be achieved by following a Systems engineering approach.

1.2 Rationale of the research

It can be surmised that Platinum Mining in South Africa is a vital industry and that optimising the production and reducing costs will ensure that a mine stays effective, efficient, and sustainable.

The machinery used at Two Rivers can provide a wealth of data that the mine can use to manage better and utilise the fleet. This can lead to efficiency improvements, reduce costs and move Two Rivers back into the 25 percentile of the cost curve.

No wireless network, data collection system or fleet management system is currently available to utilise the information. From the literature it also became apparent that wireless systems and fleet management in the board and pillar environment are not well researched.

This study contributes to the current body of knowledge. It also is a value-added proposition for Two Rivers Platinum to improve production and quality by managing the production machines, reducing operating expenditure and becoming the preferred mine of choice for potential investors.

The research proposes a combination of subsystems (data, wireless backbone and management tool) to address this problem using a systems engineering and management approach.

The systems engineering approach ensures that a better data collection and management system is produced in the challenging and complex underground mining environment.

1.3 Objectives

The objectives of this research are to develop and define a system using the systems engineering approach to use the intelligent capabilities of machines, an underground wireless network, and a computer sub-system that could better manage and maintain the Trackless Mobile Machinery at Two Rivers Platinum mine.

This system must be able to collect, interpret, integrate, manage, and verify this data continuously. The fleet management system is complex; therefore, the research will explore a systems engineering approach to ensure an optimum product for the end user and all stakeholders. The systems engineering approach will ensure that it can develop, evolve, and emerge into a management tool that any mine- and engineering manager could use to the overall advantage of the mine.

Given the objectives, the research questions are:

1. What aspects must be considered when implementing a Data sending, Collection and Fleet Management System?

1.1. How can systems engineering be used to define and develop the most efficient and effective data collection and fleet management system?

1.2. What organisational design can be used to define and develop the most efficient and effective data collection and fleet management system?

2 LITERATURE REVIEW

The three major subsystems of the underground fleet management project were highlighted, and proposed systems were investigated. The subsystems were identified as the Smart Machine, the underground data network, and the fleet management systems.

It was determined that modern machines, including Two Rivers TM3 machines, are already equipped with sensors and all the necessary hardware to communicate and send data [11].

As per [12] and [13], the onboard systems and the systems implemented in other mines were explored, and the interaction between the various sub-systems was illustrated. Signal strength and environmental challenges were also highlighted as essential aspects to consider for the machine's data-sending capabilities [6].

It was determined that underground data networks are currently not as well developed as the surface areas due to unfavourable and harsh underground conditions [7], [14]. [7] listed all the current types of data network available underground and indicated their preferences for wireless systems above permanent cabled infrastructures, echoed by [2].

A procedure for establishing a Wireless Sensor Network underground was explored by [14]. This system benefits the practical design of underground monitoring systems and applies known systems engineering processes to the environment and the controllable and uncontrollable parameters. As part of the design, positioning the underground nodes was an essential environmental aspect because of the large footprint, tunnel shapes and wave propagation of underground signals. All these aspects must be considered to ensure a cost-efficient system and continue to offer positioning solutions [2].

A data wave propagation solution for the underground board and pillar mines is proposed in [6]. Still, this theory was only tested in 6m high board and pillar tunnels and stated that further study was still needed in lower tunnel height mines. The survey into wireless data network systems for underground mines showed no examples for low profile board and pillar platinum mines where integrated data networks are used.

Very few fleet management systems are currently implemented underground, and this problem was also mentioned by [5], [7] and [15].

Productivity improvements of between 10 and 20% were achieved at surface mining operations using fleet management software and that there is no reason why this cannot be done underground because of the improvements in information and communications technology [5]. An algorithm should be used in a blasting cycle operation [5]. This algorithm considers all the production machines, including LHDs, Rigs, Bolters, and the Charging upcycle [5].

A fleet management system diagram is proposed by [13] and [5]. The Finsch model is attractive because Two Rivers uses the same OEM, and similar fleet management software will be used. The cycle algorithm will be shared with the experts from SANDVIK to adjust the fleet management system to suit the low-profile board and pillar cyclical drill and blast mines.

Lack of fleet management and automated underground mines were also mentioned by [6], [7] and [15].

Formal Systems Engineering Processes in Mining was also researched, and the conclusions were that it is currently only an emerging paradigm and there is presently a gap to explore. The advantages of the process were illustrated by [11], [13], [10], [16] and [9].

Examples are given in [9]that proved that systems engineering processes work better in complex project environments and that better results are generally achieved.

Various systems engineering and management processes were explored, and the author decided that ISO 29148 [17] would be adapted and applied to a new problem. The architectural models for the fleet management system will then be developed, and these models can be used industry wide.

3 PROPOSED MODEL OR CONCEPTUAL METHOD

The conceptual models below were used to answer the research questions. A combination of literature was used to develop a conceptual framework for the concept and development phases of the system.

3.1 Conceptual model for Concept phase of the system

A combination of the table below was used as the framework for the concept design phase of the system.

Table 3.1: Conceptual model for Concept phase of the system

Concept Phases as described in different literature			
ISO/IEC TR 24718-1 (2010:14)	ISO/IEC/IEEE 29148 (system requirements, condensed tasks)	Blanchard (2004:16)	Blanchard Requirement Process (Blanchard, 2004:17)
1. Exploratory research	Identify the stakeholders that have interest in system throughout life cycle processes	Research	Identify Need
2. Concept Selection	Elicit stakeholder requirements	Definition of need	Understand the objectives
Characterize solution space	Define stakeholder requirements	**Conceptual design**	Define the system requirements
Identify stakeholders' needs	Analyse and Maintain stakeholder requirements	Needs Analysis	Consider Alternative Configurations
Explore ideas and technologies	Define system requirements	System Operational Requirements	Compare Test Data With Requirements and Objectives
Refine stakeholders' needs	Architectual design: Define the architecture	System Maintenance Concept	Measured Characteristics
Explore feasible concepts	Architectural design: Analyse and evaluate the architecture	Advance product planning (Plans and Specification	Choose the optimum design
Propose viable solutions	Verification and Validation process		
	Management Process of the system		

3.2 Conceptual Model for developmental phase of the system

This section aims to test, using iterative processes, the best possible configuration to meet the required need. The design should be effective [18] and it should also be efficient.

A combination of the literature above will form the basis of the concept and development activities performed in the conceptual method. The method's output will ultimately be a physical system that could be implemented in the underground environment.

Table 3.2: Conceptual Model for developmental phase

Development Phases as described in different literature			
ISO/IEC TR 24718-1 (2010:14)	INCOSE (2015:71)	Blanchard (2004:16)	Blanchard Requirement Process (Blanchard, 2004:17)
Define/refine system requirements	Prepare for design definintion (1)	**Preliminary Synthesis and allocation of design criteria**	Design the system
Create solution description - architecture and design	Establish design characteristics and design enablers related to each system element	Allocation of performance factors, Design factors and effectiveness requirements	Test the system
Implement initial system	Assess alternatives for obtaining system elements	Allocation of system support requirements	Accomplish System integration
Integrate, verify and validated system	Manage the design	System Analysis	Actual characteristics
Production, Utilisation, Support and Retirement portions of the life cycle will only form part of the Concept and Development stages		**System Optimisation**	Update System Characteristics and Data
		System and Subsystem trade offs	Develop Physical System
		Evaluation of alternatives	
		System and Subsystem Analyses	
		System Synthesis and Definition	
		Preliminary Design - - Performance, Configuration and Arrangement of chosen system (Analyses, Data, Physical Models, Testing etc.	
		Detail Specifications	

3.3 Proposition development to test, verify and validate the system.

After the system has been defined and implemented, the system must be tested, verified, and validated. Null propositions were then formulated. These were used during the validation process to ensure that the suggested system adheres to the stakeholders' requirements and the literature.

The following null propositions were introduced:

- Proposition 1: The current intelligent machines do not have all the sensors necessary and the network sending capabilities to ensure proper fleet management.
- Proposition 2: A mixture of wired and wireless technology cannot be used as the backbone of the data network system.
- Proposition 3: The fleet management systems currently in use on the massive ore body mines cannot be adapted and used on a board and pillar operation.
- Proposition 4: The fleet management system cannot improve the productivity of the mine by 10 to 20%
- Proposition 5: Productivity cannot be increased by improving the availability and utilisation of the machines through continuous condition monitoring using the fleet management system.
- Proposition 6: Face time cannot be improved by determining the whereabouts of a machine underground and recording the productive start and stop times of a machine. There is not a direct correlation between more face time and productivity.

The propositions formulated above will be refined later in the process and validated or falsified as part of the results section.

4 RESEARCH METHOD OR APPROACH

The approach to answering the research question was a mixed methods using Design Science Research (DSR) [19]. DSR combines the development of theory and research intervention to answer real-world problems [20]. The method also entails reflecting on the results, learning, and validating as the research continues [21]. This, as explained, was done to get a more holistic view of the research problem because the qualitative and quantitative approaches complement each other. Design is the purpose of the study, and semi-structured interviews and experimental methods will be used to collect the data.

The DSR model shown in Figure 1 was adapted from [22]. The qualitative and quantitative steps are illustrated below.

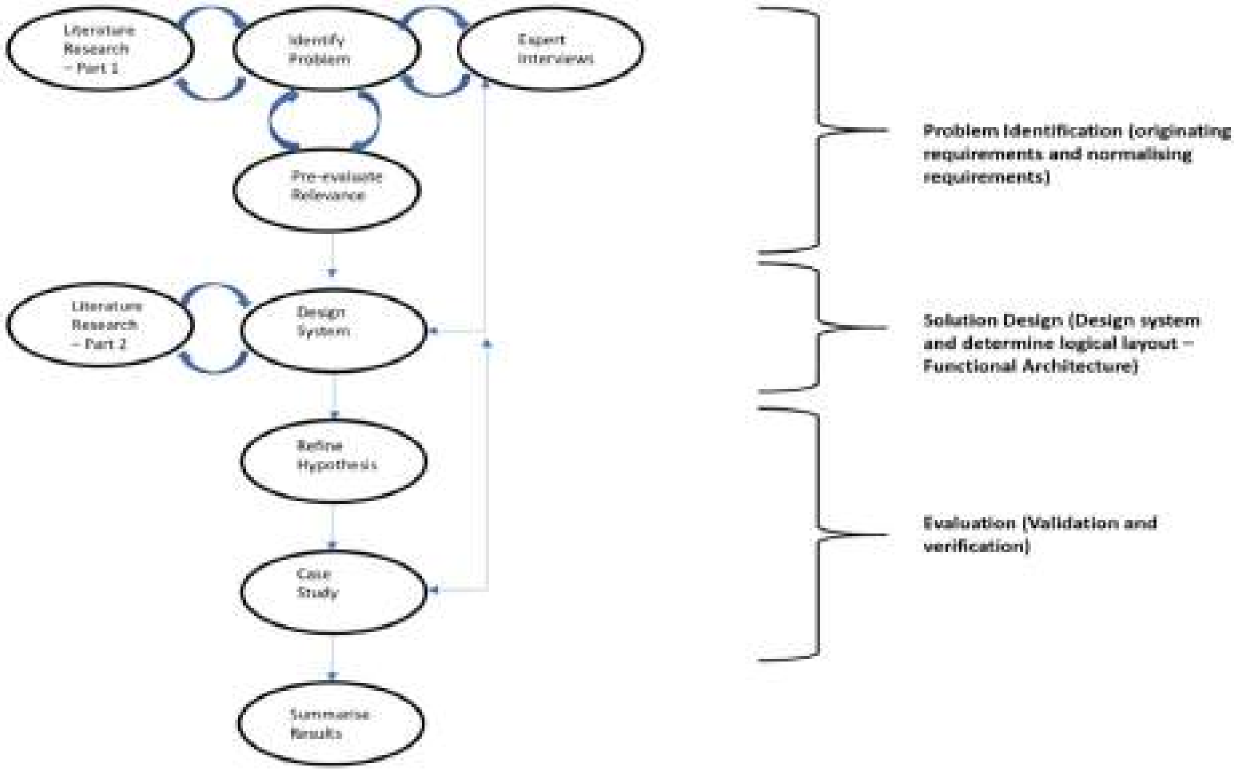

Figure 1: DSR Process (Adapted from [22])

A sequential exploratory design mixed method process was followed where qualitative methods were used first and then quantitative methods; there was not a dominant method because both were equally important to finish the study.

The qualitative methods included semi-structured expert interviews to define the requirements and all the inputs from the owners-, design-, manufacturing- and operations/Support stakeholders. Some aspects of the literature reviewed were also included in this step to define the problem correctly and to create the originating requirements.

A quantitative approach then completed the requirements engineering steps and break up the system into decomposed and normalised requirements.

After this step, inputs were again obtained from the stakeholders to ensure that the requirements were acceptable; this iteration was followed until a good list of requirements was determined. This ensured that the requirements were pre-evaluated, and the relevance and workability of each condition was determined.

The next step was a quantitative step where the system and all its sub-systems were designed to define the architectural framework. In this Solution design stage, the logical layout of the solution will be proposed. This solution was tested and optimised with the inputs from the literature as well as expert interviews.

Propositions were refined to align with the results gathered above.

The next step is to do a case study on the system and to note the results obtained.

5 RESULTS

Sub-system requirements were established using literature, with contextualisation of the problem. Literature findings were shared with mine and industry experts in data networks and fleet management, assessing requirement relevance. This led to problem identification and solution generation. The requirements process aligns literature, stakeholders, and researchers, ensuring an ideal and future-proof system. The iterative problem identification process is depicted below.

The following summarised requirements were gathered for each sub-system. These include inputs from experts, stakeholders, and literature for each sub-system:

5.1 Intelligent machines.

- The TMM machines already have the necessary telemetry to measure condition monitoring parameters.
- Intelligent machines already have a sensor data collector Controller Area Network (CAN) bus to receive all the information from the telemetry.
- Legacy machinery has sensors but no collection method. An Internet of Things (IoT) hub was suggested as a date aggregator.
- The IoT hub was suggested for both legacy and intelligent machinery. The reasoning was that an IoT hub identifies data and arranges it through artificial intelligence, making it more understandable. The IoT hub shall allow other technologies onto the machine, such as Personnel Detection System (PDS), Vehicle Detection System (VDS), Lidar, Camera systems etc.
- The Newtrax vehicle device was recommended as a solution. It is an Original Equipment Manufacturer (OEM)-approved IoT hub, and it fits all the requirements.
- The IoT hub shall be easy to install. The stakeholders noted that initial installation takes 12 hours and replacement takes an hour.
- The device shall hold onto information until data network coverage is detected and dump all the information.
- The device shall withstand the following harsh environmental conditions:
  - Ingress Protection 67 (IP 67) or a better-rated enclosure for the IoT hub to withstand dust, water, heat, and other environmental conditions.
  - Impact protection (IK 10) to withstand the concussions and blasting of the underground environment.
  - Military Standard (MIL-810M) specification ensures modularity and quality, operating in the harshest conditions and quickly achieving interoperability between components.
- Delay in transmission between the machine and the data network shall be between 0 and 5 seconds.
- The signals from the interface IoT hub shall not interfere with any other system.
- The Signal shall be relayed up to 60m if line of sight is available.
- The system shall communicate with various network configurations. 2.4 – 5 GHz and Wi-fi 6 technology was suggested by the stakeholders.
- The machine shall have a (Graphical User Interface) GUI that is interfaced with the IoT hub and indicate to the operator when there are problems and for communication purposes to the control room.

- The IoT hub and data network shall determine the positioning of the machine in the underground environment,
- The system shall be supported. Maintenance, availability, and supportability were listed as requirements.
- The IoT hub shall have a lifespan of between 2 and 5 years.

These requirements were used as the foundation to design the intelligent machine interface.

5.2 Data network

Tests were conducted on the mine to determine what data network configurations would work. These included:

- Bluetooth tags were tested as a data network option; this network layout only addressed the positioning requirements. This system as a solution was discarded.
- Data transfer over the leaky feeder system was tested. This network layout was expensive; only a small data package could be sent, and negative influences on the communication systems and proprietary monopolistic concerns made this system unsuited.
- Long-Term Evolution (LTE) networks performed the best of all the networks if tested in a straight line. Still, the contours of the tunnels, the 2m height and severe undulations in the underground environment caused signal attenuation. The signal propagation around corners was untenable, which could only be mitigated by installing an LTE unit per board. This was not a good solution as only the roadway is open in the board and pillar section, and the rest is packed with waste. The solution was discarded because of these concerns.
- Fibre backbone and Wi-Fi nodes were tested. Stability and repeatability were achieved with this configuration, and because of the vast distances to be covered, this system was seen as the only real solution. Requirements were therefore limited to fibre backbone and wi-fi nodes in the section.

5.2.1 Data network requirements

The following requirements were determined for the data network using the literature and stakeholder inputs.

- Fibre shall be used for the backbone.
- Wi-fi nodes shall be used in the section.
- The stakeholders and subject matter experts shall determine the layout of the network backbone and wi-fi nodes.
- A traditional spliced fibre, network switches and fibre nodes were measured against a Passive Optical Network (PON) system. The PON system was inexpensive, easy to install, modular, upgradeable, uncomplicated, robust, with few components, and complied with most requirements stipulated by Literature and stakeholders. The PON shall be used.
- Ease of deployment was stated as a requirement. The modularity of the PON system addressed this.
- Interfaces shall be easy to install. Plug and play are suggested.
- The environmental considerations shall be:
  - IP 67 or better-rated enclosure and interfaces for the systems to withstand dust, water, heat, and environmental harshness.
  - IK 10 impact protection to withstand the concussions of the underground environment.
  - MIL-810M specification ensures modularity and quality, operating in the harshest conditions and quickly achieving interoperability between components.

  - The network shall be installed where the underground environment cannot damage it.
- The data network shall cover the entire production areas; this includes production panels, waiting areas, production tips and workshop areas. A 12 – 24 node configuration shall be used. This ensures triangulation and total coverage.
- The data network shall be able to provide power to the components in the harsh and remote underground environment.
- Normal connection types and commercially sourced equipment shall be used for the network. This will ensure the maintainability and supportability of the system. Commercially available equipment is also less expensive than a bespoke system and is easier to obtain.
- The network's lifespan shall be 2 – 5 years to ensure economic payback on the system.
- The system shall connect with intelligent machines.
- The network shall have Wi-fi 6 capabilities and a 2.4GHz to 5 GHz frequency range. This will ensure smooth interfacing with the IoT hub.
- The data network shall have a bandwidth of 10GB/s system. This bandwidth is not needed for telemetry because the data packages are relatively small. Still, the bandwidth must be sufficient for voice-over IP and video-sending capabilities that might be required in later projects.
- The system shall segregate different signals on the data network using Virtual Local Area Network (VLAN). Telemetry data shall be ranked as critical information because of the importance of the production information.
- Network spares shall be available on the shelf. The lead time on components shall be less than three weeks. The supplier of the data network shall be a reputable company and have a track record in data networks.
- A maintenance system shall be established, and labour shall be sourced to maintain the system.
- The data system components shall be modular, and components shall be easy to replace.
- The modularity of the components shall also ensure that they can be easily upgraded if newer technology arrives.
- The data network shall be fit for purpose and only have the necessary components to ensure operability.

5.3 Fleet management system requirements

The Fleet Management System (FMS) uses the two sub-systems above, and the following requirements were listed from the literature and stakeholder inputs:

- The FMS shall manage the underground fleet same as surface operations.
- The FMS shall be able to flag any mechanical problem on a machine.
- The FMS shall be able to flag issues with the operation of the machine.
- The FMS shall measure availability of machines.
- The FMS shall measure utilisation of machines.
- The FMS shall calculate Mean-Time-To-Repair (MTTR) and Mean-Time-To-Failure (MTTF) automatically.
- The FMS shall execute as close as possible to real-time.
- The FMS shall be able to indicate the positioning of the machines underground.
- The Graphical User Interface (GUI) shall relay machine info to the operator and send responses to surface.
- The FMS shall determine when machines are due for service.
- The FMS shall display information visually through graphs, charts, and dashboards.
- The FMS shall be secure.
- The FMS shall be supported.

- People shall be trained in maintaining and operating the FMS.
- The FMS shall measure machines' aspects determined by breakdowns and leading indicators.
- LHD shall measure any of the 36 node sensors.
- Rigs and bolters shall measure percussion hours.
- Operation time and face time shall be determined by the system.
- The FMS shall adapt to changes and shall be fully customisable.

5.4 Solution Design phase and logical layout

A logical system layout was determined through iterative methods involving the requirements listed above and solutions offered by system experts.

The results of the solution design and logical layout are summarised below.

5.4.1 Intelligent machine IoT hub.

- The intelligent machines already have all the sensors to facilitate condition monitoring.
- The legacy machines have all the sensors but no data aggregation system. The literature and the stakeholders suggested an IoT hub. The IoT hub is advantageous, even on intelligent machines, to serve as an interface between multiple technologies that might be added to the machine. The hub also serves as a CAN bus replacement on the older type of machinery.
- The research only concentrated on the interface between the machine and the data network system.
- The Newtrax Vehicle Device was suggested by the stakeholders, as it is an Original Equipment Manufacturer (OEM) approved and does what was required from the stakeholders and the literature. The flow diagram between the machine and the data network is illustrated in Figure 2.

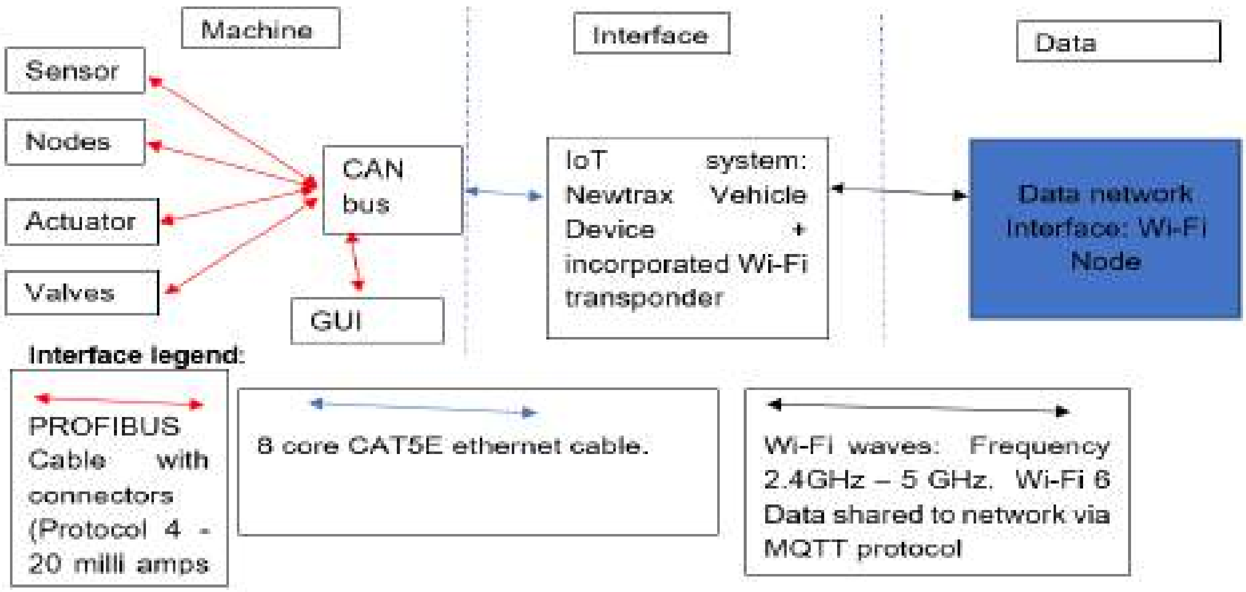

Figure 2: Flow diagram of an intelligent machine system indicating the interfaces

The IoT hub was tested, and up to 140m of transmission distance was achieved.

The hub connected freely to the data network when available. It also dumped the data when the data network was available.

5.4.2 *Data network system*

- The logical layout of the data network system was determined by testing the system underground and optimising the configuration.
- The initial plan had several access switches and aggregation access switches included in the network line after every length of the Gigabit-capable passive optical network (GPON) cable.
- There were also two distinct types of GPON cables, the 1 GB/s type, that were tested between the Optical Distribution Network (ODN) and Optical Network Unit (ONU) components and the 10 GB/s types.
- Extension plugs on the GPON cables made the aggregation access switches and access switches redundant.
- It was also decided that the 1 GB/s GPON is unnecessary and that the 10 GB/s will be the only distribution cable.
- The extension plugs on the GPON saved money due to removing the aggregate and access switches.
- That left the system with only three major electronic devices (Optical Line Network (OLT), ONU and wireless access points).
- The final logical flow diagram of the data network system is indicated below. It complies with the requirements and what is specified in the literature.

The data network in Figure 3 was tested using a layout derived by this study. Many iterative processes have been followed before the system design was determined. The 24 nodes' grid is approximately 30 meters apart, and tests illustrated that proper coverage of the entire section, as stipulated in the requirements, could be obtained using this layout.

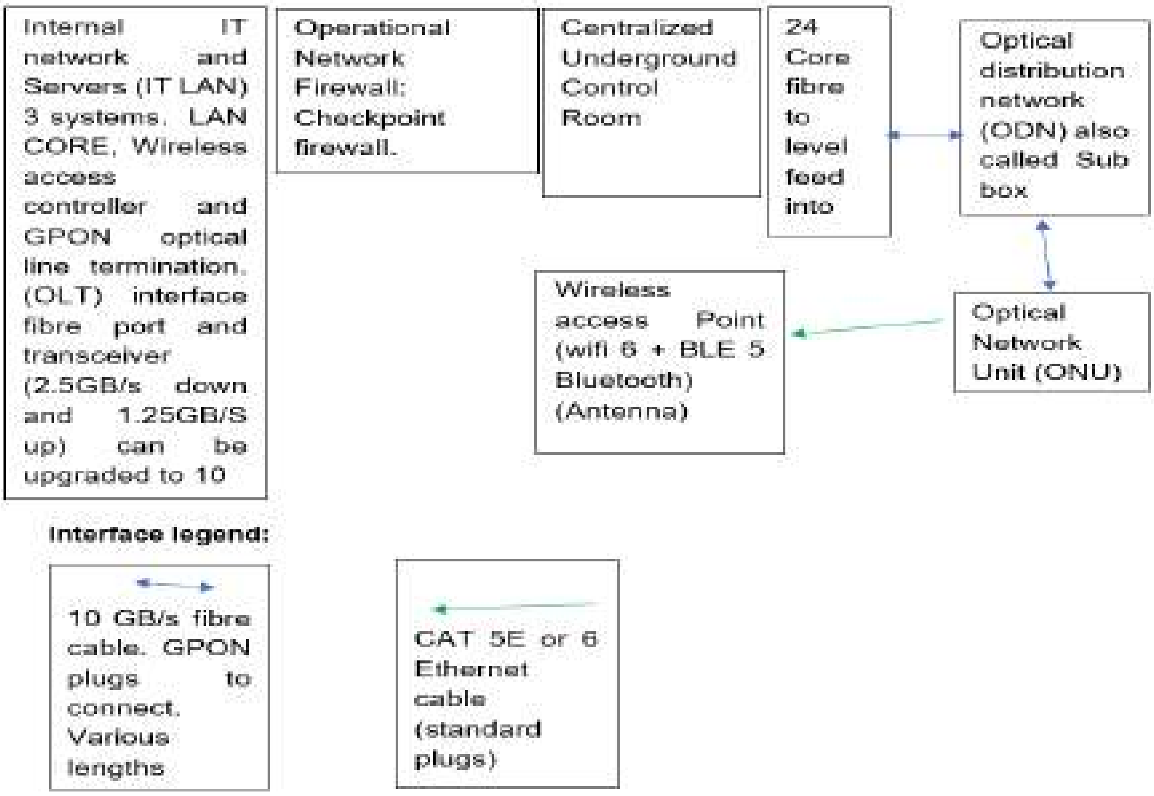

Figure 3: Flow diagram of a data network system.

All the verification processes were done on the system requirements as stipulated. And the stakeholders demonstrated, tested, and analysed each requirement to comply with the verification and validation requirements. Each test was met, and the system did what it set out to do.

The results and layout are the conclusions of multitudes of tests conducted on the mine since 2012, and the layout gave the most optimal results when tested.

5.4.3 Fleet management system

- An assumption was made in the study that OEM fleet management systems prevalent on massive ore body mines will be used to manage the fleet underground; this was not the case; these products are still in the development phase for the low-profile machinery.
- The researcher and stakeholders opted for their developed system.
- In the results, the stakeholders decided on a fully customisable mine-produced system. They used cloud-based technology and Grafana visualisation programmes to indicate the health of the machinery.
- This ensures that the system is fully customisable.
- The logical flow of the system is illustrated below.
- The system of systems was tested in Level 9 on Main Decline as a Proof of Concept. The intelligent machine, Data network and Fleet management system were configured precisely as illustrated above.
- The results conformed to the requirements as anticipated, and the system operated as intended.
- The systems engineering approach will ensure that the system is functional, economical, sustainable, reliable, obtainable, maintainable, supportable, survivable, modular, upgradeable, durable, and fit throughout the system's lifecycle.
- All the verification processes were done on the system requirements as stipulated. And the stakeholders demonstrated, tested, and analysed each requirement to comply with the verification and validation requirements.
- Test results are available for the data network and IoT hub tests performed on the intelligent machines.

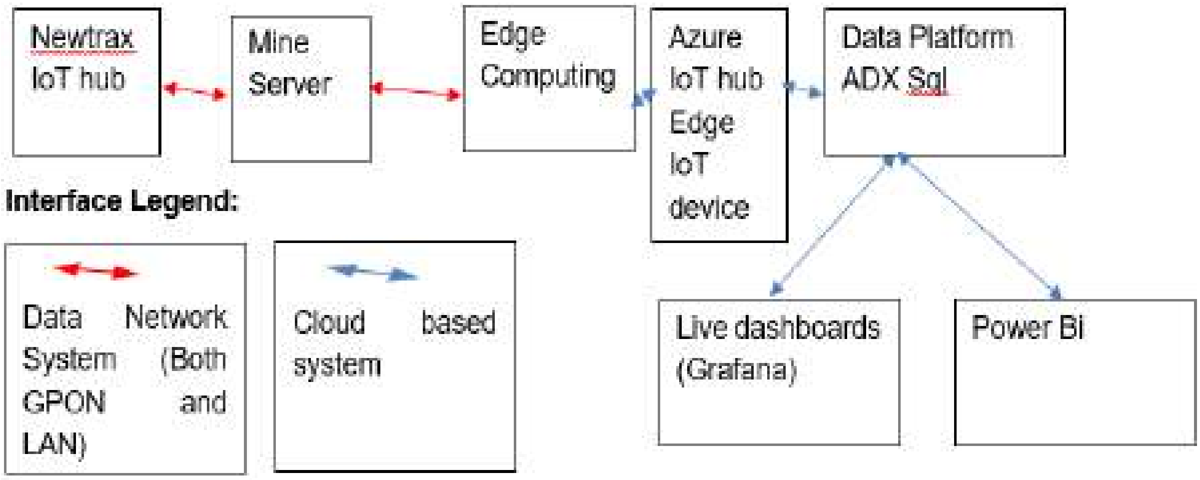

Figure 4: Flow diagram of a fleet management system.

5.5 The case study (Old manual system vs new fleet management test)

The current Two Rivers Platinum condition monitoring system was determined by conducting interviews with the engineering planning department, engineers, and production personnel. It was determined that the current system is very labour intensive and that many manual inputs must be included to calculate and track all the machine condition monitoring and production monitoring aspects on the mine.

The case study focussed on hour capturing of machines, breakdown procedures, productivity, and face time procedures and how the location of machines was determined.

A breakdown of Load Haul Dumper (LHD) 184 was also tracked to explain the current procedure. Each of the aspects of the current system above was compared to the system as it should be if fleet management is implemented.

The case study also served to validate the system and all the requirements. The requirement of the fleet management system was validated and verified. The verified requirements that were tested and validated are tabled below.

Table 5.1: Fleet management requirements

Requirement	**Literature or Stakeholders' requirement?**	**Verification and Validation**
Manage the underground fleet same as surface operations	[5] and stakeholder requirement	Demonstrate
Must be able to flag any mechanical problem on a machine.	[13], [7] and stakeholder requirement	Demonstrate
Must be able to flag issues with the operation of the machine	[13], [5] and stakeholder requirements	Demonstrate
Measure availability of machines	[23] and stakeholder requirements	Demonstrate
Measure utilisation of machines	[23] and stakeholder requirements	Demonstrate
Determine MTTR and MTTF figures automatically.	[23] and stakeholder requirements	Demonstrate
As close as possible to real-time	[5] and stakeholder requirement	Demonstrate
Must be able to indicate the positioning of the machine underground	[5] "Interaction with TMM equipment", [13] and stakeholder requirement	Demonstrate
GUI to relay info to the operator and set responses to surface	[13] and stakeholder requirement	Demonstrate
The system must determine when machines are due for service	[13] and stakeholder requirements	Demonstrate
The system must display information visually through graphs, charts, and dashboards.	Stakeholder requirement	Demonstrate
The system must be secure.	[17]	Analyse
The system must be supported.	[17] [18]	Analyse
People should be trained in the system	[18] p.37	Demonstrate
The system should be able to measure machines' aspects determined by breakdowns and leading indicators.	Stakeholders	Demonstrate
LHD measure any of the 36 nodes sensors	Stakeholders	Demonstrate

Requirement	Literature or Stakeholders' requirement?	Verification and Validation
Rigs and bolters should measure percussion hours.	Used for efficiency calculations and face time calculations. [23] [24] [25]	Demonstrate
Operation time and face time to be determined by the system	[24] [25]	Demonstrate
The system must be able to adapt to changes and be fully customisable	Design attributes - [18] p.37 and stakeholder requirements	Demonstrate

The new proposed fleet management system results are encouraging, and all the requirements are met during the case study. The new fleet management system:

- Makes the filling of checklists redundant to update the hours of each machine.
- Labour required to capture machine-hour readings can be reduced or applied elsewhere. The system reads the machine hours automatically.
- The fleet management system updates the hours in the Centralised Asset Management system (CAMS) and Delta. Availability, utilisation, MTTF and MTTR calculations can be updated constantly for each machine, and trends could be established automatically. Manual inputs into excel sheets and the labour required to perform these inputs are no longer needed.
- Breakdowns do not have to be communicated to the control room; the system does it automatically and gets flagged immediately in the control room.
- Time off is accurately captured, improving the data's integrity.
- Breakdowns can also be prioritised immediately, and the control room can already tell the artisans what the telemetry is indicating and what parts will be required.
- The system automatically registers when a machine starts working, and the trends will be documented throughout the shift.
- Face time of machines can be tracked, and the trends could be used to improve and manage the productive time of machines. Manual call-ins from underground by the Shift boss and artisan to the control room operator are no longer required to state when a machine starts working.
- The wi-fi node's IP address is superimposed on a plan. Finding machinery underground will no longer rely on writing the location of a machine on a whiteboard on the surface at the end of the shift.
- The case study verified all requirements stipulated by the literature and stakeholders to prove the concept.
- The fleet management system is fully customisable, and the immersive behaviour of the system is guaranteed.
- The system conforms to all the requirements as prescribed.

5.6 Proposition Testing

Some limitations were that there is only a short time allowed to test the results in mining environments. Longer-term test results will be available in the future. The propositions testing is discussed below, but longer-term tests will demonstrate what the impact will be.

5.6.1 Propositions of improvement

The following propositions was stated in the research, and the results of the proposition validation or disproval thereof will be listed after each statement.

- Proposition 1: The current intelligent machines do not have all the sensors necessary and the network sending capabilities to ensure proper fleet management. The research proved that telemetry and sensors are available on all machines, thus this proposition is false.
  - Thus, the alternative proposition is accepted: The current intelligent machines have all the sensors necessary and the network sending capabilities to ensure proper fleet management.
- Proposition 2: A mixture of wired and wireless technology cannot be used as the backbone of the data network system. LTE networks did not work in the board and pillar set-up, and because of the vast distances to be covered, a combination of fibre and wi-fi nodes was suggested. This echoed [2] that stipulated cost-efficient coverage with a hybrid solution.
  - Thus, this proposition is rejected, and the alternative is accepted: A mixture of wired and wireless technology can be used as the backbone of the data network system.
- Proposition 3: The fleet management systems currently in use on the massive ore body mines cannot be adapted and used on a board and pillar operation. The fleet management system provided by the OEM is more suited for massive ore body mines, and the board and pillar system is still under development.
  - This proposition is weakly accepted. It can be concluded that an own adaptable system is more advantageous.
- Proposition 4: The fleet management system cannot improve the productivity of the mine by 10 to 20%, as per [5].
  - This proposition cannot be proofed or rejected. Initial results from the case study show that productivity might improve.
- Proposition 5: Productivity cannot be increased by improving the availability and utilisation of the machines through continuous condition monitoring using the fleet management system.
  - This proposition cannot be proofed or rejected. Initial results from the case study show that productivity might improve.
- Proposition 6: Face time cannot be improved by determining the whereabouts of a machine underground and recording the productive start and stop times of a machine.
  - This proposition cannot be proofed or rejected. Initial results from the case study, shows that there is a direct correlation between more face time and productivity.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The objective of the research was to develop and define a system using the systems engineering approach that uses the intelligent capabilities of trackless underground equipment, a suggested data network, and a to-be-determined fleet management system that can be used as a business solution at Two Rivers platinum to manage better and maintain trackless mobile machinery.

The conclusion, in short, is that a fleet management system was developed using a Systems Engineering approach. The stakeholders and the literature specified the system's requirements, and these attributes were incorporated into the designed system as presented. Each sub-system's needs and the overall system were verified and validated. A case study was performed to test the system's capabilities, and the results indicated that production improvements and labour savings are likely if the system is fully implemented. The aspects one needs to consider when implementing data sending, collection and a fleet management system in a board and pillar mine were addressed through the research and will give future researchers an excellent foundation to work from. The enterprise portion of the systems engineering process has not been addressed and must be addressed in future research. If the management of the system is defined correctly, the project can be implemented, and success will be achieved.

6.2 Recommendations

- The scheduling of the fleet and reference back to the monthly planning was not addressed yet, but all the systems are adaptable to address this requirement; the IoT hub on the machine also ensures that more technology and different systems could be incorporated into the machine. Further work is needed in this area.
- Long-term testing must commence on the designed system to determine if the production's 10 – 20% improvement could be achieved (Proposition 4).
- Based on the labour savings noted in the case study, the system will reach its payback period in less than two years. It is recommended that the system be implemented to optimise the condition monitoring of machines. The scheduling portion can be added later, and the system is ready to accommodate this.
- The enterprise aspect of the system must be done to determine how the system will fit into the organisation and to address the systems engineering management process. It is recommended that SEMBASE theory be applied to the problem.
- Further development and optimisation of the fleet management visualisation dashboards are recommended to make them more user-friendly and easier to interpret.
- An evaluation plan for the evaluation of proposition 5 and 6 needs to be drafted and implemented.

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MANAGEMENT OF BASIC SERVICE DELIVERY TRACKING AND REPORTING SYSTEM IN THE SOUTH AFRICAN LOCAL GOVERNMENT

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ABSTRACT

The South African Local Government is currently experiencing a backlog in providing basic services to its citizens due to financial constraints, lack of planning, poor project management and integration between sector departments. The South African Local Government also needs a centralised and automated system that can track and report how far the government is in delivering basic services in its local municipalities. The Bill of Rights lists the following as the basic services everyone must have access to health care, clean drinking water, sanitation, electricity, waste removal/management and basic education. This research focuses on a future service delivery tracking and reporting system that can be used to capture data on how far the local government is in achieving its goal of ensuring that everyone in South Africa has access to essential services.

Relevant literature reviewed for this study includes literature on local government, service delivery, service engineering, and systems engineering will be sought in books, research journals and articles and government reports that have been published. The knowledge gained from the literature review and the concept model development led to four research propositions. The results from the proposition evaluation showed that the South African municipalities and sector departments use different tracking and reporting systems. There is a need for a centralised tracking and reporting system. The results also showed that this system would benefit all three spheres of government (national, provincial, and local.)

Keywords: basic services, systems, households, service delivery, local government

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1 INTRODUCTION

The Bill of Rights, as enshrined in the **Constitution of the Republic of South Africa, 1996**, makes provision for basic rights that include the right to access basic services. Service delivery is informed by various pieces of legislation, the custodianship of which lies with different sector departments. Furthermore, the Constitution categorises government into three spheres (national, provincial, and local) with clearly defined structures and roles. These three spheres of government are distinctive, interrelated, and interdependent as such; they must work together in a cooperative governance system prescribed by the Constitution.

The provision of basic services to communities is assigned to the local sphere of government as prescribed in section 152 of the Constitution, which mandates municipalities to provide services to communities sustainably. The Bill of Rights lists the following as the basic services everyone must have access to health care, clean drinking water, sanitation, electricity, waste removal/management and basic education.

Oversight on the performance of municipalities on the mandate of basic service delivery is done through structures established through the **Intergovernmental Relations Framework Act, 13 of 2005**, which provides for the establishment of intergovernmental structures that are meant to, amongst others, "discuss the performance in the provision of services in order to detect failures and to initiate preventive or corrective actions". This is to ensure coordination, alignment, and integration of government priorities across the three spheres of government.

Sector departments develop and fund programmes to address the need to deliver basic services. In turn, municipalities implement these programmes as service delivery projects, such as improving access to running and potable water, primary health care and housing. Even though there might be backlogs against government-set standards and priorities, there are currently many projects that have been completed such that the public has access to services intended from the implementation of those projects. However, sustainability over the long term is not guaranteed because, amongst several reasons that may burden the ability of municipalities to deliver services efficiently, there need to be systems in place to manage population growth and an influx of people at urban centres. There also needs to be a centralised management system that tracks and reports on implementing basic services in local government.

The research will focus on managing a service delivery tracking and reporting system that can be used to acquire data on how far the local government is in achieving its goal of ensuring that everyone in South Africa has access to basic services.

1.1 Research objectives

The South African Local Government is currently experiencing a backlog in providing basic services to its citizens due to financial constraints, lack of planning, poor project management and integration between sector departments. The South African Local Government also needs a centralised and automated system in place that can be used to track and report on how far the government is on the delivery of basic services in its local municipalities.

The following objectives will address the research problem:

1. To determine if there is a centralised, automated system that is used by local government to track and report on the provision of basic services in municipalities.
2. To determine if municipalities and sector departments know the number of households with access to basic services.
3. To determine the components required for a centralised, automated service tracking and reporting system.

2 LITERATURE REVIEW

2.1 Local government

The South African local government is grappling with service delivery problems such as inadequate housing, lack of healthcare facilities, and increasing levels of unemployment. The Intergovernmental Relations Framework Act 2012 can be used to ensure integration between the three spheres (national, provincial, local) of government to solve service delivery problems. It also shows the importance of integrated planning across the three spheres of government to improve cooperative governance. “It embodies an approach by which the three spheres of government and state entities work in unison in an impact-oriented way, and where there is higher performance and accountability, for coherent service delivery and development outcomes” [1].

The aspect of accountability in the service delivery continuum cannot be overemphasised. Social accountability, which is about citizens of local government holding public officials accountable for their responsibilities, can be used as a performance management tool [2]. Therefore, citizens need to be part of stakeholder discussions to express their concerns and be actively involved in assessing the performance level of service delivery in the municipality [2].

2.2 Provision of basic services

The government of South Africa should provide its citizens with the surety of continuous provision of basic services irrespective of their cultural and social background. These services must be affordable and easily accessible to all. Service delivery is part of a multifaceted relationship between the citizens and the government [3].

The General Household Survey report [1] shows that there have been remarkable improvements in providing basic services (sanitation, electricity and water) to households that did not have access to basic services previously. Addressing the number of service delivery backlogs is a crucial measure for evaluating a municipality's performance. It shows that municipalities still deal with the challenges of providing access to reliable basic services and a high-standard [1].

The perennial challenges of unserved communities interrupted services, and poor management of infrastructure projects leading to underspending leads to a decline in public trust, hence the increase in unprecedented service delivery protests and some communities taking it upon themselves to repair ailing infrastructure then billing the municipality for it. Statistics indicate that although a significant number of households have been shown not to have access to basic services, most of these households are mainly in the outlying rural areas where the cost of infrastructure provision is exceptionally high [1].

2.3 Management system

Definition: “A management system is how an organisation manages the interrelated parts of its business to achieve its objectives. These objectives can relate to several different topics, including a product or service quality, operational efficiency, environmental performance, health, and safety in the workplace and many more” [4].

A service system entails the arrangement of resources, organisations, and collective information from the service providers and their customers, to create value for the customer. [5]. The system contains a network of resources such as people, technologies, organisations, and information [6].

National and local governments worldwide are under pressure to deliver services more efficiently at a lower cost, and they have identified e-government as an option, both commercially and politically [7]. The application of e-government in government institutions has the following benefits [7]:

a. improved delivery of basic services to citizens,
b. enhanced interactions with business and industry,
c. citizen empowerment through access to information

2.3.1 Gaps identified in the existing local government systems

The South African government has yet to expedite service delivery in local governments. It is appropriate to assume that introducing a fittingly designed corporate governance system that reflects the realities of all local municipalities is a suitable substitute to simplify, develop and sustain service delivery. The literature also indicates the following gaps:

a. There needs to be an integrated service management system that measures basic service delivery performance on a regular basis.
b. There is a need for regular monitoring and evaluation to improve service delivery and check if they meet the service users' requirements. This requires a real-time, accurate, evidence-based system that guides corrective actions to be taken where there is underperformance and dealing with backlogs.
c. There is a lack of infrastructure, resources and fiscus in rural municipalities to implement quality service delivery.
d. There is a shortage of professionals in the service delivery industry that know how to analyse, break down a system and develop a new one that suits the customers' needs.

The implementation of E-government systems in developing countries such as South Africa is still low, and this indicates that there is a need to explore numerous approaches that can be used to provide basic services to communities through various avenues but in a transparent and integrated manner. The purpose of the system would be to improve collaboration between the public and private sectors and citizens through transparency in government planning. Finally, it would improve the quality of information and reduce data handling by multiple stakeholders.

3 CONCEPTUAL METHOD

The construction of concept maps is an excellent way to offer a preliminary organisation of knowledge and to structure an understanding of how a dissertation topic will be approached [8]. A concept map offers a tool to draw a plan for approaching an investigation within a specific theoretical framework [8].

The Nordic Model was developed to measure service quality. The model was created in 1981 by a Swedish firm that deals with services. This model indicates that service quality has two variables: technical quality and functional quality [9]. The technical factor refers to what the customer will receive in the process, and the functional factor refers to how the customer will receive the service. The SERVQUAL model, also known as the 'GAP MODEL', was developed by Parasuraman in 1985 as another model for measuring service quality [9]. For a customer to be satisfied with the level of service they are receiving, it has to meet or exceed their expectations. However, if the level of service is below what they had expected, then the customer is dissatisfied [10].

The District Development Model is an operational method created by the South African government to ensure that the three spheres (national, provincial, local) of government are working in unison to operate at a high-performance level and have accountability for the provision of effective service delivery. The model will also be used to improve planning and budgeting across all three spheres of government through integration and coordination [11].

3.1 The link between the current models

The Nordic, GAP, SERVQUAL and DDM models can be linked or merged based on the following [12]:

a) The Nordic model focuses on the technical factor, which is what service the customer will receive. It can be linked to GAP 1(Customers' expectations: Managements' perceptions) because it refers to the customers' expectations of the kind of service they want. SERVQUAL Reliability dimension is linked to these as it speaks to the capability of the service provider to provide what the customer wants at the same consistency and time.
b) The WHAT part of the Nordic model can also be linked to GAP 5 (Customer's expectation – Perceived service) of the customer, wherein the focus is on seeing physical evidence of the service they paid for and whether they are satisfied.
c) The HOW part of the Nordic model, which is related to the functional factor of how the customer will receive the service, is linked to GAP 4(Service delivery: External communications) and GAP 5 because they speak to how the service will be provided, how the organisation will communicate with the customer regarding the service that they expected and if it meets their requirements.
d) The DDM model is centred around integration between all sector departments and their goal of ensuring that South African citizens have access to basic services. Therefore, the Nordic will ask the questions WHAT and HOW; the GAP model will help management identify gaps they need to address to ensure quality services. SERVQUAL speaks to the dimensions used to measure the services being provided.
e) The literature also highlighted an increase in community unrest, a decline in the provision of essential services and a decrease in the trust that the communities have in the government. This speaks to all three models because it shows that the communities know what type of services they should get, how they should receive the services, the level of quality, and the fact that it should be consistent and reliable, which are all part of the five dimensions of the SERVQUAL model.

3.2 Proposed model and proposition

3.2.1 Root cause analysis

Root cause analysis was initially created in systems engineering to recognise "the essential and causal factor(s) that underlie variation in performance." [12]. In this paper it is used to derive the conceptual model in Figure 1 to be used in the research study.

Knowledge gained from the literature study forms the foundations for formulating propositions.

3.2.1.1 The local government needs to find out the number of South African citizens that have access to basic services.

Proposition 1: The South African Local government does not have a database indicating the number of households that have access to basic services.

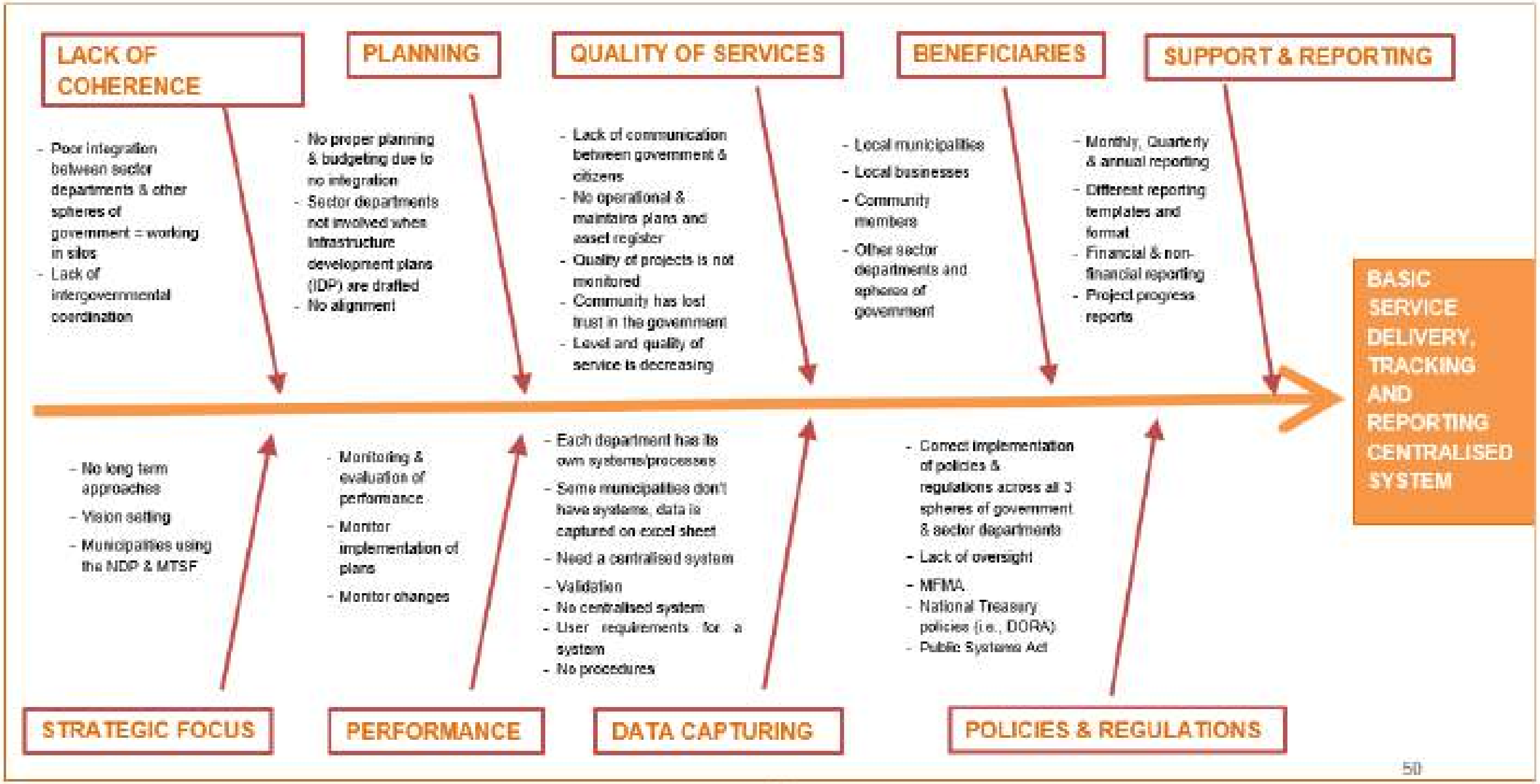

Figure 1: Concept model

3.2.1.2 Service delivery management tracking and reporting system

Proposition 2: The South African local government does not have a centralised basic service delivery tracking and reporting system.

3.2.1.3 Lack of integration between sector departments and other spheres of government affects service delivery.

Proposition 3: There is a lack of integration between sector departments and other spheres of government; they have their processes and systems, which impact the provision of basic services.

3.2.1.4 South African citizens have lost trust and confidence in the local government.

Proposition 4: South African citizens believe that government is not open and transparent when it comes to providing updates or feedback on the implementation of service delivery projects.

4 RESEARCH METHOD OR APPROACH

4.1 Research Design

Research designs organise research activity, including the collection of data, in ways that are most likely to achieve the research aims [13]. The research design will be based on a mixed method combining quantitative and qualitative methods.

4.1.1 Mixed Research

A mixed-method study involves collecting and analysing both the quantitative and qualitative data in a single study in which the data is collected concurrently or sequentially. The qualitative and quantitative information is integrated at the data analysis stage to answer the research questions [14]. The mixed method approach helps the researcher answer research questions that cannot be answered using the qualitative or qualitative methods in their own [14].

The mixed method has a list of purposes: triangulation, complementarily, development, initiation, and expansion. Triangulation was used for this study because it is used to support and corroborate the data results and the literature, as it will address the reliability and accuracy of the research [15].

4.2 Research Methodology

4.2.1 Qualitative Study

A qualitative study method is used to study a complex problem using various data sources and data collection methods. Triangulation strengthens the validity of the findings from qualitative research design by establishing converging lines of evidence. A study used for theory testing purposes is deductive, and the data results are used to validate the theory, modify it, or refine it based on the results from the study.

4.3 Sampling strategy

The sample for this research was taken from 257 South African municipalities. A non-probability sampling design is used for this research study because the sample size was based on accessibility to municipalities. The sample size is 130 municipalities with a confidence level of 90% **[16]**.

4.4 Data Collection

A questionnaire was used to collect data, the survey was done via software called Qualtrics, and a unique survey link was emailed to each Municipal Manager, their Assistant and Technical Directors. The responses to the survey were captured and stored on Qualtrics.

The close-ended questions stem from the research questions and the literature review. Questionnaires provide answers that are easy to tabulate and analyse. The questionaries are done via software therefore, the respondent's identity will be anonymous. Furthermore, questionnaires are a good way of collecting data because they are not expensive; they are more economical because one must only email the link to the respondent's [17].

The quantitative method will be the primary data, and the Qualitative method, which refers to reports and other literature, will be used as secondary data to validate the results and increase the research's accuracy.

4.5 Data Analysis

The data collected from the literature review that included the government reports will be integrated with the results from the survey to answer the research questions.

5 RESULTS

A unique survey link was generated for each participant to make it easier to track the number of municipalities that have responded. The unique link survey was sent to Municipal Manager, their Assistants, and the Technical Directors. A separate multiple-distribution survey link was created and sent to the municipality’s technical teams. The survey was conducted for a period of a month. Although the response rate from the survey is minimal (34) compared to the sample size of 130, the results will still be able to provide meaningful findings.

5.1 Proposition Evaluation

Proposition 1: The South African Local government does not have a database indicating the number of households that have access to basic services.

A municipality must have a database indicating the latest number of households that have access to basic services, as it is the foundation of the 5-year Integrated Development Plan (IDP) that municipalities draft and revise annually.

Table 1 indicates that 71% of the respondents (R) noted that their municipalities know the number of households that have access to basic services in their municipalities, and 100% of them agree that it is essential to know the actual numbers. The respondents answered additional questions to get a complete picture of how the data is captured, where it is stored and how the accuracy of the data is confirmed. Table 2 indicates that 67% of the respondents indicated that information is captured manually on a spreadsheet created internally, and 48% indicated that the municipality has a system that is used to capture the data.

The respondents were asked if their municipalities have a records management system or process; this question was asked to ascertain whether the municipality has a place where they store their information. Table 3 indicates that 50% of the respondents indicated that their municipalities have a records management system or process in place, 29% of the respondents indicated that their municipalities capture records by hand and store them in boxes, and 21% don’t have a system or process in place.

Table 1: Number of households with access to basic services

#	Do you currently know the number of households that have access to basic services (water, electricity, sanitation)?	Agree	R	Uncertain	R	Disagree	R
1	Yes (provide the numbers)	71%	15	60%	3	29%	2
2	No, I don't	29%	6	40%	2	71%	5
	Total	Total	21	Total	5	Total	7

Table 2: Current processes and system

#	How would you describe the current processes and systems that the municipal	Agree	R	Uncertain	R	Disagree	R	Total
1	There is no system/process in place	25%	5	30%	6	45%	9	20
2	The municipality captures data manually	67%	14	5%	1	29%	6	21
3	There is a system in place (please provide the name)	48%	10	19%	4	33%	7	21

Table 3: Records management system or process

#	Does the municipality currently have a records management system/process	Agree	R	Uncertain	R	Disagree	R
1	Electronic system	50%	14	33%	1	19%	4
2	Records are captured manually and stored in boxes	29%	8	33%	1	33%	7
3	There is no system/process	21%	6	33%	1	48%	10
	Total	Total	28	Total	3	Total	21

Table 4: Accuracy of data

#	How do you confirm the accuracy of the information that you have?	Agree	R	Uncertain	R	Disagree	R
1	We don't check the accuracy of the data	17%	6	50%	5	64%	9
2	We refer to the number of service delivery projects that have been completed	49%	17	20%	2	7%	1
3	Refer to government/sector department reports	34%	12	30%	3	29%	4
	Total	Total	35	Total	10	Total	14

The municipalities need to use accurate data for planning as this information will help the municipalities identify areas that they need to focus on interims of service delivery. Table 4 indicates that 49% of the respondents said their municipalities use the numbers from the service delivery projects that the municipality has completed; most of this information is generally captured on MIG-MIS, a DCOG system. 49% of the respondents indicated that they refer to sector department reports, and 17% indicated that they do not check the accuracy of the data.

The recent literature confirms that most municipalities know the number of households that have access to basic services; however, they are highly dependent on the information in the sector reports. The survey shows that 50% of respondents indicated that their municipalities have a database where the information is stored. The 34% depend on the numbers they get from sector department reports and the General Housing Survey data that StatsSA publishes. Therefore, P1 is false, that data is available however it is stored in different formats, and it is available on different sector department platforms.

Proposition 2: The South African local government does not have a centralised basic service delivery tracking and reporting system

The literature in chapter two highlighted the fact that local government needs a centralised system that tracks and reports on the provision of basic services in the municipalities. The municipalities report on the systems that the sector departments have developed. The municipalities use these systems to report on their expenditure, register projects and upload progress in order to ensure that departments such as COGTA and NT can monitor their expenditure.

Section 71(1) of the MFMA states that municipalities have to report monthly and quarterly; the survey indicated that 58% of the respondents said their municipalities report using templates, and 38% of the respondents said their municipalities utilise the sector department reports. 65% of the respondents indicated that they draft monthly progress reports on service delivery projects.

The results in table 5 indicate that 64% of the respondents said their municipalities utilise the sector department systems for reporting, and 23% of the respondents indicated that they don’t use any sector department systems. Municipalities were also asked if they currently have a records management system; over and above tracking and reporting, the municipalities need to have a POE for every single transaction and payment that is done. The results in table 6 indicate that only 50% of the respondents indicated that their municipalities have an electronic system.

Table 5: Utilisation of sector department systems

#	There are systems such as MIG-MIS, MIPMIS etc. Are these systems useful and can they be utilised for reporting on the number of households that have basic services?	Agree	R	Uncertain	R	Disagree	R
1	Yes	64%	14	31%	4	15%	3
2	No	14%	3	31%	4	45%	9
3	Municipality doesn't use any systems	23%	5	38%	5	40%	8
	Total	Total	22	Total	13	Total	20

Table 6: Records management system

#	**Does the municipality currently have a records management system/process?**	Agree	R	Uncertain	R	Disagree	R
1	Electronic system	50%	14	33%	1	19%	4
2	Records are captured manually and stored in boxes	29%	8	33%	1	33%	7
3	There is no system/process	21%	6	33%	1	48%	10
	Total	Total	28	Total	3	Total	21

The respondents that indicated that their municipalities do have an electronic system in place were also asked if the current system that they are using can track and report on the number of households that have access to basic services; 47% indicated that their systems can track and report and 37% of the respondents indicated that their municipalities have a system however it is outdated. As much as 64% of the respondents indicated that they use the sector departments for reporting, table 7 shows that 38% of the respondents said their municipalities have a system in place, but it has to be upgraded, and 35% are satisfied with the current system that the municipality is currently using, and 27% indicated that they need a new system.

Table 7: Satisfaction with the current system

#	**Are you satisfied with the system/processes that the municipality currently has in place to track and report on the number of households that have access to basic services?**	Agree	R	Uncertain	R	Disagree	R
1	Yes	35%	9	29%	4	46%	6
2	No, we need a new system	27%	7	29%	4	31%	4
3	The current system needs an upgrade	38%	10	43%	6	23%	3
	Total	Total	26	Total	14	Total	13

Municipal Systems Act states that the municipalities should have a performance management system in place for reporting, however it doesn't mention reporting on a centralised system. The result from the survey confirms that proposition 2 is true, the respective municipalities don't have a centralised system; this was confirmed by 64% of the respondents that indicated that they use the sector department systems for reporting.

Proposition 3: There is a lack of integration between sector departments and other spheres of government, they have their own processes and systems which have an impact on the provision of basic services

The problem of lack of integration between the three spheres of government was identified in the Presidency Budget Speech (2019). The speech stated that there is a "pattern of operating in silos", which impacts the planning and implementation of service delivery projects in municipalities.

The results from table 8 indicate that 42% of the respondents agree that sector departments and municipalities are indeed working in silos, and 16% indicated that there is no integration between the three spheres of government. Therefore, 58% of the respondents agree with proposition 3.

Table 8: Integration between three spheres of government

#	**Do you think there is integration between sector departments and the 3 spheres of government? or do you think they are working together?**	Agree	R	Uncertain	R	Disagree	R
1	Sector departments and the municipalities are working in silos	42%	8	33%	7	27%	3
2	No, there is no integration	16%	3	33%	7	36%	4
3	Yes, the sector departments and municipalities are working	42%	8	33%	7	36%	4
	Total	Total	19	Total	21	Total	11

The findings from the survey correlate with Chapter 13 of the National Development Plan which states the following [18]:

- The three spheres of government have struggled to achieve constructive relationships: and
- There needs to be more clarity around the separation of powers and functions, together with a lack of framework for the assignment of functions, which has created tensions between the three spheres of government.

Proposition 4: South African citizens believe that government is not open and transparent when it comes to providing updates or feedback on the implementation of service delivery projects

The Local Government: Municipal Structures Act 117 of 1998 states, "A municipal council must develop mechanisms to consult the community and community organisations in performing its functions and exercising its powers." The number of service delivery protests in South Africa has increased over the past few years due to the provision of poor basic services. The South African government system is weakened by the municipalities not being able to provide satisfactory basic services, and they are viewed as corrupt, as a result, the communities don't trust the government.

The municipalities were asked how they know whether the communities are satisfied/unhappy with the level and quality of services that they are receiving; table 9 indicates that 42% of respondents said they conducted interviews, and 39% said they received feedback from the council meetings.

The Municipal iQ recorded an increase in the number of protests for the period 2006-2021. The top three provinces were Gauteng at 24%, Eastern Cape at 16% and Western Cape at 15%. The Municipal IQ report also highlighted the types of demands that the protestors made; the following demands have been highlighted to support the proposition:

- Complaints about corruption in the municipality – 13%
- Complaints against the conduct of the councillors – 26%

Table 9: Feedback from communities

#	How does the municipality know whether the communities are satisfied/unhappy with the level and quality of services that they are receiving?	Agree	R	Uncertain	R	Disagree	R
1	Through interviews/feedback from the communities	42%	16	22%	2	10%	2
2	Through council meetings	39%	15	22%	2	10%	2
3	The municipality does not know	8%	3	11%	1	48%	10
4	Through the increase of community protests	11%	4	44%	4	33%	7
	Total	Total	38	Total	9	Total	21

5.2 Discussion of results

The discussion of the results will be based on the proposition evaluation and the research questions that were used to develop the proposition. The findings/results from the data analysis cannot be generalised because of the low response rate, therefore, the discussion will be centred around the responses from the respondents and the municipalities that they are from.

The findings from the survey highlighted that 71% of the respondents know the number of households that have access to basic services, and 50% of respondents indicated that their municipalities have a records management system in place where the data is saved. The fact that half of the respondents said that their municipalities don't have an electronic database is concerning. The utilisation of national department systems came out strongly, which confirms that the local municipalities do not have a centralised system. It also indicates that the municipalities are highly dependent on the information they receive from national and external sources, and they don't do their internal checks to ensure that the data they are using is correct and accurate.

Table 10: Centralised tracking and reporting system

#	Do you believe that a centralized tracking and reporting system would be beneficial to the municipality?	Agree	R	Uncertain	R	Disagree	R
1	Yes, it will be	73%	19	14%	1	0%	0
2	No, it will not	4%	1	14%	1	64%	9
3	Our current system is fine	23%	6	71%	5	36%	5
	Total	Total	26	Total	7	Total	14

The notion that the three spheres of government, specifically national and local government, are not working came out strongly; the fact that local government doesn't have a centralised system and instead does reporting on sector departments system is a concern, considering the fact that each system has its own intended purpose which most of them is centred around monitoring and evaluating the performance of the municipalities. The results in table 10 indicated that 73% of the respondents agreed that a centralised system would benefit their municipalities.

Table 11 in results indicated that 75% of the respondents said they want to change the current way that their municipalities are tracking and reporting on service delivery and 42% of the respondents would change the way data is collected and reported, 35% of the respondents said that the municipalities must develop a new service delivery tracking and reporting system, therefore the respondents agree that they need a centralised system that will be tailored for local municipalities.

Table 11: Current way of tracking and reporting

#	What or how would you change the current way that the municipality is tracking and reporting on service delivery?	Agree	R	Uncertain	R	Disagree	R
1	I would not change anything	23%	7	25%	3	75%	6
2	I would change the way the data is collected and reported on	42%	13	33%	4	13%	1
3	The municipality must develop a completely new service delivery tracking and reporting system	35%	11	42%	5	13%	1
	Total	Total	31	Total	12	Total	8

The results indicate that 100% of the respondents believe that the communities and the three spheres of government will benefit from the tracking and reporting system. The results also showed that 96% of respondents agree that it is essential to know the number of households that have access to basic services; these numbers are significant because the municipality has to use them for planning and drafting documents such as an Integrated Development Plan (IDP).

The survey results in table 12 indicate that the municipalities want the following requirements for the centralised system:

a. The development and implementation of a centralised web and mobile technology solution with capabilities and functionality for data capturing, external data source integration, analytics, and data analysis
b. A platform for capturing analysis and visualising data, and reporting
c. Aggregation of real-time (and/or batch processing) information on the status plans, projects, performance, and projections

A system cannot operate and be utilised for its intended purpose if the municipality doesn't have the infrastructure and human resources; the results in table 13 indicate that 34% of the respondents have access to Wi-Fi, 44% have access to laptops and computers, and they have 23% data capturers that have been trained. The results indicated that 60% of the respondents indicated that the project managers in their municipalities are the ones that do the reporting, tracking, and capturing of data on the provision of basic services. These results indicated that over 50% of respondents of the municipalities have the infrastructure and capacity required to operate and manage the tracking and reporting system. The results showed that the respondents believe that the communities, sector departments and other spheres of government would benefit from the system.

Table 12: Requirements for a centralised service delivery system

#	If a centralized service delivery tracking and reporting system were developed, what would your requirements be?	Agree	R	Uncertain	R	Disagree	R
1	Development and implementation of a centralised web and mobile technology solution with capabilities and functionality for data capturing, external data source integration, analytics, and data analysis	35%	15	40%	4	33%	1
2	Platform for capturing analysis and visualising data and reporting	33%	14	30%	3	0%	0
3	Aggregation of real time (and/or batch processing) information on the status plans, projects, performance, and projections	33%	14	30%	3	67%	2
	Total	Total	43	Total	10	Total	3

Table 13: Infrastructure and technical capacity

#	Does the municipality currently have the infrastructure and technical capacity to be able to utilize the tracking and reporting system?	Agree		Uncertain		Disagree	
1	WIFI	34%	14	22%	2	33%	4
2	Laptops and computers	44%	18	22%	2	25%	3
3	Data capturers/trained staff	22%	9	56%	5	42%	5
	Total	Total	41	Total	9	Total	12

6 CONCLUSIONS AND RECOMMENDATIONS

The analysis findings highlighted that the municipalities that were part of the study know the number of households that have access to basic services; however, they don’t do their internal check to ensure that the numbers are accurate. The consequence of not having a centralised tracking and reporting system is that local municipalities will lack adequate statistical information to make evidence-based decisions that will inform policy development, planning and budgeting. Due to the low response rate, one could not determine whether these findings apply to all 257 South African municipalities. The results confirm that The South African local government does not have a centralised tracking and reporting tool designed specifically for their needs; reporting is done on sector department systems, which can be confirmed through the District Development Model (DDM) literature.

The system through which the South African national and provincial governments have been monitoring the local government has not been as effective as one would have imagined. The absence of coordination and integration between the national government and the local municipalities has resulted in duplication and burdensome reporting obligations for municipalities. The current reporting system is mainly going up awards to the provinces and national departments; however, there needs to be reporting going downwards to the municipalities that need the information for their annual planning.

DCOG's mandate is to monitor the provision of free basic services in municipalities; therefore, a centralised tracking system would improve integration and coordination between the three spheres of government to ensure proper planning, proper allocation of resources and efficient implementation of basic services programmes that are at the desired level of economic and social impacts. The system will provide a platform where the local government can measure the impact it has made in providing basic services and has improved the quality of life of South African citizens.

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A BUSINESS CASE FOR RECYCLING COMPUTER E-WASTE

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ABSTRACT

The e-Waste Association of South Africa indicated that each South African generates 6.2 kilograms of e-waste annually with only 12% recycled, and the rest being refurbished and reused or ending up in disposal sites. e-Waste includes anything that requires electricity to function e.g., cellular phones, computers, printers, fridges, kettles, toasters etc. As of the 23rd August 2021, environmental regulation was passed that prohibits the disposal of all electrical and electronic waste to landfill in South Africa. In this study the feasibility of setting up a business case for an e-Waste recycling business was explored using system dynamics as a modelling methodology. The study considered the costs linked to the physical layout and business requirements to be economically feasible based on the annual throughput of the end-of-life computers. Based on a collection rate of 0.14 and a recycling rate of 0.12, simulation runs indicated that the approximately 24.65 Mtons of computer e-Waste would end up in landfill. Results also indicated that the biggest impact on obtaining a net profit for the business was inflation. Even with high volumes of laptops (51,975) and desktops (15,525), the business starts making a net loss after 13 years in operation.

Keywords: System dynamics, desktops, laptops, recycling.

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1. INTRODUCTION

Electronic waste (e-waste) refers to end-of-life or discarded electrical and electronic equipment powered by electricity e.g., household appliances, office and communication equipment, lighting, tools etc. E-Waste is also referred to as waste electrical and electronic equipment (WEEE). Although e-waste has several toxic substances and materials which can be harmful to the environment and human health, it can also be a source of secondary raw material, thus reducing the need for primary material mining and related environmental impacts.

Global e-waste generation was estimated at 54 million metric tons in 2019, with China being the largest producer of this type of waste (more than 10 million metric tons in 2019), followed by the United States at 7 million metric tons [1]. Although there are no exact figures for South Africa, the Department of Environmental Affairs believes that e-waste is growing at a rate three times faster than any other form of waste while according to the e-Waste Association of South Africa, 6.2 kg of e-waste is generated per person with only 12% recycled [2]. A study in 2015 indicated that ICT and consumer electronics made up 79% of the total e-waste stream [3].

The National Environmental Management: Waste Act (Waste Act; Act 59 of 2008) was promulgated and effected since July 2009, to legislate waste management to regulate the waste industry. However, on the 23rd of August 2021, the National Norms and Standards for Disposal of Waste to Landfill was implemented, thus banning WEEE from being dumped in waste disposal sites [4]. This of course, compels industry to become more environmentally responsible and to find ways of reusing, refurbishing or recycling their WEEE.

In this study, the national landscape with respect to computer volumes was first calculated. Thereafter, laptop and desktop e-waste were selected to determine if there would be a business case for a company to set up its own recycling facility as part of their other product and services offerings, as opposed to paying an external recycling company for disposal and recycling. The possible number of Small to Medium Enterprises (SMEs) was calculated based on the national number of computers and the SME throughput. A system dynamics methodology was followed to build a simulation model in order to run scenarios.

2. METHODOLOGY

2.1 National Computer E-Waste

The first step was trying to estimate the number of computers that would be eligible for recycling. In doing this, the projection for population and for households was required by year 2050. A logistics equation was used to set a target based on historical information and on principles that all systems will tend to plateau at some stage because the physical constraints of systems are generally based on principles of classical, quantum or solid-state physics or thermodynamics.

In order to determine an estimate of the national number of computers in South Africa, three methods were used and the most plausible one chosen.

Method 1

The population in South Africa based on 2020 estimates was 61.04 million [5]. Based on the historical information, the target for 2050 was set at 75.50 million using a logistic S-curve equation. The population who are of working age (considered to be 15-64 years) is 39.09 million, and of the working age population, 38% are employed [6]. This value was then used to establish how many people in industry have computers and used in Eqn. 1. The high-level assumption was that all employed people have computers at work which is not accurate because some industries would not require employees to have computers e.g., cashiers, unskilled workers.

$$Computers_{commercial\ sector} = population \times working\ age\% \times employed\% \quad (1)$$

In order to calculate the number of people who have computers in the residential sector, the number of households until 2050 was calculated (with a goal setting target of 21.5 million by 2050). The fraction of households with a computer in Africa is estimated to be 7.7%, however in South Africa, this value is approximated at 21.5% [7] (refer to Eqn. 2).

$$Computers_{residential\ sector} = Households \times fraction\ with\ computers \quad (2)$$

The number of computers in the industrial sector was then added to the residential sector computers (Refer to Eqn. 3).

$$Computers_{SA} = Computers_{commercial\ sector} \times Computers_{residential\ sector} \quad (3)$$

Not all the computers in circulation are electronic waste so the total national number of computers was then multiplied by the fraction of e-Waste to consumed electronic goods (6.63/9.94 which was 0.67) [8].

Method 2

In the second method, the e-Waste per capita (6.2 kg/person) [9] was multiplied by the population. This was then divided by the average device mass (refer to Eqn. 4).

$$Computers_{SA} = (eWaste\ per\ capita \times population)/Computer\ Mass \quad (4)$$

Method 3

In this third method, it is estimated that there are 8.28 computers per 100 people in South Africa [10]. This value was then used to calculate the total number of computers based on the population (refer to Eqn. 5).

$$Computers_{SA} = Computers\ per\ capita \times population \quad (5)$$

The results for all three methods were compared and is shown in Figure 1. Methods 1 and 3 yield fairly similar results but Method 2 is by an order of magnitude higher. For purposes of this study, Method 1 was used, based on plausibility.

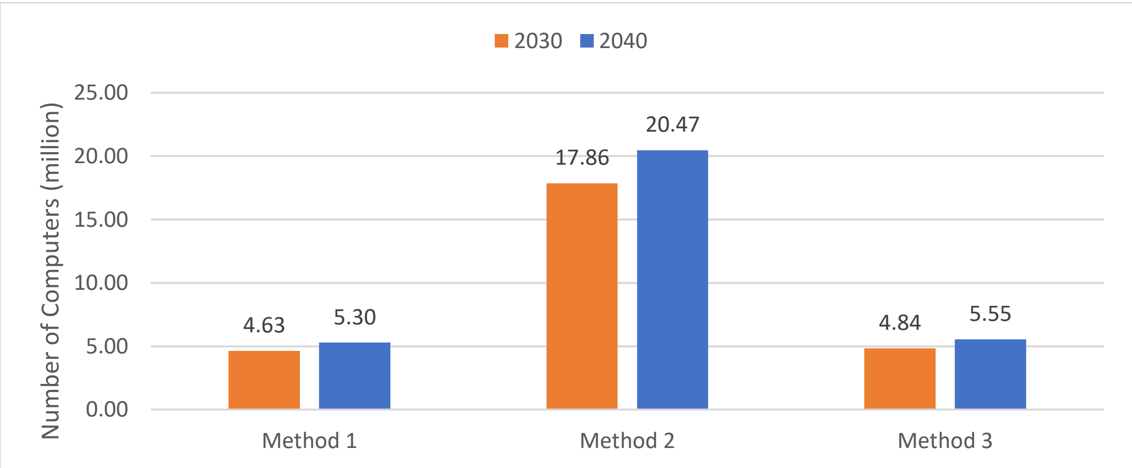

Figure 1: Comparison of different methods to estimate the number of computers in South Africa

After determining the possible number of computers in circulation, the number of computers collected was calculated based on an e-waste collection rate of 0.14 [11]. Of the computers collected, 12% were allocated to recycling [9], and 5% to refurbishment (there is no validated number that could be found through the literature review).

There is also a fraction of e-waste which is referred to as being “diverted from landfill” (25%) and included devices that are kept in storage or illegally disposed or exported [8]. This diverted value was excluded from the remaining uncollected computers sent to landfill sites.

2.2 SME computers

Computers were split into desktops and laptops due to the weight difference which would then impact the income sales calculations and the waste tonnages. Laptops weigh less than desktops so a fraction of 77% laptops was used and the rest allocated to desktops [12]. The base laptop mass was pinned at 2.2 kg [13] and desktop mass at 21.7 kg [14] – although the simulator does allow for these values to be adjusted.

The fractional masses of the various parts of the computer used are shown in Table 1 [15]. Desktop sales were also divided into a fraction (0.5) that would be sold as a batch of parts (tower, monitor, keyboard & the mouse) and the remaining fraction would be dismantled and discrete elements sold like the printed circuit board (PCB), plastics, cables etc.

Table 1: Fraction of total mass - computers [15]

FRACTION OF MASS	
	Value
Cable frac of computer mass	0.0197
plastic frac of computer mass	0.1521
PCB frac of computer mass	0.0275

The value of the sales in Rand per kg was based on the values shown in Table 2 for the PCB [16], plastics, cables, hard drive destruction [17] and lithium-ion battery (LIB). All of these values can be user defined and changed to run various scenarios.

Table 2: Price per unit - computers

ITEM R/UNIT	
	Value
Cables R/kg	10
Plastics R/kg	7
LIB R/unit	2
Hard drive destruction R per unit	20

Desktops that are dismantled have their tower, monitor, keyboard and mouse sold as a batch either locally or exported (again assuming that 50% of the throughput goes to the batch part sales department and the remaining are sent for recycling and refurbishment). If they are exported the sales prices are higher but then an exporters licence for the SME would be required.

The inflation rate used was an average of 7.8% [18] and annual sales increases was also kept at 7.8% to keep up with inflation. The average retail price for a desktop computer was taken as R28,000 [19]. The average retail price of a laptop was taken as R12,000 [20]. The takeback fraction could have been 0.1 based on a value quoted by Lenovo [21] or a fixed value for laptops (R500-R1000) and desktops (R500 – R750) older than 5 years [22]. The fraction as a function of the retail price was chosen, which allowed for a dynamic retail price.

In terms of the start-up costs: The business plan value selected was R8,000 [3], company registration was R750 [24], opening a bank account with a deposit was R5,000 with monthly fees of R85 [25], the facility setup and layout (to include a kitchen, eating area, ablution facilities) was taken to be R200,000 (verbal estimate from a building contractor); the registration fee for BBBEE was provisioned for in the structure but set at zero. The fee for the South African Chamber of Commerce and Industry (SACCI) was R135,150 [26]; for EWASA registration was R3,230 [27]; for a waste management licence was R3,965 using an inflation rate of 7.9% on the 2015 value [28]; for vendor registration with the government departments was R500 [29]; registration on the Provincial Waste Management System was R0 [30]. If exports were included in the simulator, it triggered a waste exporters licence cost of R2,450 [31]. ISO accreditation was also factored in at R17,000 [32].

In terms of the equipment required, the simulator allowed for the user to input the number of items required which was then multiplied by the unit cost per item. The lockable security cage was set at R6,884 [33]; the wire metal locker cage (2 tier) at R3,280 [33]; a pallet at R1,808; WEEE bin at R8,500; forklift at R50,000; a pallet jack at R3,967 [34]; pallets at R805 each [35]; a container trolley at R3,832 [36], 4 drawer steel cabinet for tools at R3,295 [37]; and a 3 ton forklift at R77,530 [8].

The start-up costs also assume a hard driver shredder for R204,128 [39]. A 20% deposit and 20% depreciation per year, as well as an interest rate of 12% and a payback period of 5 years was used. Other once-off start-up costs were allocated to purchasing a computer and printer (R55,129); software R25,000 [40]; security R25,000 [41]; insurance R756 [42]; and for the website R30,000 [43].

Additionally, training costs were included to ensure that the skills were appropriately equipped to handle the operations. With respect to this, costs were assigned for computer refurbishment training, Computer disassembly training and soft data and hard drive destruction.

If all of the above costs are factored in for start-up, the total required capital is R748,217.

Two calculations were carried out to determine the most cost-effective option in the long-term for the factory site. The first option was to rent the factory and property space and the second option was to buy the property. The area required for the factory was based on areas allocated to the offices, the workstations and factory. Other space considerations were for the tea and canteen area as well as the ablution facilities and the parking. The factory rental costs per square meter used was R85 [44].

Instead of rental, the other option would be to buy a property and pay it off over 15 years. Buying a factory of 943m^2 is approximately R4.3M [45]. Repayments (on purchase of the property) were calculated based on a 12% interest rate, a repayment period of 15 years and a once-off deposit of R500,000. A 1.6% bond registration cost and a 15% property transfer cost were also added which means that an upfront, once off total payment of R1,205,800 would be required.

The base scenario assumes a default of a manager, 1 administrator, 1 person for soft data and hard drive destruction, 1 floor & logistics supervisor, 1 cleaner, 1 security guard and 1 material handler. Depending on the number of computers that each dismantler can handle per day, the simulator then calculated the required number of dismantlers linked to the throughput. A similar process was followed to calculate the number of refurbishers.

Other annual operating expenditure costs included eWASA fees, insurance costs, telecommunications, property rates & taxes, and staff travel costs. Consumable costs such as for brooms, brushes, sanitizer, cleaning products, tea/coffee, toilet rolls etc. were also accounted for.

In terms of electricity costs, calculations assumed that the business operated 5 days a week for 8 hours a day. Electricity would then have been required for the following - Table 3. The initial electricity cost at the start of the SME business was R2,07/kWh [46] which would increase over a 10-year period to R4.07/kWh based on an annual inflation rate of 7.8%

Table 3: Costs linked to electricity consumption [47]

	kW	SME hrs/month	kWh/ month	kWh/ year
Desktop Computer	0,4	160	128	1,536
Monitor	0,02	160	3,2	38,4
Laptop	0,1	160	80	960
laser Printer	0,8	160	128	1,536
Internet router	0,015	160	2,4	28,8
Fluorescent light	0,015	720	162	1,944
Hard drive shredder	7,5	40	300	3,600
Kettle	1	40	80	960
Microwave oven	1,3	40	104	1,248
Coffee machine	0,8	40	64	768
Fridge	0,15	720	108	1,296
Other electricity (e.g., power tools)	0,5	160	2,400	28,800

It was difficult to get a good estimate for water costs. The average daily water used per day per person in South Africa is 237 litres in a residential area [48]. In trying to estimate the water used per person (toilets, drinking, coffee etc.), a value of 50 litres was used. It is a conservative value noting that a toilet flush uses 10 litres of water. This is one area that can be optimised by getting more accurate data from recycling companies.

In calculating the cost of transporting waste away from the site and transporting end-of-life equipment to site, it was assumed that a truck would be hired as and when required instead of employing a full-time truck driver which would add to the operating and capital expenditure costs. Depending on the volumes transported, costs were then calculated for a 3-ton truck or an 8-ton truck. The number of trips would depend on the number of computers being transported to the factory as a function of the throughput; and the volume of e-Waste away from the factory. Other assumptions used in calculating the transport costs was that an 8-ton truck would be used to bring in all of the computers and a 3-ton truck would be used to transport the waste away. The numbers of computers that could be carried in an 8-ton truck was approximated at 190 while the waste volume for 3-ton truck was 3 tons.

Recycling tool costs were factored in the simulation. Depending on the number of dismantlers and refurbishers, the model automatically calculated the number of tools and PPE required. The assumption on PPE as well as the refurbishment and recycling tools was that they would have to be replaced at certain periods or intervals (Table 4).

Table 4: Replacement periods

REPLACEMENT PERIODS	Value
SME Refurb tool replacement period yrs	5
PPE replacement period yrs	3
Safety Equip replacement period yr	3
Recycling tool replacement period yrs	6

Based on these costs and assumptions, various scenarios were run using a system dynamics simulator. The time frame of the simulator used an SME start-up year of 2022 and an operating period of 25 years. The engagement interface used to run the scenarios for the SME is shown in Figure 2.

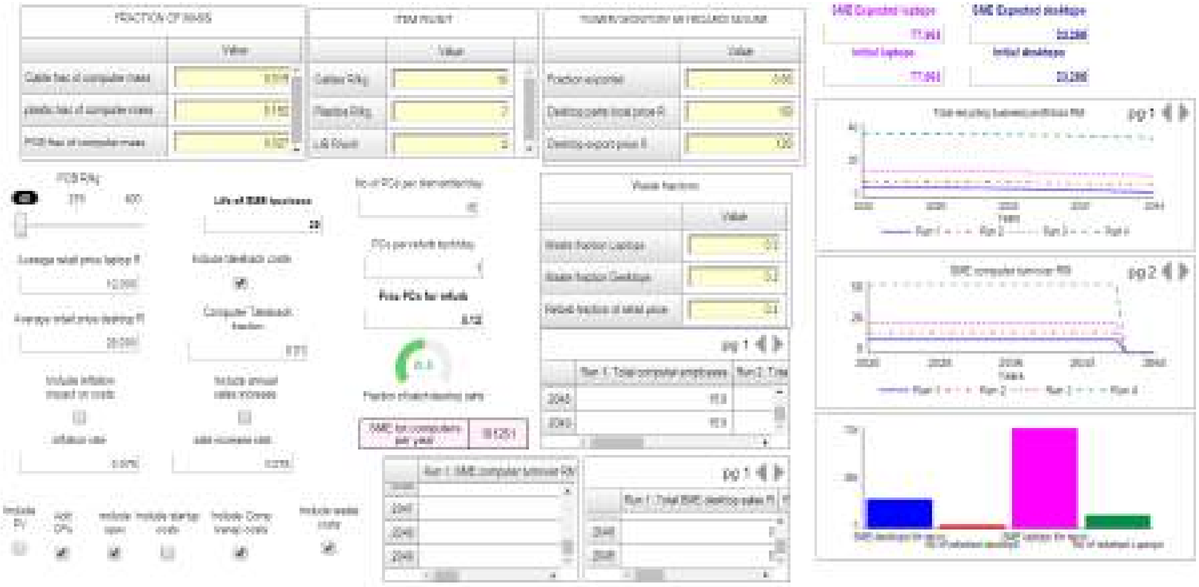

Figure 2: Engagement Interface for Scenario Runs

3. RESULTS AND DISCUSSION

3.1 National Computers

Based on the default parameters explained in Section 2, the base case for the results showing the volumes of computers in each category is reflected in Figure 3 for years 2022, 2030 and 2040. This included a collection rate of 0.14, a recycling fraction of 0.12, and a refurbishment fraction of 0.05. The “Diverted from landfill” refers to those computers that are not collected for recycling and refurbishment and are not in landfill sites either i.e., they are unlocated.

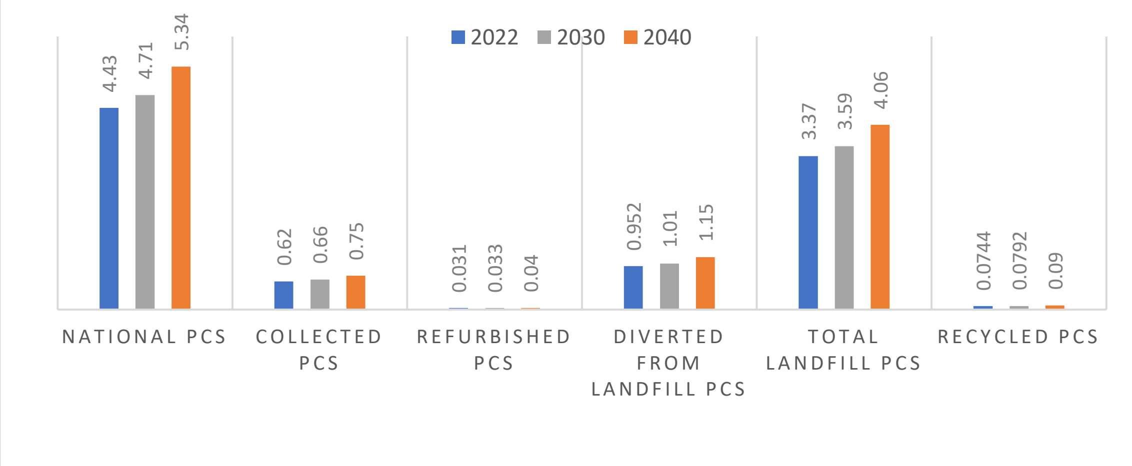

Figure 3: National Computers available and end-of-life categories in year 2040

The results show that there may be 5.34 mill computers in the country by 2040 and if the collection rates remain low and the reliance on landfill options is still high, only 0.09 mill computers would be recycled in year 2040. In terms of estimating what could currently be available, it would be about 4.43 million computers.

There are a lot more computers that would be diverted from the landfill in year 2040 (1.15 mill) and that are unaccounted for due to them being incorrectly disposed in illegal dumpsites or just kept in personal storage. If 5% of the computers are refurbished, this translates to 0.04 mill computers refurbished. The total number of computers going to landfill would be 4.06 mill.

The volume of landfilled computers and those that would likely be recycled based on the base recycling rates is shown in Figure 4.

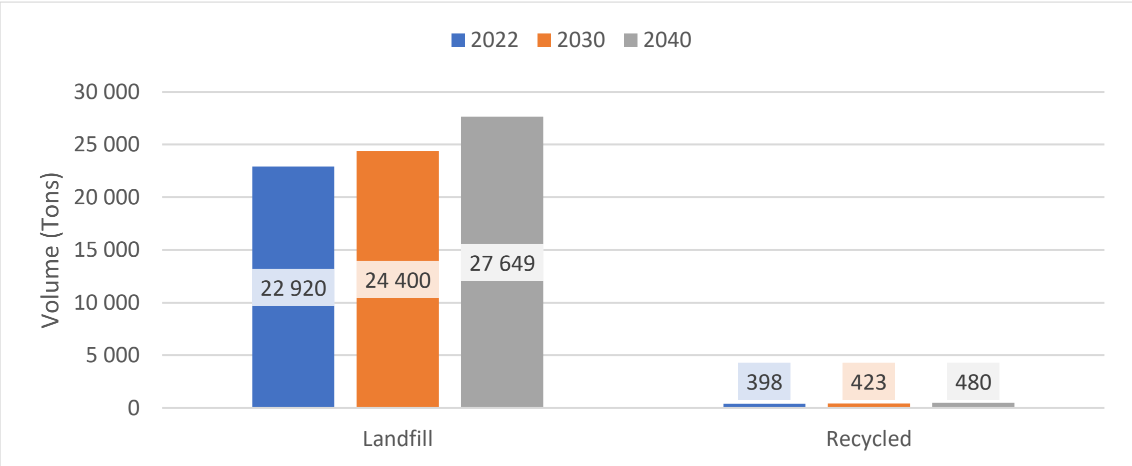

Figure 4: National Computer Tonnages

If collection rates remained at 0.14 and the recycling rate at 0.12, the expected volumes of computers ending up in landfill sites in year 2040 would have been 27,649 tons and the volume of computers that could be recycled would be 480 tons.

The collection rates for WEEE in the European Union measured in 2019 were 48.5%, with three member states achieving 65% [49]. If the collection rate (CR) was changed from 0.14 to 0.25 to 0.50, the impact on the recycled volume for computers was calculated for year 2040 and is shown in Figure 5.

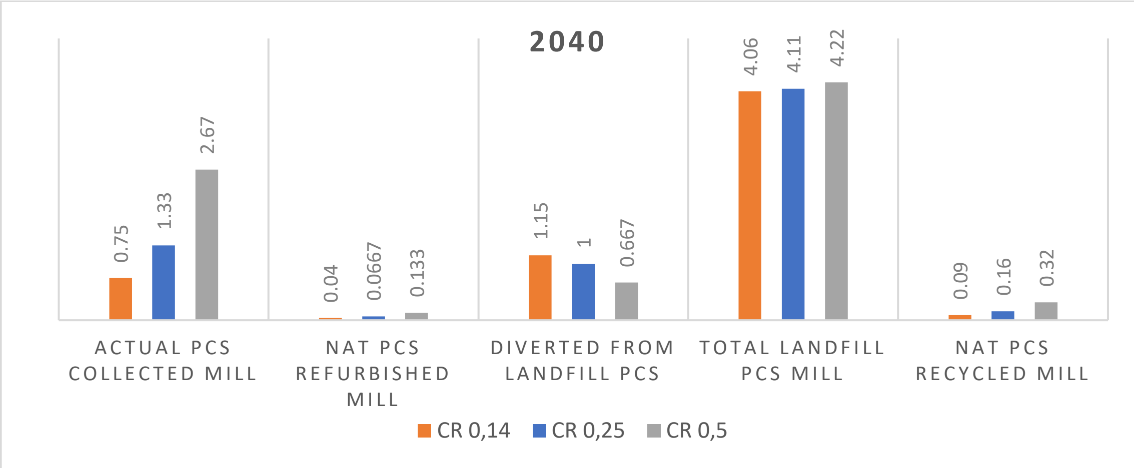

Figure 5: Comparison for different collection rates in 2040

As expected, as the collection rate increases (0.14; 0.25; 0.50), the number of recycled PCs increases and the number that would be refurbished. Additionally, since the collection rate increases, there is a smaller fraction of the uncollected that is expected to remain unaccounted for. The total number of computers at the landfill, however, gradually increases. The reason for this is a feedback loop that returns the computers that have been collected and not refurbished or recycled back to the landfill site. This value will thus increase as more computers are collected. It is also then added to the uncollected fraction that also ends up in landfill sites (decreasing trend).

The scenarios to compare the sensitivity of collection rate and recycling rate on recycled volumes is shown in Table 5.

Table 5: Impact of collection rate and recycling rate on recycled tonnages

	Collection rate	Recycling Rate
Scenario 1	0.14	0.12
Scenario 2	0.25	0.25
Scenario 3	0.50	0.50

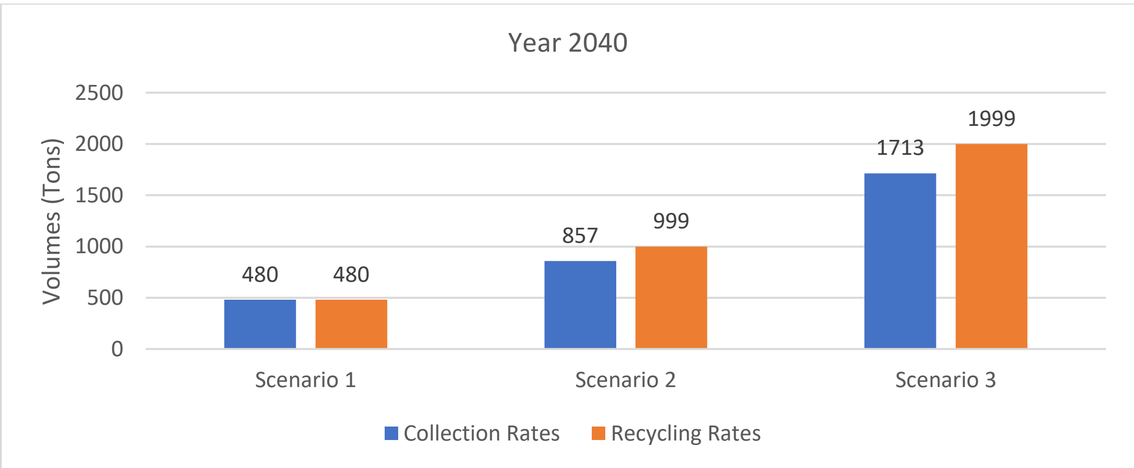

Figure 6: Comparison collection and recycling rates on recycled volumes

Results indicate that even though collection rates can increase, there must be a concerted effort at actively increasing the recycling rates in order to increase recycled computer tonnages.

3.2 SME Scenarios

Scenarios were also run to understand the impact on revenue based on various changing parameters shown in Table 6. For these scenarios, a base value of 15,400 laptops were used and 4,600 desktops with an average of 15 computers dismantled per day and 1 computer refurbished per day.

Table 6: SME Scenarios - Cost elements affecting SME Profit/loss

	Computer Sales	Operating & Capital Expenditure	Transport & Waste Costs	Computer Takeback	Inflation
Scenario 1	X				
Scenario 2	X	X			
Scenario 3	X	X	X		
Scenario 4	X	X	X	X	
Scenario 5	X	X	X	X	X

For each subsequent scenario, one additional parameter was added to determine the relative impact on profit/loss of the SME. Results are shown in Figure 7.

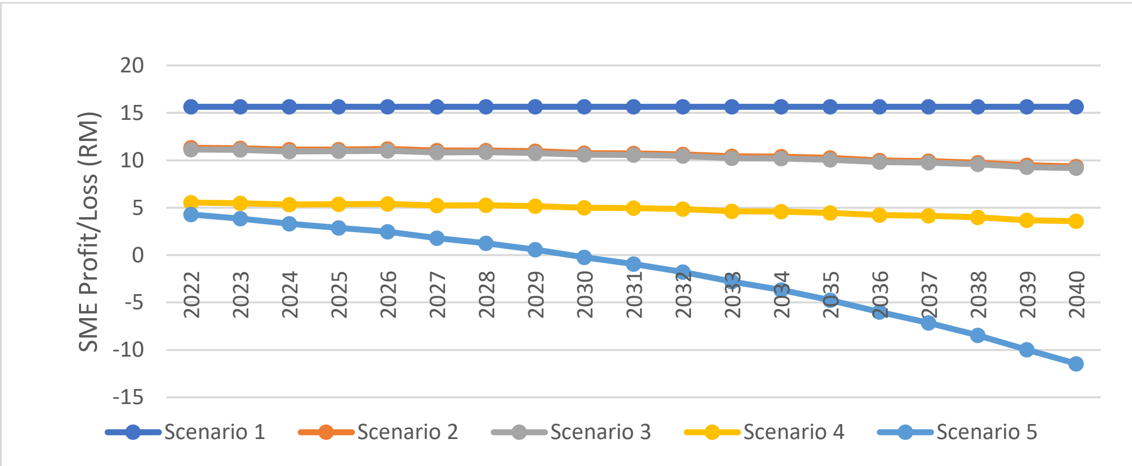

Figure 7: Comparison of various parameters on SME revenue

Scenario 1 disregards any costs and expenses for the SME and would mean an annual revenue of R15.6M. Scenario 2 considers all the operating expenses (dismantling & refurbishing tools, salaries, factory costs, utility bill etc) and capital expenditure which yields a revenue of approximately R11.3M in 2022 and R9.35M in year 2040. In 2022, Scenario 3 where waste costs (fraction of materials that cannot be reused or recycled) are factored in, has a revenue of R11.14M and R9.17M in year 2040.

A significant drop in revenue is if a computer takeback cost is factored (even at 1% of the retail price of the computers), as shown in Scenario 4, although still profitable at R5.53M in year 2022 and R3.57M in year 2040. If 7.8% annual inflationary increases are factored in then after 7 years, the SME will have to relook at strategies since they would be making significant financial losses from year 2030.

The next scenarios (Table 7) looked at changing the throughput of the computers considering all of the costs to find a breakeven point. Each scenario was increased by 50% of the preceding scenario.

Table 7: SME Scenarios - Changing the Computer Throughput

	Desktops	Laptops
Scenario 1	4,600	15,400
Scenario 2	6,900	23,100
Scenario 3	10,350	34,650
Scenario 4	15,525	51,975

The results in Figure 8 show the impact of changing throughputs (without inflation) and Figure 9 shows the impact on revenue with inflationary considerations. The assumption is that the sales prices does not increase at the same rate.

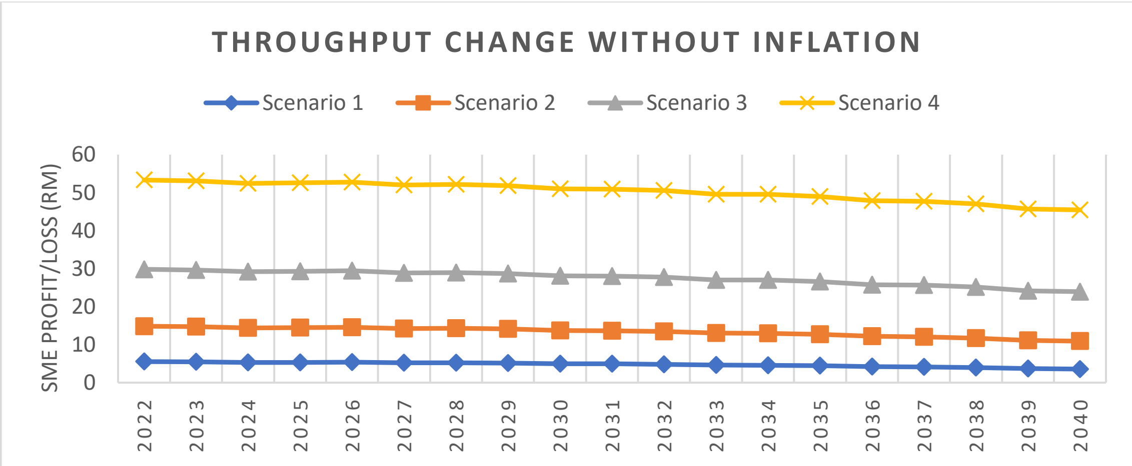

Figure 8: Comparison of various throughputs (without inflationary impacts)

Without considering inflation, the higher the throughput, the higher the profit for the SME with Scenario 4 yielding a 2022 profit of R23.48M and in year 2040, a profit of R21.52M. The least profitable is Scenario 1 but nonetheless profitable throughout the life of the SME.

Based on the results in Figure 8 and Figure 9, the impact of inflation is marked and even at the highest throughput of 15,525 desktops and 51,975 laptops (Scenario 4). The business would end up making losses for Scenario 1 in year 2030 and for Scenario 4 in year 2035.

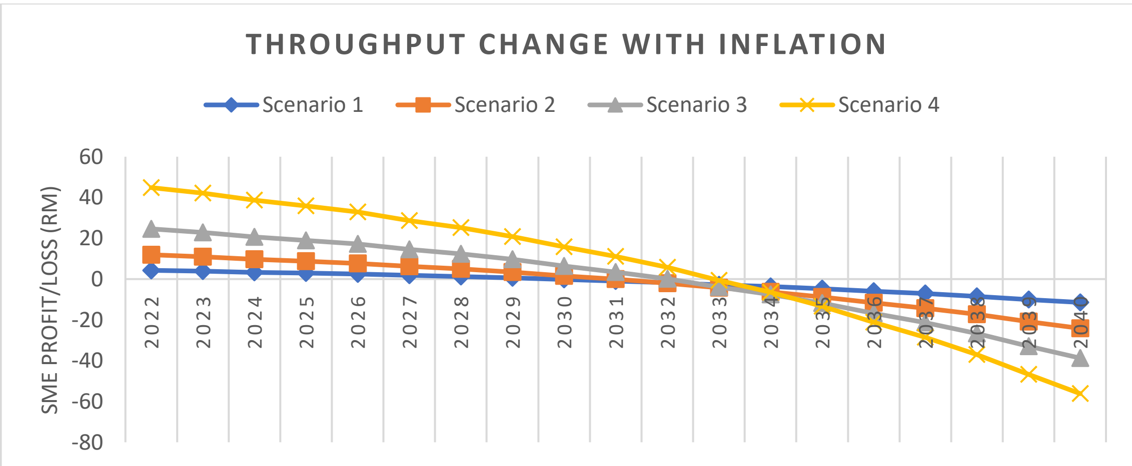

Figure 9: Comparison of various throughputs (with inflationary impacts)

It must be noted that as the throughput increases, so too does the number of dismantlers and refurbishers to be able to handle the volume which means a higher salary expenditure and dismantling & refurbishing equipment, personal protective equipment, utility costs etc.

The next Table 8 shows the number of SMEs that would be possible based on the national number of computers and the SME throughput of 4,600 desktops and 15,400 laptops.

Table 8: Possible number of SMEs

	SMEs
Scenario 1 (based on national collected volumes)	31
Scenario 2 (based on recycled volumes)	4

The results shown above are based on the low collection and recycling rates and would be much higher if the rates were increased for computers. There is also a significant difference in results by an order of magnitude depending on whether the collected volumes are used or whether only the fraction of recycled computers are used for the calculations.

4. CONCLUSIONS

It is likely that there will be 5.34 mill computers in the country by 2040 and if the collection rates remain low and the reliance on landfill options would remain high with only 0.09 mill computers recycled in year 2040 (a volume of 480 tons). The volume that would end up in landfill would be 27.65 Mtons. However, due to the changing legislature in August 2021 which prohibits the disposal of WEEE in landfill sites, recycling and refurbishment would have to increase significantly.

Increasing the collection rates would mean a higher volume of computers routed to recycling. Results indicated that increasing collection rates was not as impactful than if more recycling took place.

In the case of the SME, if all the operating expenses (dismantling & refurbishing tools, salaries, factory costs, utility bill etc), waste costs (fraction of materials that cannot be reused or recycled) and takeback costs are factored in, the business is able to generate a profit of R5.53M in year 2022 and R3.57M in year 2040. However, if a 7.8% annual inflationary is factored in then after 8 years, the SME will experience a revenue loss of R0.22M. This means that the SME would have to consider various business and operating strategies to mitigate the significant financial losses. Some of these strategies would include having more computers dismantled and refurbished per employee besides increasing the sales values of products sold. It could also include sourcing computers from businesses that do not expect a financial incentive in the form of a takeback cost.

Even if the annual throughput increases to 15,525 desktops and 51,975 laptops; the business would end up making losses after 13 years in operation with inflationary impacts. Electricity tariffs were increased at a 7.8% rate but based on the historical and expected electricity tariff hikes in South Africa, it is likely that the electricity costs will also add to an overall decrease in revenue so the current calculations are still too conservative. Together with throughput increases, so too does the number of dismantlers and refurbishers increase to be able to handle the volume which means a higher salary expenditure and dismantling & refurbishing equipment, personal protective gear, water costs etc.

There is also a marked difference in the number of SMEs that could be expected if calculations were based on national collection rates (31 SMEs) compared to recycling rates (4 SMEs).

System dynamics proved to be an excellent modelling method because it allowed various simulation runs and scenarios to test the sensitivity of various parameters, to optimise the business elements for the SME. It also allowed feedback loops to be included in the structure of the model.

5. RECOMMENDATIONS

It would be valuable to obtain data on the actual refurbishment rates of the national volumes of computers since value of 5% was assumed due to lack of information.

A national recycling strategy needs to be actively driven with requirements from every business to consider this in their business operating models.

Actual costs linked to training and skilling workers would have to be factored in. Provincial breakdowns of the end-of-life categories of computers will be useful in supporting strategies for recycling in the provinces.

6. ACKNOWLEDGEMENTS

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THE ROLE OF THE 4TH INDUSTRIAL REVOLUTION IN ENHANCING PERFORMANCE WITHIN THE CONSTRUCTION INDUSTRY: A LITERATURE REVIEW

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ABSTRACT

The construction operation is not an exception to the Fourth Industrial Revolution (4IR), which is expanding and challenging multiple sectors. There is currently limited evidence that 4IR technologies are being adopted in the construction industry, especially in the least developed countries. The objective of this research was to conduct an extensive literature review regarding how the Fourth Industrial Revolution contributed to better performance in the construction sector. This paper reviews the published literature on the Fourth Industrial Revolution in the construction industry ranging from 2013-2023. A systematic literature review methodology was used to conduct a search. The findings indicate that there is still a lack of study on the positive impacts of sector 4.0 in the context of the construction sector, particularly with regard to the effect on performance. The several PESTEL (political, economic, social, technical, environmental, and legal) concerns must be addressed by the construction industry.

Keywords: adoption, construction industry, fourth industrial revolution, technologies

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1 INTRODUCTION

One of the largest worldwide industries is construction, and the foundation it creates is the cornerstone of economic development and competitiveness. The construction industry's scope of work is diverse, ranging from residential, industrial, and commercial projects to infrastructure construction [1]. According to the World Economic Forum, the construction industry contributes 6% to the global GDP and more than 8% to the GDP of emerging countries [2].

The term "Industry 4.0" originated in Germany as a proposal for a new concept of German economic strategy based on modern technologies. The concept evolved to express the fourth industrial revolution, which is based on a variety of technologies such as cyber-physical systems (CPS), the Internet of Things (IoT), cloud computing, and mobile computing, among many others. The goal of Industrial Revolution (IR) 4.0 is to digitize industrial processes in order to create a flexible yet extensive production and service network. like the manufacturing industry, the construction industry's performance can be enhanced through IR 4.0 [3]. The adoption of IR 4.0 creates a space where all automated machinery is connected via technology improvements to function and transmit information without the assistance of people, increasing efficiency [4].

When used, it enhances product quality while reducing time to market and improving operational performance, so the advantages are evident. Despite the numerous advantages that other industries have to offer, the construction industry has been slow to adopt these ideas [5]. World Economic Forum [6] states that businesses will increase productivity, streamline their operations, and reduce costs by implementing innovations including 3D printing and scanning, enhanced building materials, augmented reality, autonomous equipment, and drones. Project and process management, as well as improvements to quality, health, and safety. The 4IR technologies have the potential to raise building quality, boost health and safety, work conditions, and sustainability, and increase construction productivity while reducing project delays [7].

2 BACKGROUND

2.1 Fourth Industry Revolution 4.0

The 4IR entails process automation and information sharing among physical systems, manufacturing technology, and people. The Internet of Things, cloud computing, cyber-physical systems, and cognitive computing are also included in this. In the future, learning algorithms-powered computer systems will be remotely connected to robotic devices. This means that these machines require relatively minimal assistance from human operators to understand and operate robotic machinery [8]. The 4IR is South Africa's best hope for reviving the country's ailing economy. More investment in the automation of the construction industry is the most important factor in boosting the economy [9].

2.2 Productivity

Levin and Cunningham [2] said labor productivity in the American construction industry has actually decreased over the last 40 years, and it has stayed steady for the last 50 years. Farmer [10] argues that the severely low productivity of the construction industry is a crucial problem, highlighting both the glaring disparity relative to other industries in absolute terms and how the gap has grown over time. The development of digitalization has made it possible to address construction difficulties in new ways. The design, development, and operation of the built environment are being transformed by the Internet of Things (IoT) and Building Information. Modeling (BIM) [11]. Utilizing these technological improvements offers the chance to boost productivity [12].

2.3 Project delays

Worldwide, delays are a common issue with construction projects. In terms of the experience of delays, global research established that over a period of three years, 25% of construction projects were completed within 10% of their scheduled completion dates [13]. Toor and Ogunlana [14] examined the viability of incorporating BIM into a project management framework to track the progress of the building. The existing way of tracking work on sites presents a problem in terms of reducing delays. They say that using BIM and progress monitoring software has increased efficiency on construction sites, mostly because it has made information more readily available.

2.4 The construction industry and 4IR

When compared to other sectors, the construction industry has not changed despite the challenges it faces and the effects of the industrial revolutions (1-3) in Figure 1. In contrast to other sectors, the construction industry was noted to have adopted technology more slowly during past industrial revolutions [15]. The fourth industrial revolution distinguishes between digitalization and digitization. Numerous sectors have seen their processes change as a result of digitization. Digital technology has the potential to completely transform the building sector. Therefore, the construction industry shouldn't adopt the same sluggish mindset as it did throughout the preceding industrial revolution. Other industries have embraced various technologies in the 4IR to bring about change and gain an advantage. The fourth industrial revolution (4IR) is technologically driven, less dependent on human intervention, and more dependent on connecting and interacting with machines [2].

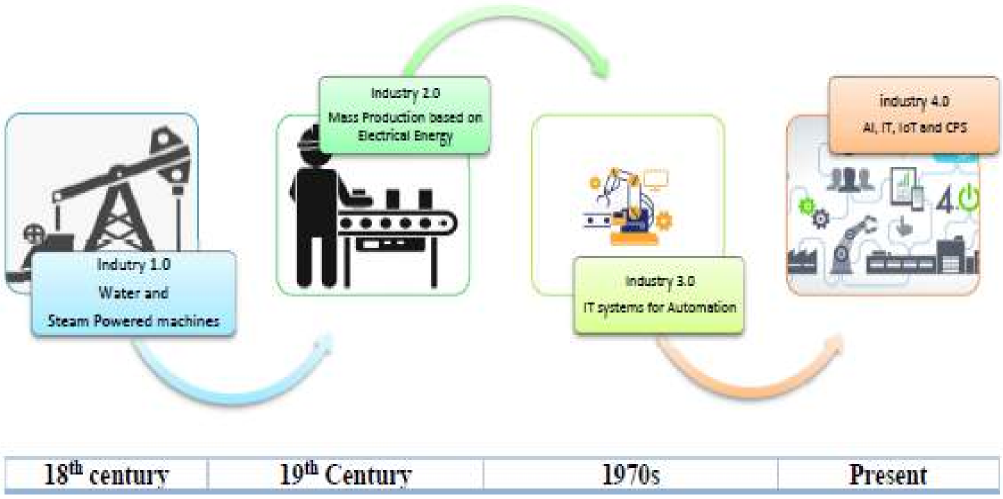

Figure 1:Industrial Revolution. Source: Adapted from[15]

In contrast to the previous industrial revolution, the fourth has a faster acceptance and change rate. In contrast to earlier industrial revolutions' experiences, the building industry seems to be catching up with technology more quickly. Another significant factor in the construction industry's quicker adoption of technologies is related to the coronavirus epidemic, in addition to meeting customer demands and obligations [16]. Researchers have recently introduced the phrase "construction 4.0" to describe the incorporation of Industry 4.0 into the construction industry. Few studies have looked at Industry 4.0 in construction, according to a survey of the literature. Then, a framework for construction 4.0 was provided in Figure 2 below [15].

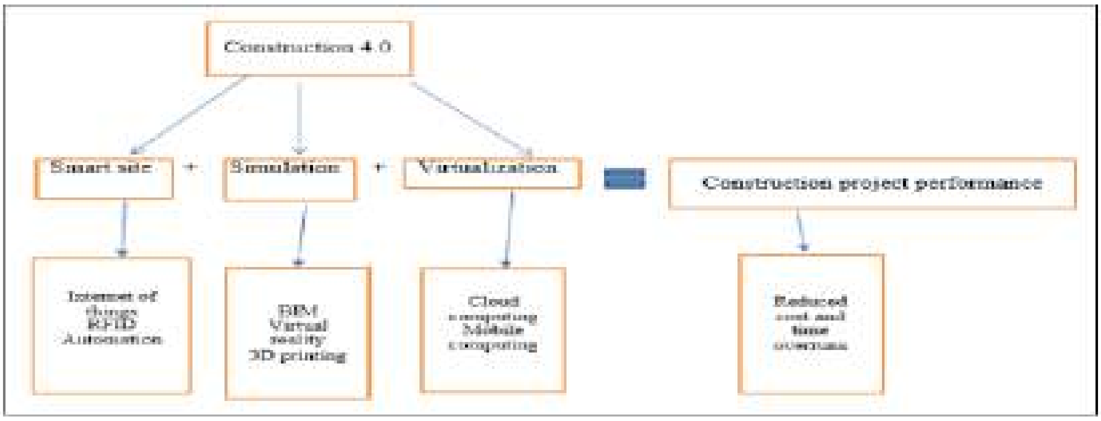

Figure 2: Construction 4.0 Conceptual Framework Source: Adapted from [17]

[18]were the first to introduce the phrase "Industry 4.0" to the literature in the construction industry. In an effort to assess the current research efforts in the fields of Industry 4.0 and construction, they conducted the study. It becomes evident that there are still no scientific papers in this field since their efforts are fruitless. Construction 4.0 research often concentrates on difficulties facing the construction sector, sector 4.0 preparedness, and applications of Industry 4.0 in construction [19]. However, certain researchers were intrigued by building 4.0's benefits and its role in improving performance. They stated that the adoption of Industry 4.0 technology in the construction sector will improve the efficiency of construction projects. The following studies have previously looked at the benefits of Industry 4.0 for the construction sector, [18] conducted a study to know how Industry 4.0 will affect the construction business. They discovered its potential advantages in terms of enhancements in productivity and quality using the PESTEL framework (political, economic, social, environmental, and legal), which they used to highlight the advantages of its adoption. Osunsanmi, Aigbavboa and Oke [15] state that the research was an assessment of the knowledge and preparedness of construction professionals for construction 4.0 and was conducted as part of research on sector 4.0 adoption within the construction sector in South Africa. The results showed that implementing Construction 4.0 would improve efficiency in terms of cost and time savings as well as the creation of sustainable buildings.

2.5 Construction 4.0 Technologies

A variety of technologies that are being used more widely as part of Industry 4.0 enable the implementation of the fundamentals of Construction 4.0. The following technologies will all appear in one or more ways in the engineering as well as construction industries[3].

- **Internet of Things (IoT) -** cooperation, shared decision-making, and object-to-object communication
- **Internet of Services -** a business model enabler for product as a service (PaaS). These may include smart equipment operating system software updates based on the real site conditions encountered
- **Internet of People -** People are a node in a dynamic information mesh, not merely a point source of data and information or a consumer of it
- **Simulation and Modeling -** promotes life-cycle design and design optimization
- **Augmented Reality (AR) -**Visualizing computer models and visuals in the real world
- **Virtual Reality (VR) -**enables the use of virtual objects as a platform for operations and maintenance (O&M) evaluations and construction

- **Big Data Analytics-**In order to find information such as buried patterns, correlations, trends, and preferences that aid in making educated decisions, big data analytics examines large data (that which contains greater diversity and arrives in growing volumes and with ever-higher velocity)
- **Cloud Computing -**Industry 4.0 is establishing data collaboration and sharing, although construction is still maturing

Figure 3: Construction 4.0 Technologies Source: Adapted from [3]

3 OBJECTIVES

The objective of the proposed study was to conduct a systematic literature review relating to the role of the 4th Industrial Revolution in enhancing performance within the construction industry. With the goal of focusing on the contribution of the 4th industrial revolution in the construction industry and shortfalls in the literature to enhance performance within the construction industry.

4 RESEARCH METHODOLOGY

The research methodology entailed the systematic review approach. A systematic literature review comprises a thorough examination of the literature on the subject at hand. Through literature review, the relevant literature is considered and analyzed, with the aim of finding possible research gaps [20]. The research gaps should be such that, if worked upon, they would help strengthen the field of study. According to [21] a structured literature review through an iterative cycle of defining suitable search keywords, searching the relevant literature, and performing the analysis at the end. In this paper, the authors adopted a similar review procedure.

To improve the analysis of the reviewed literature, the process began with the identification of the key ideas that related to the research objectives. The criteria included a generic review of the area under research, as well as limiting reviewed papers to those in English, and ensuring the relevance of the reviewed articles to the area under study. Data was then categorized and collected from the included studies in order to summarise and assess the results and characterize the characteristics of the role of the fourth industrial revolution in improving performance within the construction industry. In this work, a total of roughly 15 articles were identified. During the investigation, a well-defined and repeatable search strategy was adopted, and studies were either accepted or denied depending on the inclusion criteria. Due to the knowledge of the methodology's advantages and disadvantages, bias-free research controls were implemented.

4.1 Search strategy

General web searches conducted through the Google Scholar database have been utilized to evaluate and report on the contribution of 4IR to improving performance in the construction sector. The research methodology that was used was a combination of articles selection and procedures as shown in Figure 1 below. The following search term was used by the Google Scholar search engine: *4IR improving performance in construction industry*.

An initial search using the search string was conducted which yielded 85 articles. The researchers conducted a preliminary assessment based on reading the abstracts of all selected papers in order to concentrate on the most pertinent literature. According to Figure 4, this study starts with the initial collection as step number one of four steps. Collecting from search engine Google Scholar within the year from 2013 until 2023. A total of 15 articles were identified for the systematic review. The final articles to be included in this review were chosen by the authors using the probability sampling method, in which researchers randomly choose people from the population at predetermined intervals. A practical screening was done based on the inclusion criteria and flow diagram in Figure 4.

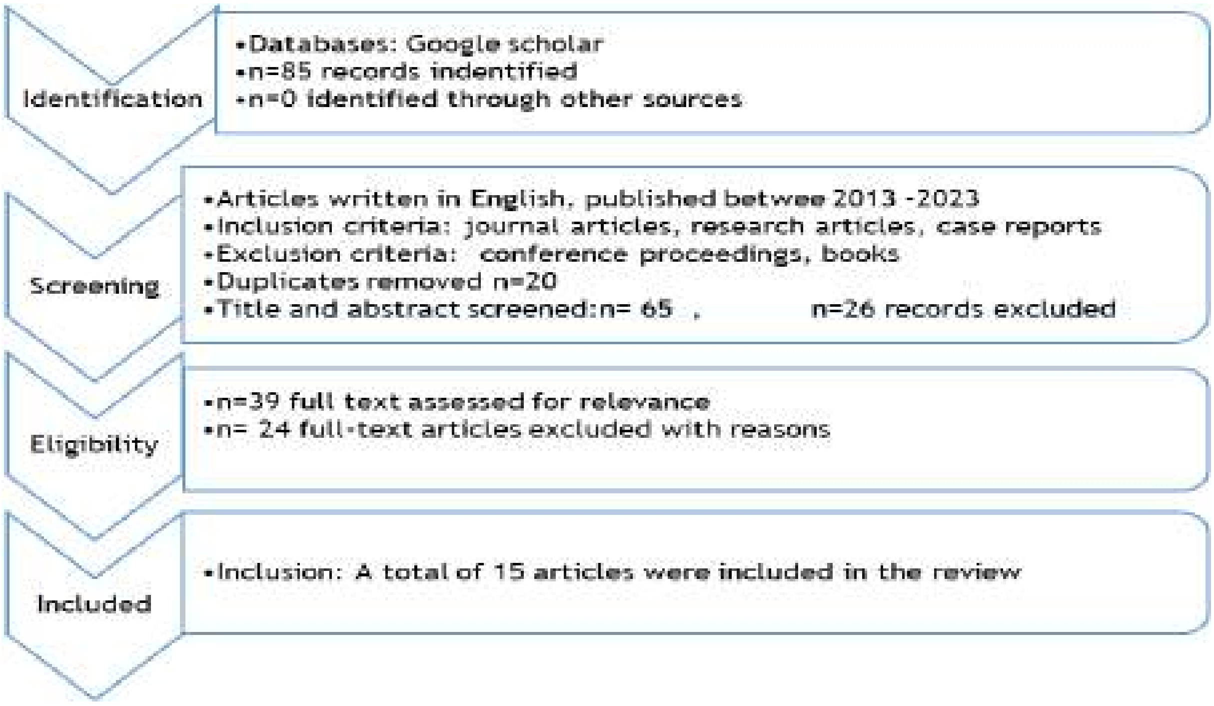

Figure 4: Systematic Review Flow Diagram. Source: Adapted from [20]

4.2 Inclusion criteria

On 3rd May 2023, a generic internet search produced 985 results for the first search. The first, tenth, twenty-first, thirty-first, forty-second, five hundred and fifty-fifth, seventy-eighth, and ninety-fifth websites were used as the basis for the sampling, and each of those pages had a maximum of ten articles. The 900 records were excluded as a representative sample was obtained. Systematic sampling provided the author with 85 studies. 85 studies were obtained by the author by systematic sampling. Additional information is provided in Figure 4 above regarding the screening and filtering that was conducted in accordance with the inclusion/exclusion criteria (Table 1). Studies that were released between 2013 and 2023 were considered. This includes 15 journal articles, research articles, and case reports. This procedure was followed to help the peer reviewers quickly determine the study's consistency in order to increase their confidence in the findings [20].

Table 1: Inclusion Criteria

Item	Description
Database searched	Google Scholar
Date of search	3rd May 2023
Language	English
Timespan	2013-2023
No.of records obtained	15
Search string	“4IR improving performance in the construction industry’’

Braun and Clarke [22]said that to find the pertinent themes, all of the articles that had met the standards were examined and coded using qualitative data analysis. The results of the 4IR improving performance in the construction industry have been listed in Table 2.

5 RESULTS

The researchers reported their findings related to the role of the 4th Industrial Revolution in enhancing performance within the construction industry. The findings of the literature research indicate that there is a growing body of knowledge on the subject of the role that the 4th Industrial Revolution had with regard to enhancing performance within the construction industry [23]. The studies shall characterize the studies by year of publication, industry sector, and type of publication.

5.1 Distribution of articles based on year of publication

The number of articles on 4IR in the construction industry published from 2013 to 2023 is presented in Figure 5. Although the absolute quantity of articles is small, it demonstrates an increasing trend, from 1 in 2013 to a maximum of 7 in 2021. This trend indicates the increasing amount of attention 4IR in the construction industry field received from researchers.

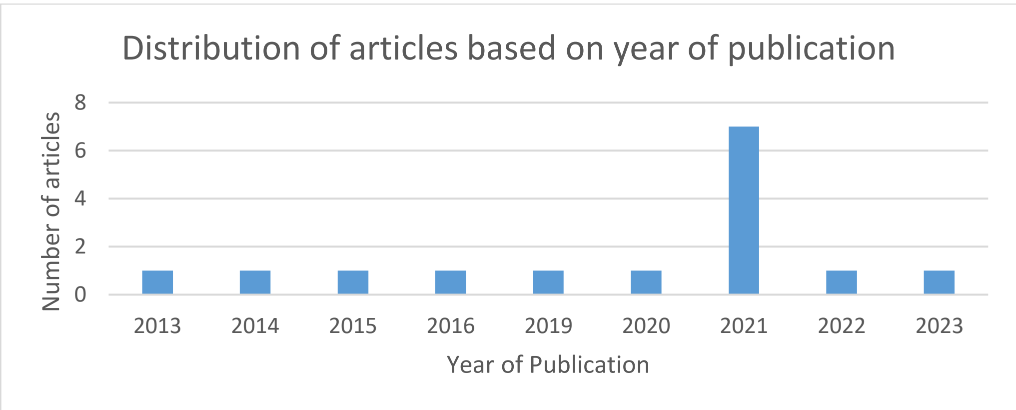

Figure 5: Articles based on year of publication

5.2 Distribution of articles based on industrial area of research

Among the papers looked at as per Figure 6, 6 research paper show Industry 4.0's implementations is mostly in manufacturing firms, 3 research paper shows Industry 4.0's implementations in supply chain management, and 2 papers show the application of Industry 4.0 in Supply chain sustainability. There is still a gap in terms of research done in other industries such as logistics and construction.

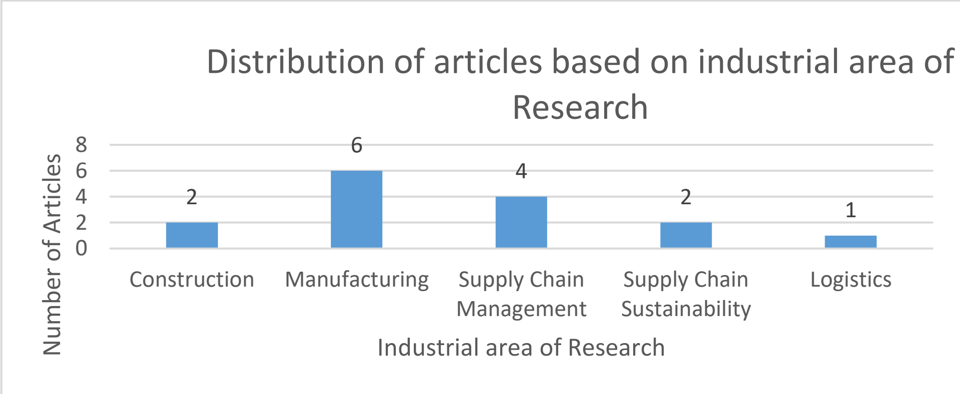

Figure 6: Distribution of articles based on the industrial area of research

5.3 Distribution of articles based on the Journal name

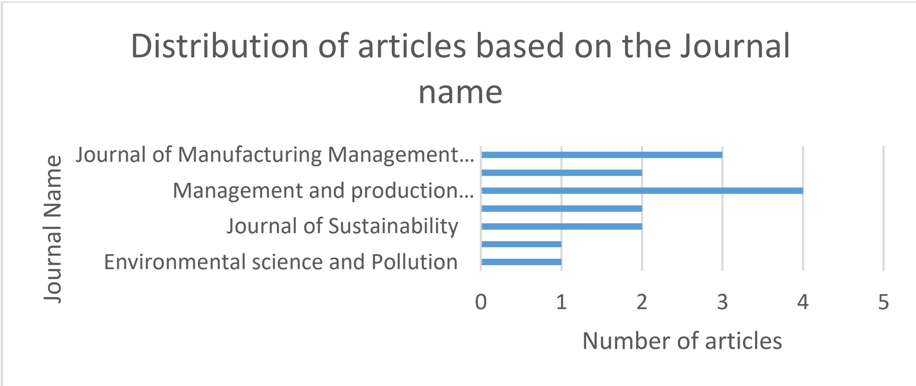

Figure 7:Distibution of articles based on the Journal name

Among the papers looked at as per Figure 7, the most journal that is publishing work on 4IR is Journal of Engineering and Applied Science, followed by the Journal of Manufacturing Management. There is still a gap in other journals as few articles are published there as compared to the Journal of Engineering and Applied Science.

6 DISCUSSION

Table 2 below provides a summary of the systematic literature review and learnings that are important for people in the construction industry regarding 4IR. Table 2 highlights what has been specified on the objective to say that indeed 4IR in the construction industry enhances performance as highlighted by the authors stipulated in Table 2 below.

Table 2: Studies related to 4IR in the construction industry

Published	Authors	Title	Purpose	Conclusion
2013	Enshassi, Adnan,Mohamed, Sherif, Abushaban, Saleh	Factors affecting the performance of construction	Finding the variables influencing local	Continuous coordination and participation from all project stakeholders is

Published	Authors	Title	Purpose	Conclusion
		projects in the Gaza Strip	construction project performance and eliciting opinions on their relative relevance are the goals of this study.	required to ensure performance in a project
2014	Tipili, Luka Goji et al	Evaluating the effects of communication in construction project delivery in Nigeria	Comparing the effects of communication in construction project delivery in Nigeria	Communication is essential in the construction industry
2015	Succar, Bilal, Kassem, Mohamad	Macro-BIM adoption: Conceptual structures	This paper introduces a number of macro-adoption models, matrices, and charts	Building information modeling (BIM), a collection of technology, procedures, and regulations that influence the industry's outputs, is the contemporary manifestation of innovation in the construction sector.
2016	Oesterreich, Thuy Duong Teuteberg, Frank	Computers in Industry Understanding the implications of digitisation and automation in the context of Industry 4 . 0 : A triangulation approach and elements of a research agenda for the construction industry	The primary objective of this paper is to look at the current level of knowledge and practice in relation to Industry 4.0 technologies in the construction sector by highlighting the political, economic, social, technological, environmental, and legal implications of its implementation.	They discovered its potential advantages in terms of enhancements in productivity and quality using the PESTEL framework (political, economic, social, environmental, and legal), which they used to highlight the advantages of its adoption.
2019	Lau, Santi Edra Nisa et al	Revolutionizing the future of the construction industry: Strategizing and redefining challenges	Using survey data, this study evaluated large construction enterprises' perspectives on the difficulties facing the sector in the era of Revolution 4.0.	The findings show that numerous PESTEL (political, economic, social, technical, environmental, and legal) problems must be overcome by building enterprises.
2020	Mamphiswana, Rendani	The fourth industrial revolution prospects and	This study examined the opportunities and difficulties facing	Policy recommendations are made based on the findings to assist Africa position itself for success.

Published	Authors	Title	Purpose	Conclusion
		challenges for africa	Africa in the 4IR era	
2021	Osunsanmi, Temidayo, O Aigbavboa, Clinton Oke, Ayodeji	Construction 4 . 0 : The Future of the Construction Industry in South Africa	So, using construction 4.0, this study assesses the understanding and willingness of construction professionals to embrace a fully digital construction business.	The results showed that implementing construction 4.0 would improve efficiency in terms of cost and time savings as well as the creation of sustainable buildings.used in conjunction with other research approaches.
2021	Adinyira, Emmanuel Agyekum, Kofi	The construction industry: Global trends, job burnout and safety issues	To look at the global trends and issues in the construction industry	If we want to take full advantage of Industry 4.0, we need to be equipped to recognize the Internet's potential beyond social media platforms and to use it to acquire the knowledge and skills we need to solve challenges.
2021	Husam Mansour et al	Industry 4 . 0 and Construction Performance : From Literature Review To Conceptual Framework	With the construction industry's complex context and integration issues in mind, the study aims to comprehend the influence of Industry 4.0 technologies as resources and the mediating function of IT and operational capabilities.	Research on the advantages of sector 4.0 in the context of the construction sector is still lacking, according to a survey of the literature, especially with regard to how it will affect performance.
2021	Ayodele, T. O. Kajimo-Shakantu, K.	The fourth industrial revolution (4thIR) and the construction industry - The role of data sharing and assemblage	The project aims to investigate how the 4thIR and industry data sharing and assemblage are related.	This study represents the first attempts to investigate the level of readiness of the construction sector for the 4thIR from the standpoint of the sector's data and information requirements.
2021	Taher, Ghada	Industrial Revolution 4.0 in the Construction Industry : Challenges and Opportunities	The purpose of this study is to identify the main obstacles to the adoption of IR 4.0-related technologies in the construction sector as well as the opportunities	The report comes to the conclusion that, despite the difficulties, implementing IR 4.0 inside the construction industry would boost the sector's performance to par with that of its competitors in

Published	Authors	Title	Purpose	Conclusion
			that may arise in the future.	the manufacturing and automotive industries.
2021	Keogh, M. Smallwood, J. J.	The role of the 4th Industrial Revolution (4IR) in enhancing performance within the construction industry	The role of the 4th Industrial Revolution (4IR) in enhancing performance within the construction industry	Conclusions state that there is a need for improvement in construction performance, the potential for improvement, a perceived need for Industry 4.0 implementation, and a need for interventions to increase awareness and integrate such technologies into built environment/construction education and training.
2021	Ross, Philip Maynard, Kasia	Towards a 4th industrial revolution	The Fourth Industrial Revolution's opportunities and difficulties are discussed in this paper.	It comes to the conclusion that the Fourth Industrial Revolution is a change catalyst that will alter how we interact with one another, learn, behave, and relate to our environment, and it gives an upbeat picture of the possibilities for change.
2022	Massimo Regona , Tan Yigitcanlar , Bo Xia and Rita Yi Man Li	Artificial Intelligent Technologies for the Construction Industry: How Are They Perceived and Utilized in Australia?	This study aims to explore AI technology adoption prospects and constraints in the Australian construction industry by analyzing social media dat	The findings inform the construction industry on public perceptions and prospects and constraints of AI adoption
2023	Rashid Maqbool1 · Mohammed Rayan Saiba1 · Saleha Ashfaq	Emerging industry 4.0 and Internet of Things (IoT) technologies in the Ghanaian construction industry: sustainability, implementation challenges, and benefts	This study reviews the research work in industry 4.0 and the Internet of Things as they relate to construction and examines key Ghana-based construction professionals and frms to ascertain their level of understanding of these emerging innovative technologies, including the challenges and benefits associated	It was discovered from the fndings that smart construction was the most popular industry 4.0 technology in the Ghanaian construction industry

Published	Authors	Title	Purpose	Conclusion
			with their implementation	

6 CONCLUSION

The number of articles on 4IR in the construction industry indicated an upward trend between 2013- 2023 indicating the importance of 4IR in the construction industry by researchers. The majority of the studies that were reviewed were from Manufacturing, which indicated an interest in the Manufacturing sector.

A wide range of multidisciplinary technologies is included in the industry-specific definition of the Industry 4.0 concept for the construction sector to enable the digitization, automation, and integration of the construction process at all stages of the construction value chain. A few of the key ones include Building Information Modeling (BIM), Cloud Computing, and the Internet of Things. Industry 4.0 is a relatively recent area of research that is dominated by developed Western nations and is headed by Germany [23]. Although several disciplines are covered, the field of construction management stands out as being glaringly under-represented given that it is a globally major industry that employs millions of people and makes a considerable contribution to the GDP of individual countries as well as the global economy [2].

Their implementation can help to improve safety, sustainability, decision-making, and productivity in addition to the economic benefits for enhancing productivity, efficiency, quality, and collaboration, helping to improve the construction industry's negative reputation over time [24]. The adoption of sector 4.0 technology will have a significant impact on the whole construction sector, the companies involved, the environment, and workers. Construction industry performance would improve with the adoption of IR 4.0, enabling it to compete with its peers in the manufacturing and automotive industries. Industry 4.0 must be embraced since it is the direction of the future. Digitization is the only option, even on construction sites, construction must keep up [25]. Osunsanmi, Aigbavboa and Oke [15] said that implementing Construction 4.0 would improve efficiency in terms of cost and time savings as well as the creation of sustainable buildings.

7 FUTURE RESEARCH

Further research in science and practice is required to further the innovative idea of Industry 4.0 in the complicated context of the construction industry. Future work should address the challenges that were raised in terms of the adoption of 4IR in the construction industry.

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INVESTIGATING SAJIE'S PUBLICATIONS: UNLOCKING THE MISSING PUZZLE PIECES

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ABSTRACT

As of recent times, Industrial Engineering has become one of the top ten scarce skills in South Africa. Given the versatility and resilience the field has, much of its success has contributed to its diversity of application. However, during the last few years there has been an increase in research within different niche areas that belong to Industrial Engineering. A larger question comes to mind, what are the current gaps (missing puzzle pieces) in this puzzle of research? This paper aims to investigate the SAJIE publications over the past five years, to unlock and evaluate the Industrial Engineering application domains. This research highlights the gaps in current literature, ergo emphasising opportunities for future research endeavours.

Keywords: Industrial Engineering, Knowledge domains, discussion paper, South Africa

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1 INTRODUCTION

Industrial Engineering is a wide and deep field of study, which is known for its diversity in applications. Although there are varying definitions and explanations of Industrial engineering, one of the earliest comes from 1985, when the Institute of Industrial Engineers (IIE) defined it as [1, 2, 3]:

> *"Industrial Engineering is concerned with the design, improvement and installation of integrated systems of people, material, information, equipment and energy. It draws upon specialized knowledge and skill in the mathematical, physical and social sciences together with the principles and methods of engineering analysis and design to specify, predict and evaluate the results to be obtained from such systems."*

As of recent times, Industrial Engineering has become one of the top ten scarce skills in South Africa [4]. Industrial engineering is widely known for its creative problem solving via integrated solutions. Its range of applications may be broken down into different areas. Salvendy [2] explained this by breaking down Industrial and Systems Engineering (ISE) into four basic areas (operations research, human factors engineering, management systems and manufacturing systems engineering), with overlapping knowledge and application areas (statistics, psychology, economics, accounting and mathematics). Figure 1 depicts this relationship and composition of the domains of Industrial and Systems Engineering (ISE).

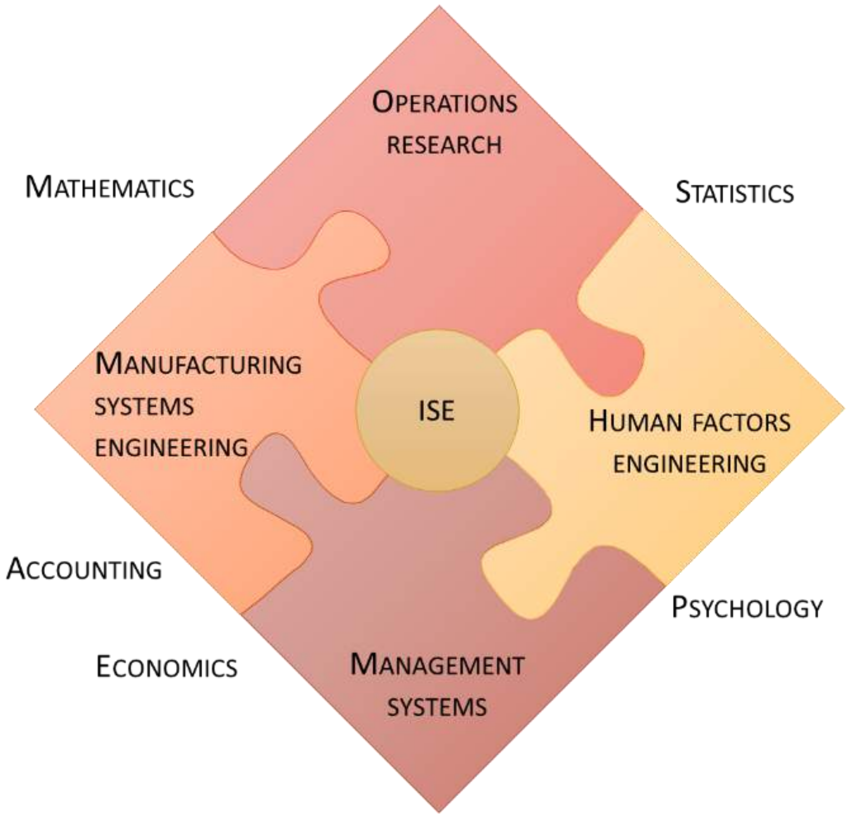

Figure 1: Domains of Industrial and Systems Engineering (ISE) (Adapted from Salvendy [2])

However, by 2022 the groups have been expanded upon by the Institute of Industrial and Systems Engineering (IISE) [5]. Ergo, according to IISE, there are 14 knowledge areas of Industrial and Systems Engineering. These 14 knowledge areas are captured in figure 2.

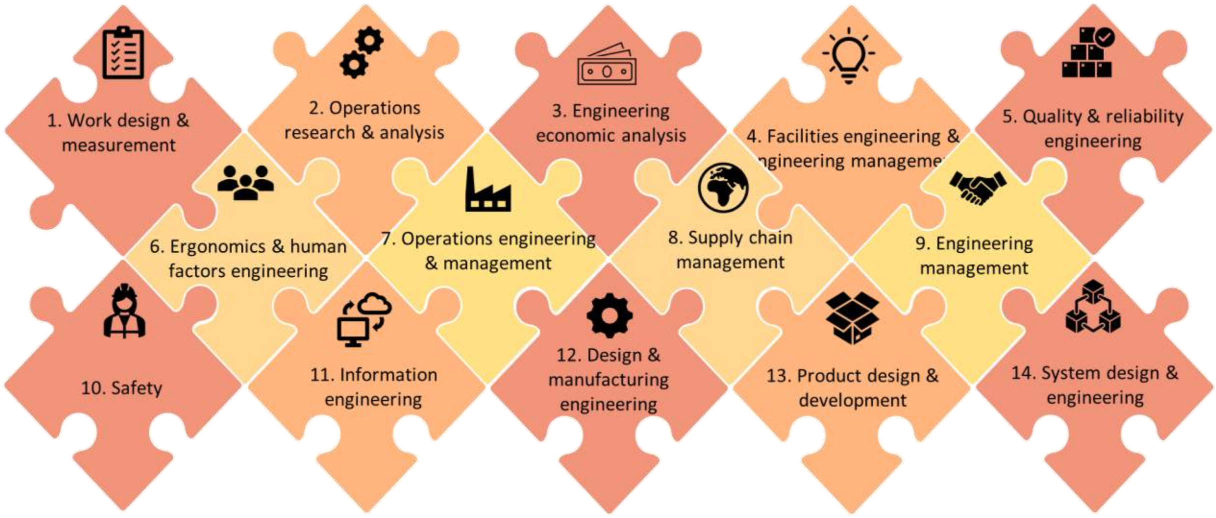

Figure 2: Knowledge areas of Industrial and systems engineering (Adapted from the institute of Industrial and systems engineering body of knowledge (IISE) [5])

From figures 1 and 2, it is evident that there are several complex building blocks to the Industrial Engineering skills and its understanding. The development of Industrial Engineering as an academic discipline in South Africa is relatively new, with the first group of industrial engineers graduating in 1964 (less than 50 years ago) [6, 4]. However, in the last 50 years the Industrial engineers have developed the field in South Africa at an exponential rate [7].

The South African Industrial Engineer is a complex person, not only do the embody the various knowledge areas and domains of Industrial engineering, but they also focus on several local issues in research and development. Darwish and van Dyk [8] focused on conceptualising the Industrial Engineering Identity. They found that there are eight levels to this identity, namely: Societal perceptions, external behaviours, skills and capabilities, knowledge fields, values, and motivators, thinking style, core belief, and fundamental belief [8]. These eight levels influence the research produced by Industrial engineering practitioners and academics [8].

As previously mentioned, Industrial engineering is inherently broad and interdisciplinary. A study in 2021 found that there are some misperceptions surrounding the disciple due to various job titles in practice [9]. The author explains that the true value of Industrial Engineering is found in the ability of IEs to improve concepts, processes, systems and/or industries; regardless of the job titles [9].

However, given the discussion above, during the last few years there has been an increase in research within the field of Industrial Engineering. A larger question comes to mind, what are the current gaps (missing puzzle pieces) in this puzzle of research?

2 RESEARCH AIM

This paper aims to investigate the South African Journal for Industrial Engineering (SAJIE) publications over the past five years (2018 – 2022), to unlock and evaluate the Industrial Engineering research areas.

3 RESEARCH QUESTIONS

The following research questions were set to achieve the research aim:

a) What are the most prominent domains of IE that feature in SAJIE over the past 5 years?
b) What are the most prominent Knowledge areas that feature in SAJIE over the past 5 years?

c) What are the most prominent countries of publication that feature in SAJIE over the past 5 years?
d) What is the gap/missing puzzle pieces in the puzzle of research?

4 RESEARCH METHODOLOGY

This study employs an adapted systematic review (SLR) methodology [10] to ensure research rigour throughout the study. The specific methodology consists out of the following three steps:

1. Planning - Develop a research protocol (Section 4.1)
2. Searching - Search the literature (Section 5.1)
3. Analysing - Data extraction and analysis (Section 5.2)

4.1 Step 1 – Planning - Develop research protocol.

It is imperative to note that while this study utilises an adapted SLR methodology, it is not by any means an SLR study itself; rather it is utilising a systematic review method to analyse the research output of the SAJIE journal over the last five years. Given the background, the research protocol was developed and is captured in table 1.

Table 1: Research Protocol table

Purpose of the study	To investigate the SAJIE publications over the past five years (2018 – 2022), to unlock and evaluate the Industrial Engineering application domains.
Inclusion criteria	All studies published in SAJIE
Database	South African Journal of Industrial Engineering (SAJIE)
Timeframe	2018 – 2022

5 FINDINGS

5.1 Searching - Search the literature.

The research protocol (table 1) was utilised to retrieve the past five years of articles from SAJIE. Table 2 encapsulates the totals of the search results per issue in each year.

Table 2: Results from literature search

Year	Volume	Issue	Number of articles
2018	Volume 29	Issue 1	15
		Issue 2	13
		Issue 3	21
		Issue 4	19
2019	Volume 30	Issue 1	12
		Issue 2	14
		Issue 3	21
		Issue 4	12
2020	Volume 31	Issue 1	13
		Issue 2	12
		Issue 3	22
		Issue 4	16
2021	Volume 32	Issue 1	16
		Issue 2	10
		Issue 3	27
		Issue 4	10
2022	Volume 33	Issue 1	14
		Issue 2	12
		Issue 3	26
		Issue 4	12
Total number of articles			**317**

5.2 Step 3 - Analysing - Data extraction and analysis.

After the retrieval of the articles captured in table 2, the full texts were read, and data was extracted and analysed. The following sections detail the analysis and answer the specific research questions.

5.2.1 What are the most prominent domains of IE that feature in SAJIE over the past 5 years?

The analysis begins with an evaluation and categorisation of the 317 articles subject to the domains of Industrial Engineering. Figure 3 demonstrates the number of occurrences per IE domain.

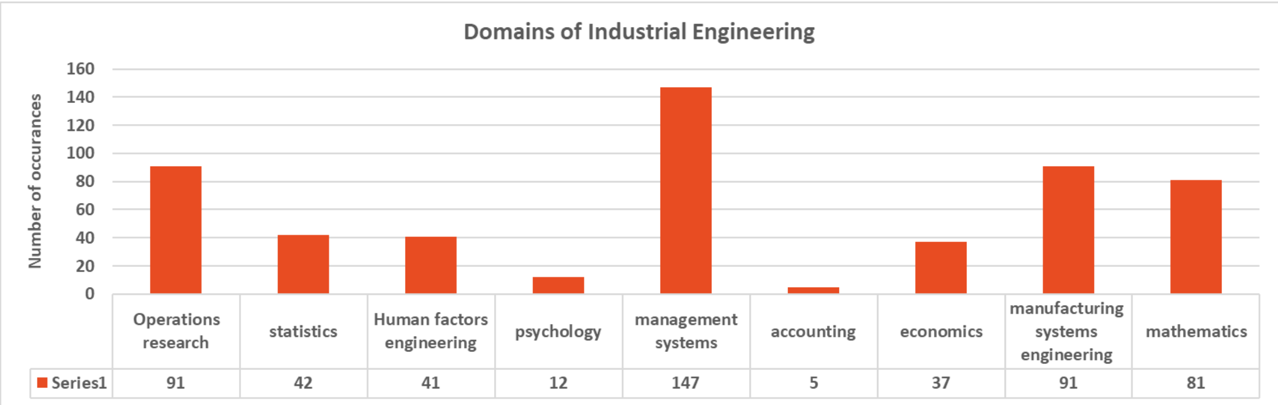

Figure 3: Bar graphic depicting the number of occurrences per domain of Industrial Engineering

Based on the results obtained in figure 3, a more detailed analysis was conducted on the number of publications per year for each IE domain. The results are depicted in figure 4.

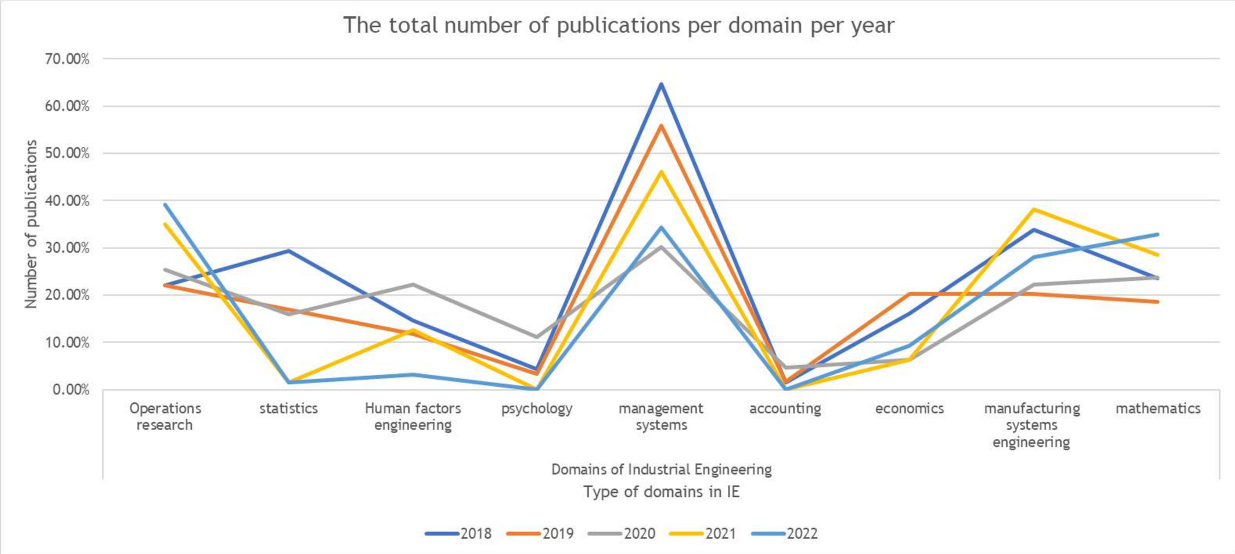

Figure 4: Number of publications per IE domain per year

A surge in publications is prevalent within management systems for each year. In 2018, more publications focused on statistics, manufacturing systems engineering and management systems. Economics orientated papers were more popular during 2019 while mathematics and operations research studies were at their lowest. By 2020, the distribution of publications is more balanced between each IE domain. It is also important to note in 2020, the journal had the highest publications for human factors engineering. Ironically enough, 2020-2022 saw a decline in management systems although the world was plagued with adjusting management systems to adhere to COVID-19 regulations.

In 2021, manufacturing systems engineering peaked in popularity. However, psychology and accounting studies were not featured. Operations research and mathematics constituted nearly 40% of the total publications in 2022. Between 2021 and 2022, there was a large decline in statistics and human factors engineering studies.

5.2.2 What are the most prominent Knowledge areas that feature in SAJIE over the past 5 years?

The analysis continues with an evaluation and categorisation of the 317 articles subject to the IISE bodies of knowledge. Figure 5 illustrates the total number of occurrences per body of knowledge.

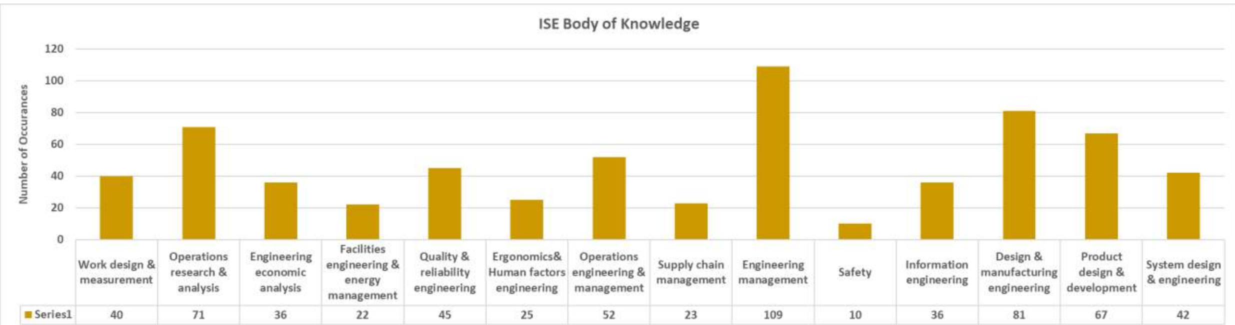

Figure 5: Bar graph depicting the number of occurrences per IISE body of knowledge.

Based on the results obtained in Figure 5, a further analysis was conducted on the number of publications per year for each industrial engineering body of knowledge. The results are depicted in figure 6.

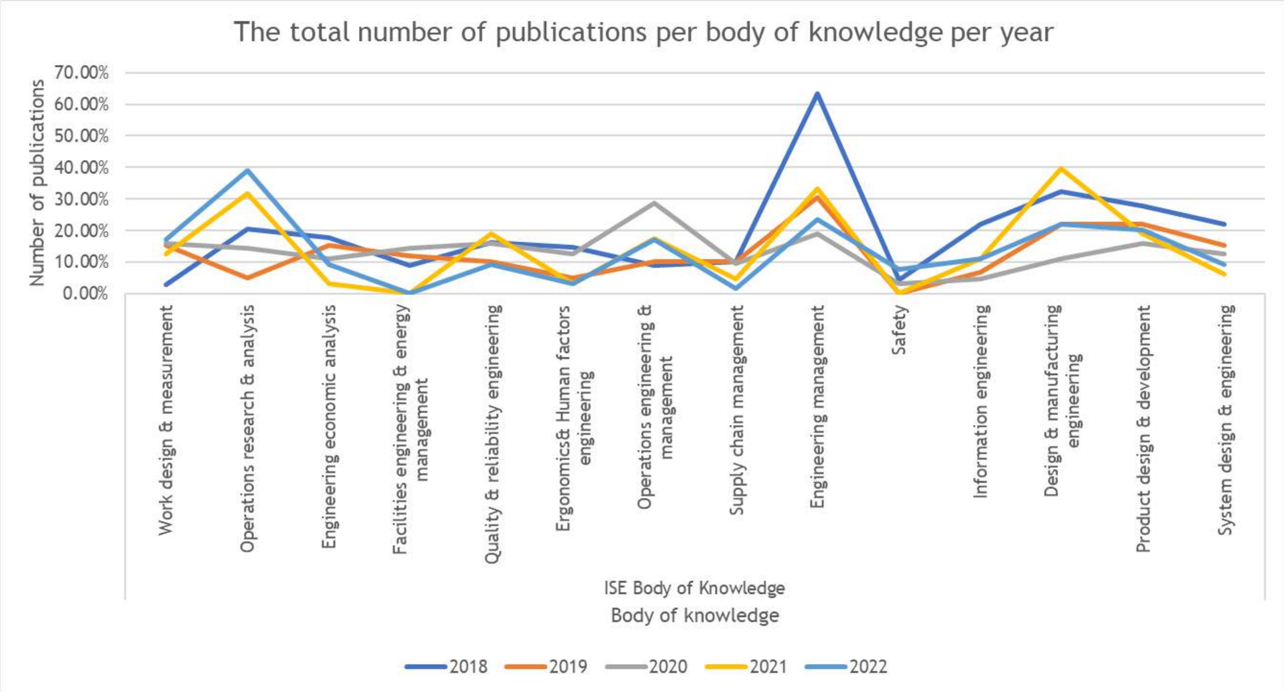

Figure 6: Total number of publications per body of knowledge per year

In a similar vein to the IE domains, engineering management was the most popular body of knowledge in 2018-2019. Generally, safety studies were the most under-researched body of knowledge. For 2018, work design and measurement were at the lowest while studies focusing on operations research, design and manufacturing engineering, systems design, information engineering and product design were at their highest. However, in 2019, operations research and analysis were least popular. As previously witnessed in figure 4, a more balanced distribution of studies is predominant for 2020. 2021 played host to a peak in design and manufacturing engineering whilst neglecting facilities engineering and energy management. Operations research and analysis was at its highest in 2022 while facilities engineering and energy management, supply chain management, quality and reliability engineering, and ergonomics and human factors engineering were lowest.

5.2.3 What are the most prominent countries of publication that feature in SAJIE over the past 5 years?

While SAJIE is a South African journal, it welcomes international publications. Figure 7 categorise the publications according to the most prominent countries over the past five years.

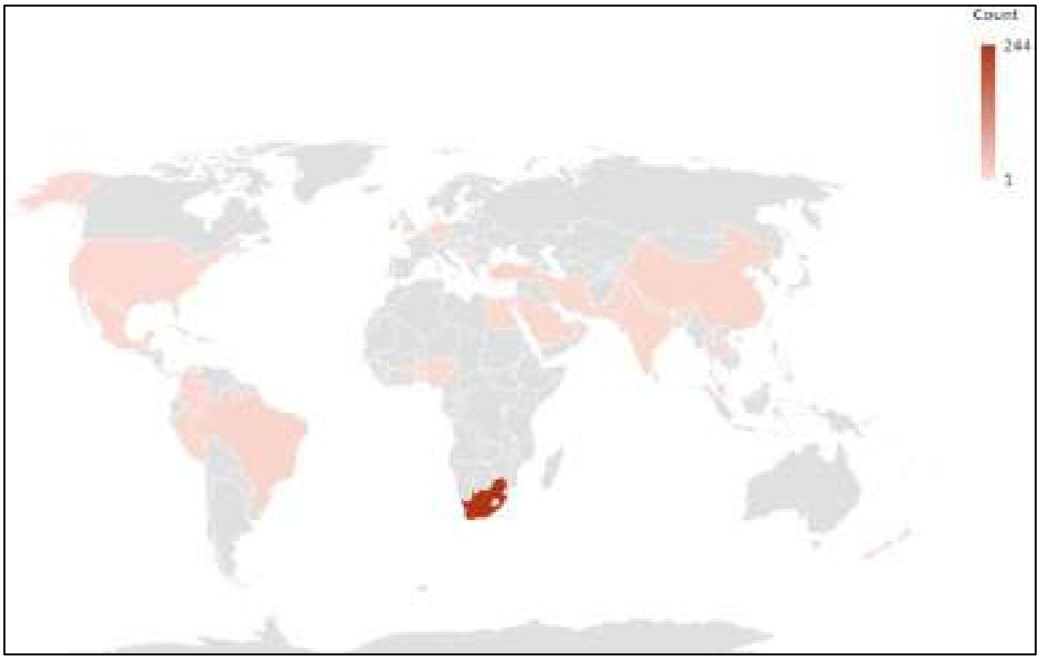

Figure 7: Global representation of author country of affiliation

Amongst these countries, 244 out of the 317 publications are located in South Africa. Brazil, China, and India were found to have the highest publications outside South Africa with nine, seven and six papers respectively. It could be argued that more studies within Africa could consider the journal for publication, to encourage the development of our neighbouring countries.

5.2.4 What is the gap/missing puzzle pieces in the puzzle of research?

The Southern African Conference of Industrial Engineering (SAIIE) is hosted each year in South Africa [11]. In 2022, it was hosted at Zimbali in Kwazulu-Natal and 2023 it will be hosted in the Western Cape. It is seen as a prestigious event where industrial engineers from all over the world are granted the opportunity to present their conference papers. However, during this event, a specific portion of the highest quality publications of conference papers is selected to be published in the special edition of SAJIE [11]. Subsequently, this is volume three of each year's publication in SAJIE. The theme of each conference from 2018 - 2022 is presented in figure 8.

Figure 8: Conference themes from 2018-2022 [11]

Figure 9 demonstrates the number of SAIIE's publications selected for the special edition each year, specifically focusing on each IE domain.

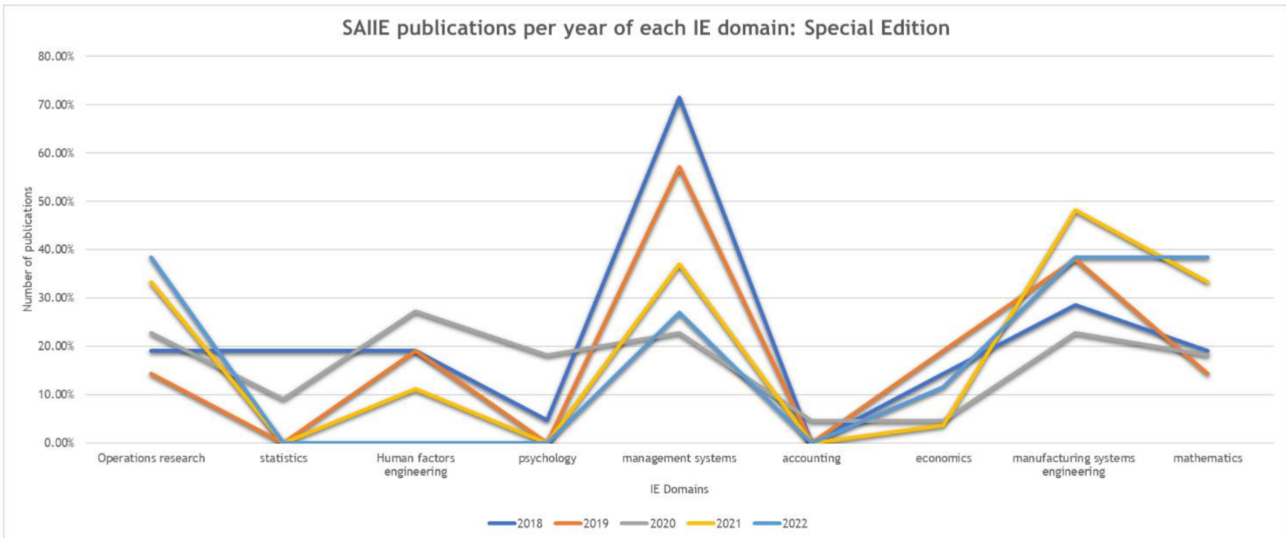

Figure 9: SAIIE publications per year of each IE domain: Special Edition

In 2018, the Fourth Industrial Revolution was the theme for the conference. We see a height in manufacturing systems engineering and management systems that is attributed to authors exploring the theme of the conference. 2019 embraced human factors engineering, management systems and manufacturing systems engineering as its most researched studies. The 2019 conference was aligned with alternative realities, real alternatives which ties in with the prominent domains highlighted in the graph. As for 2020, the data was more evenly distributed across each domain. This is indicative of the generalisation of the theme SAIIE "Green", as sustainability is non-biased to a specific domain.

Steps served as the 2021 conference theme, and it was found that the most prominent domains were manufacturing systems engineering, management systems and operations research. It is important to note that statistics, psychology and accounting had no representation during this year. Manufacturing systems engineering, operations research and mathematics were the most popular domains in the 2022 conference special edition. The theme for this conference was the Industrials which had a superhero flavour to it. This edition of the journal showcases the "superpowers" that Industrial engineers bring to the different domains. However, statistics, human factors engineering, psychology and accounting had no representation in this edition.

Figure 10 demonstrates the number of SAIIE's publications selected for the special edition each year, specifically focusing on the body of knowledge.

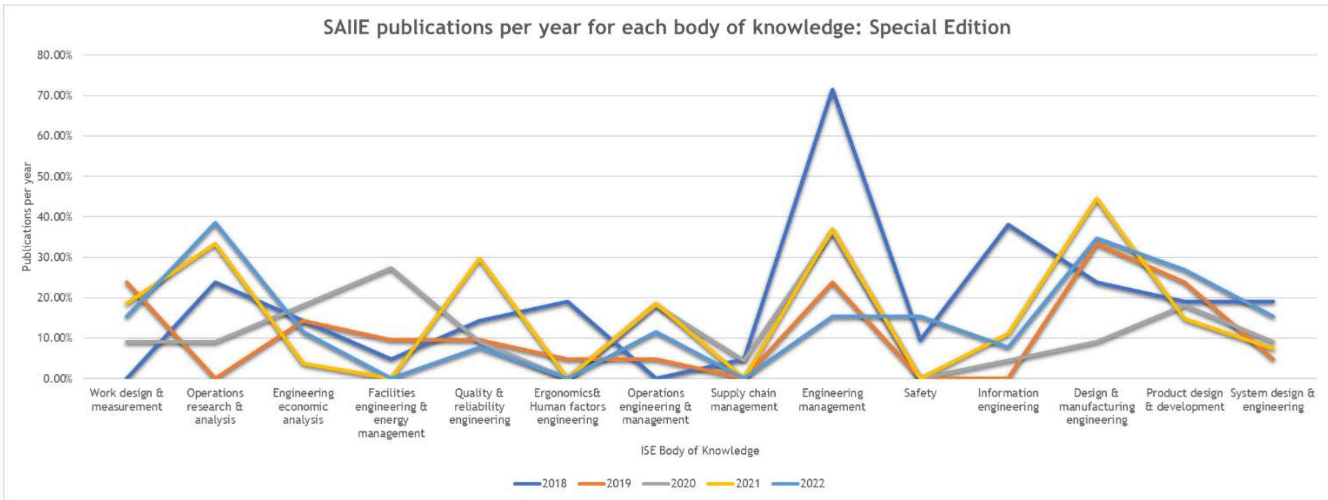

Figure 10: SAIIE publications per year for each body of Knowledge: Special edition

From figure 10, it can be deduced that engineering management is one of the foremost bodies of knowledge over the entire five-year time horizon. Design and manufacturing engineering closely follows with most of the studies over this period. This is indicative of the roots of Industrial engineering lying in the manufacturing industry. Operations research and analysis, and information engineering featured as the third highest bodies of knowledge. This pays homage to the growing research in Industrial engineering focused on introducing Industry 4.0 technologies and responding to the needs of a more data driven society that require the application of optimisation techniques. Unsuspectingly, supply chain management, facilities engineering, and energy management were the lowest bodies of knowledge over majority of the years, followed by safety. Given the political climate and energy crisis in South Africa, these topics are in dire need of more research focus going forward.

Co-occurrence tables

To better understand the relationship between the various domains of Industrial engineering, in terms of journal publications, a co-occurrence table was developed (Table 3).

Table 3: Co-occurrence table of the Domains of Industrial Engineering

Domains of Industrial Engineering	Operations research	statistics	Human factors engineering	psychology	management systems	accounting	economics	manufacturing systems engineering	mathematics
Operations research	91	25	1	0	11	0	7	22	64
statistics	25	42	0	0	14	0	7	10	19
Human factors engineering	1	0	41	10	19	0	1	7	2
psychology	0	0	10	12	3	0	0	0	0
management systems	11	14	19	3	147	1	16	27	16
accounting	0	0	0	0	1	5	4	0	1
economics	7	7	1	0	16	4	37	5	9
manufacturing systems engineering	22	10	7	0	27	0	5	91	23
mathematics	64	19	2	0	16	1	9	23	81

As can be seen from table 3, there exists a strong relationship between Operations research papers and statistics and mathematics articles. It is also worth noting that a large contribution of the operations research articles is based within the manufacturing systems engineering domains. The most integrated domain belongs to management systems, this is no surprise as this domain is all encompassing in nature.

Human factors engineering studies had close links with psychology and management systems. It is reasonable to assume that this is due their close links in theory as well. However, it is evident that little to no overlap exists amongst the rest of the domains. The accounting domain shares the weakest relationship with majority of the others. The only close link is that with economics. More research could explore operations research and statistics applications. Table 4 demonstrates the co-occurrence amongst the bodies of knowledge.

Table 4: Co-occurrence table of the ISE body of knowledge

ISE Body of Knowledge	Work design & measurement	Operations research & analysis	Engineering economic analysis	Facilities engineering & energy management	Quality & reliability engineering	Ergonomics& Human factors engineering	Operations engineering & management	Supply chain management	Engineering management	Safety	Information engineering	Design & manufacturing engineering	Product design & development	System design & engineering
Work design & measurement	40	9	1	2	5	3	11	2	8	2	4	7	8	2
Operations research & analysis	9	71	6	4	8	2	11	3	11	4	11	17	9	7
Engineering economic analysis	1	6	36	5	4	2	1	2	12	1	4	4	4	5
Facilities engineering &	2	4	5	22	3	1	1	2	7	1	2	0	1	2

ISE Body of Knowledge	Work design & measurement	Operations research & analysis	Engineering economic analysis	Facilities engineering & energy management	Quality & reliability engineering	Ergonomics& Human factors engineering	Operations engineering & management	Supply chain management	Engineering management	Safety	Information engineering	Design & manufacturing engineering	Product design & development	System design & engineering
energy maagement														
Quality & reliability engineering	5	8	4	3	45	3	10	1	12	4	3	12	8	3
Ergonomics& Human factors engineering	3	2	2	1	3	25	6	1	11	1	1	3	3	4
Operations engineering & management	11	11	1	1	10	6	52	4	19	0	5	11	8	7
Supply chain management	2	3	2	2	1	1	4	23	8	0	3	2	2	2
Engineering management	8	11	12	7	12	11	19	8	109	1	24	16	12	21
Safety	2	4	1	1	4	1	0	0	1	10	0	2	3	1
Information engineering	4	11	4	2	3	1	5	3	24	0	36	4	6	10
Design & manufacturing engineering	7	17	4	0	12	3	11	2	16	2	4	81	44	6
Product design & development	8	9	4	1	8	3	8	2	12	3	6	44	67	5
System design & engineering	2	7	5	2	3	4	7	2	21	1	10	6	5	42

From table 4, one can see a similar trend to that of table 3, with engineering management being the most dominant body of knowledge. In addition to this, it is also the most integrated body of knowledge due to its multidisciplinary applications. Design and manufacturing engineering is the next most integrated group. The gaps and opportunities in research are highlighted by the lack of papers in safety, facilities engineering and energy management, and supply chain management. These groups seem to function in silos. This presents an opportunity for future research as these bodies of knowledge have the potential to contribute greatly to the development of South Africa.

Table 5 illustrates the relationship between the bodies of knowledge and the domains of Industrial engineering. It is important to note that the domains of Industrial engineering encompass the breakdown of the bodies of knowledge.

Table 5: Co-occurrence table of ISE body of knowledge and the domains of industrial engineering

	ISE Body of Knowledge													
Domains of Industrial Engineering	Work design & measurement	Operations research & analysis	Engineering economic analysis	Facilities engineering & energy management	Quality & reliability engineering	Ergonomics& Human factors engineering	Operations engineering & management	Supply chain management	Engineering management	Safety	Information engineering	Design & manufacturing engineering	Product design & development	System design & engineering
Operations research	12	67	8	9	11	2	12	9	12	4	12	21	12	8
Statistics	4	18	9	4	4	1	7	5	14	1	6	10	6	7
Human factors engineering	6	1	2	3	8	18	9	3	17	3	2	5	7	7
Psychology	1	0	0	2	0	5	4	0	5	0	0	0	1	2
Management systems	19	12	14	8	23	17	30	12	96	3	25	25	23	30
Accounting	0	0	5	3	1	0	0	0	1	0	1	0	1	0
Economics	2	5	31	6	6	2	1	4	11	1	4	5	6	4
Manufacturing systems engineering	10	21	5	2	18	5	20	2	21	4	6	67	45	7
Mathematics	11	52	9	6	11	1	10	6	13	3	12	20	18	8

From Table 5, there are obvious relationships between the same topics such as operations research (domain) and operations research and analysis (body of knowledge); similarly with management systems (domain) and engineering management (body of knowledge). A counterintuitive relationship presents an opportunity to leverage operations research techniques in the facilities engineering and energy management space. More research is needed in the safety body of knowledge, this can integrate with almost every domain of Industrial Engineering.

To further evaluate the relationship between the Industrial Engineering domains and Body of Knowledge, table 6 outlines the difference in percentage of studies conducted in South Africa and other countries in terms of the Industrial Engineering domains.

Table 6: Industrial Engineering Domain comparison between South Africa and other countries

Domains of Industrial Engineering	South Africa	Other countries (avg)
Operations research	15,1%	23,6%
Statistics	6,7%	11,4%

Domains of Industrial Engineering	South Africa	Other countries (avg)
Human factors engineering	7,8%	5,7%
Psychology	2,5%	0,8%
Management systems	28,7%	20,3%
Accounting	0,7%	1,6%
Economics	6,7%	8,1%
Manufacturing systems engineering	17,7%	12,2%
Mathematics	14,2%	16,3%

Similarly, majority of the research tackles management systems in South Africa and other parts of the world. However, South African work then focuses more on manufacturing systems and mathematics, while other countries speak to operations research and mathematics. For example, publications from Turkey are found to have the highest proportion focused on operations research [12, 13, 14, 15, 16, 17]. Research addressing accounting is limited in South Africa, while psychology orientated work was found to be the least in other countries. This is indicative of the opportunities available for local researchers and practitioners to explore collaborations with international scholars on the aforementioned topics.

Table 7 provides the difference in percentage of local and international studies focused on the Industrial Engineering bodies of knowledge.

Table 7: Industrial Engineering Bodies of Knowledge comparison between South Africa and other countries

ISE Body of Knowledge	South Africa	Other countries (avg)
Work design & measurement	6,1%	6,8%
Operations research & analysis	10,4%	12,3%
Engineering economic analysis	5,7%	4,8%
Facilities engineering & energy management	3,0%	5,5%
Quality & reliability engineering	6,6%	8,9%
Ergonomics& Human factors engineering	3,8%	3,4%
Operations engineering & management	7,6%	8,2%
Supply chain management	3,0%	5,5%
Engineering management	18,0%	10,3%
Safety	1,7%	0,7%
Information engineering	5,7%	4,1%
Design & manufacturing engineering	12,3%	11,6%
Product design & development	9,7%	11,6%
System design & engineering	6,4%	6,2%

As can be seen from table 7, the highest proportion of engineering management is reaffirmed. The most under-researched knowledge area is found to be safety. Research from China was found to have the highest proportion of product design and development knowledge as opposed to other countries. Facilities engineering and energy management was the most popular knowledge area for publications from Iran. This presents the opportunity for local authors to leverage international collaborations with their counterparts on the aforementioned areas. For instance, supply chain management, facilities engineering and energy management, engineering management, operations research and analysis, and product design research can be supported by other international scholars. Conversely, South African researchers can offer support to international counterparts in their respective research fields.

Word cloud

The titles of each of the 317 studies were imported into a software to generate a word cloud (figure 11), which highlights the most recursive terms used by authors.

Figure 11: Word cloud of the most frequent words within the titles of articles

Unsurprisingly, figure 11 showcases the words management and industry as the most used terms. This talks to management engineering the most popular domain and body of knowledge. The terms performance, manufacturing, framework, model, development, implementation, systems and analysis were moderately popular. This is testament to the various conceptual solutions that are implemented (primarily in manufacturing contexts) to assess performance in an organisation.

6 CONCLUSIONS AND RECOMMENDATIONS

This study demonstrated the innovative research presented in SAJIE over the past five years. Furthermore, it emphasises the contribution SAJIE has made to the Industrial Engineering community globally. While this paper showcases the gaps (missing puzzle pieces) in certain research areas, it is imperative that this is seen as valuable research opportunities for future scholars.

The findings illustrate management systems as the most popular Industrial engineering domain. This is closely accompanied by operations research and manufacturing systems engineering. When analysing the domain, it is evident that the gaps in the puzzle are statistics, psychology, accounting and economics.

These are critical areas of research that Industrial engineers can invest their interests in, to address the current challenges that South Africa faces in terms of socio-economic issues including and not limited to youth unemployment rates and economic sustainability [12]. Another pertinent area of research is the role Industrial engineers may have in combating climate change.

In terms of the body of knowledge, engineering management, design and manufacturing engineering, product design and development, and operations research and analysis had the highest surge in research. Given the current research trends in Industry 4.0 adoption in South Africa, the aforementioned bodies of knowledge are critical to ensure successful implementation. Ergo, these bodies of knowledge are currently the highest in terms of publications.

Inadvertently, given the political climate and energy crisis in South Africa, it is surprising that supply chain management, facilities engineering, and energy management were the lowest bodies of knowledge, followed by safety. Subsequently, these bodies of knowledge present the opportunity for new pieces in the IE puzzle of research. This research study articulates the value of the current research in SAJIE, whilst illustrating the missing pieces of the IE research puzzle. Much like the process of completing a puzzle requiring concentration, patience and strategy, research endeavours should also adapt these techniques when exploring future research topics.

While the 1985 definition of Industrial Engineering is old, much of the traits of the modern industrial engineer are still aligned with this definition. The missing pieces of the IE research puzzle should be leveraged for future research in Industrial Engineering to encompass and expand on the 1985 definition.

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FOLLOWING A SYSTEMS ENGINEERING APPROACH TO ESTABLISH A CANINE SYSTEM FOR FORCE MULTIPLICATION

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ABSTRACT

This paper explores the use of a systems engineering approach to establish a canine system for application as one of the force multipliers to address complex challenges such as illicit wildlife trafficking, policing and border management. The proposed approach takes a life cycle view of the system, focussing on all life-cycle aspects from idea inception, through acquisition, operations and support to phase-out. The paper describes the systems engineering viewpoint taken and subsequent approach followed, in context of relevant international standards, to tackle the problem at hand, showing that systems engineering may be used as a valuable tool in tackling non-traditional engineering problems. The paper discusses activities undertaken during conceptualisation such as requirements definition for the capability (including pointers on how to specify the canine itself); provides guidance for executing development and acquisition; details aspects to be considered and managed during utilisation and support; and proposes a process for canine retirement.

Keywords: systems engineering approach, life cycle view, canine system

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1 INTRODUCTION

Our new normal is a multi-dimensional, ever evolving puzzle, where the interrelationships between the pieces is not necessarily apparent. As puzzle builders shaping our next normal, engineers are required to architect equally complex, innovative and/or integrated solutions in response.

The establishment of a canine system is in all likelihood a less traditional problem engineers are required to architect, innovate and/or integrate a solution for. Typically it would be viewed as a simple procurement of canines that would rapidly expand into additional procurements for the missing supporting elements, still without ever recognising it as a system. This paper addresses aspects that may be considered by humans (engineers and other stakeholders) when establishing a canine system by taking a systems engineering viewpoint of the life cycle (conceptualization, realization, utilisation and disposal [1]) of such a system.

The International Organization for Standardisation (ISO) and International Electrotechnical Commission (IEC) Standard ISO/IEC 15288:2008 [2] was in effect at the time of executing the project that inspired this paper and was then used to guide the establishment of that canine system. For the purposes of drafting this paper, the relevant life cycle processes as defined in South African National Standard (SANS) 15288:2020 [1] and elaborated on in SANS 24748-2:2021 [4] were consulted and the tailoring thereof described in the paper. There is a specific focus on a sub-set of the technical processes. It is acknowledged that other life cycle processes (e.g. technical management processes such as the configuration management process [1]) are applicable and that the life cycle processes may be applied iteratively and recursively during the life cycle of the system [1], but these aspects are not addressed in this paper. The paper also strives to describe aspects that would typically be considered during the establishment of a canine system to be used in wider safety and security applications. This is consciously done in an effort to desensitize information.

2 BACKGROUND

2.1 The Canine System

This paper should be read in the context of a scenario where a project is launched to establish a canine system. The canine system includes the canines, their handlers and the support "products" required to enable the functioning of the system e.g. veterinary services, canine housing, training services, recreational facilities and logistic support services such as the supply of food, grooming products, canine transportation and recreational equipment. The canine system is used as a force multiplier in combating illicit wildlife trafficking, policing, the rendering of security services or border management. As a force multiplier, the canine system forms part of a system of systems (SoS) and may be treated as a constituent system in line with SANS 21840:2020 [3] where the technical processes may be employed for both the SoS and the constituent system or, where applicable, for the constituent system rather than for the whole system [3].

With the understanding that the presence of the canines in the operational context impacts the behaviours of the actors in the various scenarios, who adapt and evolve to counter the canine impact, the operational context could be considered complex adaptive. In the same way, in order to remain relevant and effective, the canine system has to adapt and evolve with the continuously changing environment, making it a complex adaptive system [10]. As we are dealing with this complex adaptive context, the canine system cannot simply be procured and integrated as a fully functional system. One rather has to view the canines, their handlers and other elements as analogous to raw materials that have to be shaped into a product that stakeholders desire.

2.2 Systems Engineering and the Value of Following a Systems Engineering Approach

SANS 15288:2020 defines systems engineering as an "interdisciplinary approach governing the total technical and managerial effort required to transform a set of stakeholder needs, expectations, and constraints into a solution and to support that solution throughout its life" [1]. Systems engineering is typically used when developing more traditional systems such as aircraft systems, space exploration systems and power generation systems.

Following a systems engineering approach allows the solution developers (or puzzle builders) to take a bigger picture, life cycle view of the problem and to, in the context of that, construct the solution puzzle pieces that address the problem and is supportable throughout its life. It should therefore also be applicable to the development of more non-traditional systems, as explored in this paper. The paper strives to highlight this take on the application of the technical processes [1].

2.3 Systems Engineering Standards

There are a number of international standards that guide the application of systems engineering and it may therefore be regarded as best practice to follow such standards when applying a systems engineering approach. The following standards were consulted and utilised during the development of the canine system:

- The "Systems and software engineering – System life cycle processes" standard (SANS 15288:2020) [1]. The intent of SANS 15288:2020 "is to provide a defined set of processes to facilitate communication among acquirers, suppliers and other stakeholders in the life cycle of a system" [1].
- The "Systems and software engineering – Guidelines for the utilization of ISO/IEC/IEEE 15288 in the context of systems of systems (SoS)" standard (SANS 21840:2020) [3] that "provides guidance on the application of processes in ISO/IEC/IEEE 15288 to systems of systems" [3].
- The "Systems and software engineering – Life cycle management - Part2: Guidelines for the application of ISO/IEC/IEEE 15288 (System life cycle processes)" standard (SANS 24748-2:2021) [4]. This standard provides application guidance for the SANS 15288 standard [4].

The standards above are South African versions of the corresponding international standards and are prepared by the South African Bureau of Standards in line with an international agreement [1], [3] and [4].

3 TECHNICAL PROCESSES CONSIDERED IN THE ESTABLISHMENT OF A CANINE SYSTEMS

SANS 15288:2020 clarifies that the technical processes are employed "to define the requirements for a system, to transform the requirements into an effective product, to permit consistent reproduction of the product where necessary, to use the product to provide the required services, to sustain the provision of those services and to dispose of the product when it is retired from service" [1]. During the establishment of the canine system, the tailoring and application of the technical processes specifically focuses on the processes, activities, tasks and outcomes that contribute to requirements definition, the transformation of requirements into an effective product/service (development and procurement/acquisition), the use and sustainment/support of the product/service, as well as the disposal of the product/service. These are discussed in more detail in the sub-paragraphs below. An overview is provided of the processes that either provide an input to (e.g. mission analysis and stakeholder needs and requirements definition) or are triggered as a result of the aforementioned processes.

3.1 Mission Analysis Process

The problem/opportunity space [1], [3] is typically defined at SoS level and the resulting objectives provide the context and key parameters [1] for the establishment of the canine system.

When characterizing the solution space [1], [3], the following aspects should be addressed:

- The preliminary life cycle concepts [1] are considered. Typical functions that the canine system may fulfil include "tracking, trailing and identification" [5]; "suspect apprehension" [5]; as well as "detection" [5]. The defined objectives serve as a guideline to determine the deployment concept for employing one or a combination of these functions. For combating illicit wildlife trafficking, the acquirer may wish to use canines for the tracking of poachers in a protected wildlife area and/or for the detection of wildlife products at entry/exit points, whereas detection canines may need to be employed at border posts to detect plant and animal matter, as well as narcotic substances illegally being smuggled.
  Preliminary concepts for support also need to be considered, as this impacts the procurement strategy e.g. when a turn-key solution is considered as a solution alternative, this could include training for canines and handlers, kennelling and veterinary services, whereas an in-house solution alternative may include the establishment of a breeding program and veterinary services amongst others.
  In addition, preliminary concepts for the retirement of the individual canines and the canine system need to be developed.
- The interface and interaction [3] between the canine system and current/planned systems (e.g. the existing/planned patrol functions using foot patrols, vehicle patrols and/or aircraft patrols and existing/planned access control/management functions) need to be considered and defined. The canine system is employed in conjunction with existing/planned functions e.g. tracking canines and their handlers may be used along with vehicle/aircraft patrols or may replace/supplement foot patrols. Access control/management functions may be supplemented by the canine detection function. Other constituent systems in the SoS and their functioning may therefore have an impact on the preliminary deployment, operations and/or support concepts.

The output of the solution space characterization yields a list of potential services and broad sustainment options for selection based on criteria developed during the execution of the decision management process [1].

3.2 Stakeholder Needs and Requirements Definition Process

Various stakeholders have an interest in the canine system, these include the project sponsor, donors, the acquirer, the canine unit, canine handlers, suppliers (e.g. breeders, training providers, veterinarians), the regulator, the relevant Sector Education and Training Authority (SETA) and/or interest groups (e.g. general public, World Wildlife Fund, etc.).

Stakeholder needs are identified through direct interaction with relevant stakeholders [1] and through exploring inherent and unstated needs [1]. This may require that the engineer steps out of their normal comfort zone of the "traditional" system and engages with recognized domain experts such as other service providers using canines as a force multiplier (these include the South African Police Service (SAPS), the Department of Agriculture, Land Reform and Rural Development (DALRRD) and conservation organisations such as Singita [11] who use working canines); veterinarians; working canine breeders and animal behaviouralists. These engagements are generally extremely valuable and are indispensable when it comes to gaining a thorough understanding that supports effective needs and requirements definition.

Gaining an understanding of relevant legislation and the stance of professional bodies/councils is essential to ensure that requirements are formulated in context. An example where this is applicable, is the docking of canine tails. Tail docking is not condoned by the South African Veterinary Council (SAVC) (the statutory body regulating the South African veterinary and para-veterinary professions) [6] as it may be regarded as maiming of an animal [7] in terms of the Animals Protection Act No 71 of 1962 [8]. This essentially makes tail docking illegal in South Africa as a person docking the tail of a canine, without a sound medical reason [6], [7], may be prosecuted for contravening the Animals Protection Act No 71 of 1962 [6], [7], [8]. It should be ensured that this (possibly unstated) need be translated into a stakeholder requirement, by specifying that canine tails shall not be docked.

The preliminary life cycle concepts identified should also be explored and unpacked to identify and develop the required capabilities [1]. It should be clarified what operational function or combination of functions the canine system should fulfil. Typical questions to be resolved, include:

- If tracking canines are required, will they need to work individually or as a pack?
- Will tracking canines be required to protect their handler? And suppress hostile elements?
- Will detection canines be employed in an environment where there is an interface to the general public?
- In what environment will the canines be deployed?
- Do the project sponsor and acquirer require a turn-key solution? If so, it needs to be unpacked to what extent “turn-key” is envisioned, for instance, does it include that the supplier also identifies canine handlers, secure their services and provide those handlers as a contracted-in service. Will canines be acquired or “leased”? Will canine kennelling and/or handler accommodation need to be provided by the supplier?
- What enabling systems are required for the canine system throughout its life?
- How will canines be retired?

The answers to these questions aids in the formulation of the stakeholder requirements set.

In some instances, the stakeholder needs are not aligned, as an example when considering the retirement options for individual canines, a representative from a stakeholder group may have a need that the sole retirement option for the canine is rehoming with the handler, whereas another stakeholder group may require that broader options are considered.

It is therefore important that stated and derived stakeholder needs and requirements are prioritized and formalized into a defined requirements set [1] which is approved by the project sponsor and acquirer (as a minimum).

Constraints [1] on the canine system and quality characteristics [1] of the system should also be identified and the stakeholder requirements should be formulated in the context of these. Examples of constraints that may have an impact, are:

- A working canine and handler pair form a very close bond [12]. If the canine or the handler is not available, introducing a substitute canine or handler will likely decrease the effectiveness of canine operations. This imposes a constraint during the operations phase.
- The personal circumstances of handlers and their families (handlers may live in accommodation where pets are not allowed) may preclude the option of rehoming the retired canine with its handler. This puts a constraint on the system in terms of retirement options.
- If donor funding is used to establish and initial operations and support of the canine system for a limited period, this may put constraints on system options in terms of long-term sustainability.

Performance characteristics during establishment, operations, support and retirement should be determined. Examples are illustrated in the table below.

Table 1: Performance Characteristic Examples

Establishment	Operations and Support	Retirement
Canine provider track record	Canine and handler competency test results	Eligibility criteria for canine retirement
Training provider accreditation	Measures of stakeholder satisfaction e.g. detection success rate and/or tracking success rate	Suitability criteria for rehoming canine with handler
Handler screening criteria	Response time of veterinarian to attend case	New owner selection criteria
Canine screening criteria	Timeliness of canine food delivery	Post-rehoming assessment criteria
Canine and handler competency test results		

Once the stakeholder requirement set is formalized, it should be ensured that they are aligned with and traceable [1] to the project brief.

3.3 System Requirements Definition Process

The objective of the system requirements definition process is the creation of a measurable requirements set specifying the characteristics, functionality and performance [1] of the canine system. The sub-paragraphs in this section provide an overview of some aspects that should be addressed for canine system requirements definition.

3.3.1 Canines and Canine Selection Requirements

3.3.1.1 Requirements Generally Applicable to Working Canines

There is a sub-set of requirements that will need to be specified for all working canines. Some of the more interesting requirements and the rationale behind them are highlighted in this section.

The environmental conditions under which canines will work, impacts the requirements. Should the canines be deployed in a nature conservation area to combat illicit wildlife trafficking, it is important that they can co-exist with the wild animals in the area. This necessitates that requirements related to the following be considered:

- That females be spayed to ensure that they do not need to be withdrawn from service for the duration of their heat cycle as the attraction of hyenas may pose a danger to the working canine and the handler.
- The harsh heat and humidity conditions in Sub-Saharan Africa may also impose requirement(s) that canines, which are predominantly deployed outdoors, have suitable skin (no light skin pigmentation) and coat conditions to work in such an environment.
- Another environmental aspect that should be considered, may be the requirement for canines to able to work in noisy environments where they may be exposed to operational hazards such as gun shots, vehicle noise and aircraft noise. It may even be necessary to specify that canines be socialised to travel in vehicles and aircraft or to work in the proximity of humans or wild animals.

Should the working canines be required to work in an environment where the general public are exposed to them (e.g. detection canines working in aircraft terminals), a sound temperament and proper socialisation are requirements.

Some of the more obvious requirements that may be specified for canines relate to the health of the canine and include aspects such as:

- Proportionate height, weight and build.
- Age.
- The absence of congenital abnormalities and social anomalies.
- Good general health (no broken/damaged teeth, no external parasites and valid vaccinations and deworming).

3.3.1.2 Requirements Applicable to Tracking Canines

In the context of a canine system used as a force multiplier in safety and security applications, tracking canines are required to track human scent and locate article handled by a human. It is important to identify and specify the articles that the canine should be able to find e.g. clothes and discarded items such as fabric/leather objects (e.g. bags), plastic/glass objects (e.g. bottles) and metal objects (e.g. knives).

For tracking canines, the environment and terrain in which they will work influences the requirements. The heat and humidity experienced may preclude certain breeds from being suitable. Ambient conditions such as temperature and humidity influence the location and detectability of the scent ("airborne odour plume") to be tracked [9] and it may be necessary to specify the maximum age of the scent (say 3 hours [9]) that can be tracked. When tracking canines are required to work in all terrain, it may be a requirement that the canine can swim.

The required behaviour (e.g. to lie down and stay) of the canine in dangerous situations (e.g. during gun fire) should also be specified.

3.3.1.3 Requirements Applicable to Detection Canines

The following aspects are typically specified for detection canines:

- The specific items to be detected.
- Whether the canine is required to work on- or off-leash.
- Whether passive or active indication of detected items is required.
- That canines should be able to detect items located in vehicles/luggage without the vehicle/luggage being unpacked.

3.3.1.4 Requirements Applicable to Canine Selection

Physical characteristics (as described in paragraph 3.3.1.1) and behavioural characteristics play a role in canine selection [12]. Required behavioural characteristics include "playfulness" [12], "intelligence and obedience" [12], "fearlessness" [12] and "boldness" [12].

Depending on the specific application of the canines and the environment in which the canine will be applied, it may be necessary to specify specific dog breeds. Breeds such as Labrador Retrievers, German Shepherds, Terriers, English Springer Spaniels and Border Collies [12], as well as Belgian Shepherds and Weimaraners [11] are popular detection canines. Due to environmental conditions, it may be wise to exclude German Shepherds as detection canines in a nature conservation area subjected to frequent hot, humid conditions due to their thick coats.

3.3.2 Canine Handler Requirements

Canine handlers are required, as a minimum, to be fit [12], motivated to work as a canine handler and well trained [12].

3.3.3 Enabling System Requirements

Enabling systems are deployed to provide the canine system with support as needed throughout its life [4]. It is important that consideration be given to this, as these systems should also be planned for and established to ensure that the "product", desired by the stakeholders, functions throughout the life as expected. To this extent, as an example, the training system for canines and handlers may be viewed as a production and maintenance system, with its own requirement set. Individual canines and handlers are inputs to the training system. These inputs are subjected to the production process (initial training) and shaped into the required product. This "product" needs to meet its performance requirements (e.g. be able to track a 3 hour old scent [9] or identify a specified number of different types of plant/animal/narcotic materials/substances), before it is delivered into service. While in service, the training system receives previously trained canine and handler pairings for "maintenance" (refresher training or adapted/enhanced training). Following maintenance, the "product" will again need to be subjected to "acceptance testing" to ensure that the performance requirements can still be met.

Some of the more interesting requirements that need to be considered for the enabling system, are:

- In what type of an environment will the canines be housed? If canines are exposed to extreme conditions such as a harsh climate with high ambient temperatures and high humidity or even an extremely cold environment, it may be a requirement to house canines in an environmentally controlled kennel.
- Canines will require a recreational area. If the canine unit is based in a town/city, a park may be considered as a recreation area, but in a nature conservation area, it may be necessary to create a dedicated area for canines to relax and play.
- Canines and handlers will require a training area. If the canine unit is not too geographically dispersed, it may be most effective to consider a centralized training area.
- Training aids will also need to be specified. It may even be necessary that it be specified that training service providers be in possession of the necessary licenses to keep training aids such as wildlife products, explosives or narcotic substance required for the training of detection canines.
- Logistic aspects such as the supply of food, leads, grooming products and veterinary services need to be addressed as requirements.
- Training instructors should be registered with the relevant SETA to provide training to canines and handlers.

Some of the enabling systems may be dependent on customer furnished items (CFI), such as kennels and handler accommodation, being provided by the acquirer. This poses a risk to the system establishment schedule. The timeliness and quality characteristics of CFIs should therefore also be specified.

3.4 Architecture Definition Process

Iteration(s) of architecture definitions are applied and evolved during the execution of the preceding processes [1] with the output being an agreed upon solution that is selected from the alternatives presented [1].

In the case of canine system establishment, this will be chosen options for:

- The types of working canines (tracker canines, suspect apprehension canines and/or detection canines [5]) to be employed.
- The way handlers, training, veterinary services and logistic support services will be "contracted" i.e. in-house or contracted-in.

- Re-supply i.e. will future “product batches” be “produced” in-house through the establishment of a breeding program and/or a handler training academy or will “resupply” take place through procurement of canines and/or the appointment of handlers.
- The way canines will be retired.

3.5 Design Definition and System Analysis Processes

For the establishment of a canine system, it is necessary to dip into design definition and system analysis iteratively, while undertaking system requirements definition. This ensures that the “design” characteristics of each of the system elements are unpacked in sufficient detail to produce comprehensive procurement and development specifications that are traceable to the original stakeholder requirements.

3.6 Implementation and Integration Processes

3.6.1 Preparation for Implementation

The implementation process is kicked-off with preparation activities [1]. In the case of canine system establishment this includes preparing a procurement specification for the procurements of canines, handlers and/or enabling system components/services. The procurement specification is supplemented by defined functionality evaluation criteria and associated definitions of the functionality scores (scoring points) for each criteria, allowing the acquirer to objectively assess proposals before selecting supplier(s). Typical criteria that may be considered, include the supplier’s track record and experience; facilities and perceived quality of service; compliance to stated requirements (including schedule requirements); quality of proposed training curriculum for the training of canines and canine and handler pairings.

Table 2: Facilities and Perceived Quality of Service Example Criteria

Aspect to be evaluated:	The supplier's facility and quality of service shall be evaluated by means of site visits by the acquirer.

Criteria for evaluation:	During the inspection, verify that the supplier has: • A sufficient supply of canines available for selection (say 30% more than the required number). • Onsite canine kennels, food, veterinary services, training facilities, training material and -aids. • Access to facilities to accommodate canines and handlers during training. • An active hygiene and pest control program is in place at the kennels. This is evidenced by processes, procedures and/or records. • Facilities to safeguard training aids such as firearms, ammunition and/or contraband items.

Proposed assessment of functionality score:

Scoring points	5	During the site visit the facilities and perceived quality of service is excellent with all requirements fulfilled.
	3	During the site visit the facilities and perceived quality of service is satisfactory with 1 deviation from the requirement.
	1	During the site visit the facilities and perceived quality of service is mediocre with 2 deviations from the requirement.
	0	Don't comply i.e. during the site visit the facilities and perceived quality of service is unacceptable/poor with 3 or more deviations from the requirement.

3.6.2 Undertaking Implementation and Integration

During implementation, the focus is on the realisation of all the system elements within the constraints [1]. For the canine system establishment, the coordination and timing of implementing the various elements is key. This includes actively managing the delivery of CFI to ensure that it is well coordinated with other project activities. Implementation therefore requires dedicated project management and liaison between all parties to ensure that kennels are ready, food is available, veterinary services are in place and training is concluded before the canines are delivered.

During integration the various system elements are integrated, the interfaces activated and it is verified that the integrated elements work together as required [1]. Typical aspects that require attention during the establishment of the canine system include that the external interface with existing systems function as required e.g., that trained canines are indeed able to travel in vehicles/aircraft and react appropriately to noisy environments or that detection canines are docile enough not to threaten travellers at border posts while executing their detection duties. For internal interfaces, it can typically involve verifying that the training was effective and that the kennels/recreational areas fulfil the intended purpose. Evaluation of the effectiveness and efficiency of the canine and handling pairing is also an important integrated component that needs to be evaluated and managed. It is clear that integration can never be a once-off for a complex adaptive system like a canine system and that through-life effort is required to manage certain aspects of integration.

3.7 Verification Process

Even though the scope of verification spans wider, this paragraph specifically focusses on the verification of canines and handlers.

Verification criteria are predefined as well as the remedial actions should the "item" not comply with the specified requirements.

3.7.1 Preliminary Verification

During establishment it is confirmed that the canine is "built right" [1]. This is initially done though preliminary acceptance where the canine and its documentation are examined to determine:

- Its general condition and health (assessment for build, condition of teeth and absence of parasites).
- Compliance to the absence of physical abnormalities such as the specified grade of hip dysplasia. This is typically done by means of x-ray examination.
- Its age, breed and vaccination status.

Another aspect to be verified during the preliminary acceptance, is the potential of the canine to successfully work in the role assigned to it. Here the canine's personality is evaluated to check it's response to strangers (important for canines with public facing assignments), as well as it's "playfulness" [12], "intelligence and obedience" [12], "fearlessness" [12] and "boldness" [12].

By the same token, potential handlers are assessed for their suitability to become a professional canine handler. Some of the criteria that may be used to assess the suitability of handlers include "level of fitness" [12] and the handler's "knowledge of dog training and handling principles" [12].

Should a canine or a handler not meet the criteria, the "item" is rejected and an alternative subjected to verification.

3.7.2 Interim Verification

By this time the canine and handler have been integrated as a pair and initial training is concluded. An assessment is used to verify that the pair functions as required in a training environment.

Should it be found at this point that the canine, handler or canine and handler pair is not suitable for performing the intended assignment(s), retraining should be considered or it will be necessary to make some replacements.

3.7.3 Final Verification

Once ready for deployment, the canine and handler pair are independently assessed in the operational environment, prior to the release for service. This final step of verification also verifies the implementation of the interfaces (see paragraph 3.6.2).

A similar acceptance strategy may be followed to that implemented for interim verification.

3.8 Transition Process

During the execution of this process the canine system, comprising of the canines, handlers, enabling systems (kennels, recreational facilities, logistic support, training system and veterinary services), is introduced into service and functions together with the other SoS elements employed as force multipliers. During this period the operation of the system and its interfaces are closely monitored as (the initial) part of the validation process.

3.9 Validation Process

Here it is confirmed that the “right product is built” [1] i.e., that the canine system is the right product to fulfil the intended purpose [1]. Typical measures that may be used to quantify this for the canine system include a specified improvement in the suspect apprehension rate and a reduction in poaching statistics [11].

3.10 Operation and Support Processes

The management of operations and support of the canine system should be done in the complex adaptive context, where changes (such as changes in the intended purpose, the environment or the scope of services required from the system) are proactively monitored and their impact used to guide the rejuvenation of the canine system. As an example, when initially introduced, detection canines may be trained to detect elephant ivory [11], [13], but as conservation threats evolve it may become necessary to add other animal products (e.g. pangolin scales [13] and rhino horn [11], [13]) to this.

As a minimum the canine and handler pairs should be continuously assessed for competency and refresher training undertaken regularly.

3.11 Disposal Process

Disposal of the canine spans far wider, but for the purpose of this paper, only canine retirement and rehoming is addressed here. If a canine needs to be retired due to medical reasons, euthanasia could be considered as a viable option. If this is not the case, the canine can either be rehomed with its handler or a suitable new owner. This process [14] is illustrated in Figure 1.

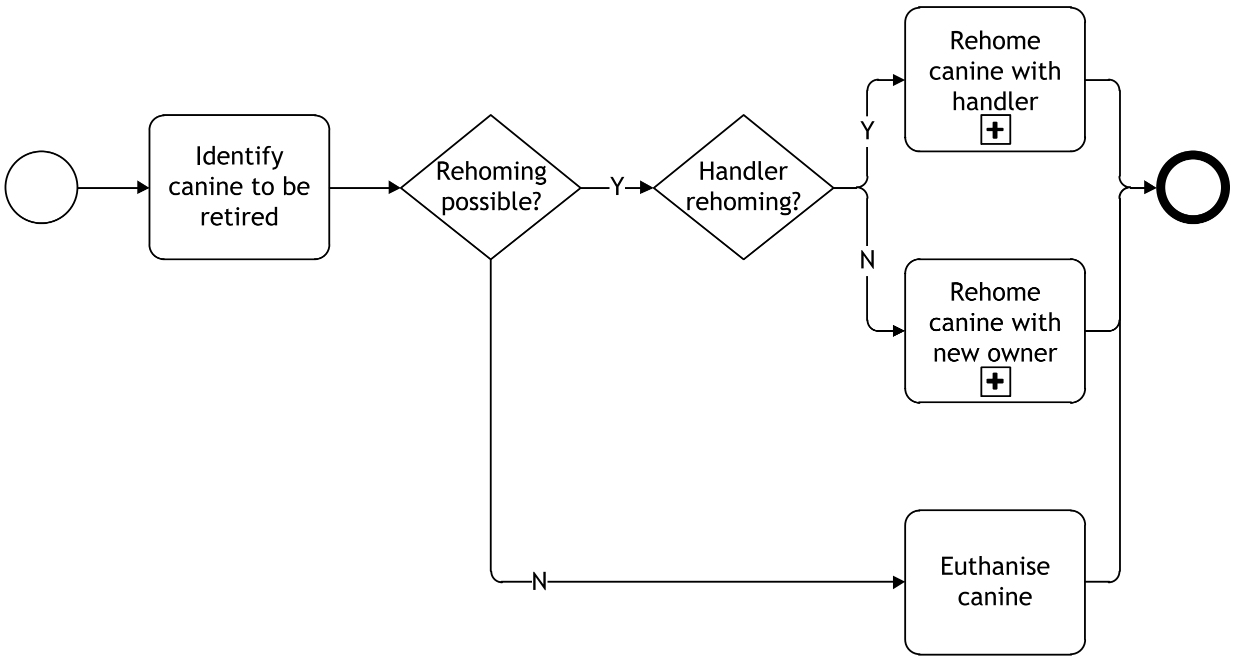

Figure 1: Potential Canine Retirement and Rehoming Process [14]

Depending on the circumstances, the “sub-processes” [15] (shown with a [+]) are to be unpacked to cater to the unique situation posed.

4 CONCLUSION

With the evolving problem spaces faced by engineers, the non-traditional application of tools and techniques at our disposal may be required to architect complex, innovative and integrated solutions for our next normal.

This paper illustrates that system engineering processes and principles may be used to address non-traditional problems such as the establishment and operation of a canine system for utilisation as a force multiplier in combating illicit wildlife trafficking, policing, rendering of security services or border management, as well as other socio-technical problems posed in the International Council on Systems Engineering (INCOSE) South Africa's annual "Greatest Young Systems Engineers of the Year Challenge" [16]. It is therefore recommended, and readers are encouraged to consider applying a systems engineering life cycle view when engineering appropriate solutions for our next normal.

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CUSTOMISED TECHNOLOGY ROADMAPPING FRAMEWORK FOR THE FOURTH INDUSTRIAL REVOLUTION IN THE RAIL SECTOR

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ABSTRACT

South African (SA) rail network has struggled with challenges of theft and vandalism of the infrastructure, and the accidents caused by human interface to the system. It is for these reasons that there is a need to seek engineering solutions, such as cyber-physical rail, enabled by the fourth industrial revolution (4IR) technologies. For the SA rail organisations to better prepare for introducing these technologies, the emphasis should be made on the planning process. One of a better-suited planning tool for this type of complex technologies is technology roadmapping. A qualitative study was used to find the ideal framework for the development of the customised technology roadmap for the SA rail sector and investigate the critical factors of the 4IR which must be considered during planning process in the context of rail. Using a mixture of deductive and inductive qualitative analysis approaches, this study identified a set of factors for the customisation of the technology roadmap for the SA rail sector.

Keywords: fourth industrial revolution, technology roadmap, rail sector, planning

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1 INTRODUCTION

Changes in markets and technologies necessitate the need for organisations to be dynamic and adaptable. Organisations use technology strategic plans to deal with these changes, as well as come up with new technologies that will meet the requirements of customers and gain competitive advantages. Technology management is an important activity within an organisation, to meet customers' needs; this requires techniques or tools to support the planning process of technology management [1]. It may be defined as, "the process of managing activities within the framework of technology management to improve the technology capability of the organisation". A technology management framework incorporates the following activities: identification, selection, learning, acquisition, exploitation, and protection" [2].

One of tools that can be used to manage technology in dynamic and complex environments is technology roadmapping. Technology roadmap is a long-term plan for the strategic management of technology; it is a guide an organisation must follow to achieve its technology strategies. Before a technology roadmap may be developed, an assessment of the organisation or sector must be conducted to evaluate what type of technology roadmap would be valuable.

Therefore, the objectives of this research were (i) to investigate the customisation of the technology roadmapping for the South African rail sector and (ii) to investigate the critical factors that can be incorporated in the development of technology roadmap for planning of the fourth industrial revolution (4IR) technologies.

Like any sector, the South African rail sector has major challenges, and the use of the 4IR technologies could possibly reduce most of these challenges. Some of the challenges within the South African rail industry include driver inattention and distractions, train collisions due to manual authorisation, overloading of trains, run-through and derailments, theft and vandalism, and level crossing incidents. The following are technological challenges: unreliability of the network due to old equipment and constant failure, unavailability of the network due to lack of maintenance, power failures or unstable power supply, rolling stock failures and lack of technological surveillance.

There is an agreement that the transport industry is one of the top three industries for Internet of Things (IoT) investment, based on the spending estimates [3-4]. While both PRASA and Transnet have projects running in the rolling stock department to adopt some of the 4IR technologies, this is not enough, as the challenges in maintenance and customer experience are still affecting the organisation. The South African rail sector will benefit from the 4IR as a solution to the technological challenges and other challenges that may be solved by automation of the operations. Transnet is one of the largest rail operators in Africa, as it links to other countries; it is both a passenger and logistic rail operator. Transnet owns blue trains, which are the passenger trains and Transnet freight, for transporting goods. PRASA is a passenger rail owner and operator; it owns both Shosholoza Meyl, the long-distance passenger rail service within South Africa and Metrorail, the urban passenger rail service within South Africa.

2 LITERATURE REVIEW

2.1 The rail technologies network and the fourth industrial revolution

The network of the Radio Train Control Systems is made of the advanced train administration and communications system (ATACS) and communication-based train control system (CBTC). These systems allow the train to auto-detect its own position on the network, and also allow control through the dual radio transmission between the onboard and the trackside system. They reduce the number of the trackside or wayside equipment and also allow for corporation between onboard and trackside equipment using advance radio technology to allow high density operation, power saving and automatic operation. These are some of the systems that can be installed in the South African network to assist reduce theft of trackside as there will be less equipment outside.

Van Der Meulen [5] states that rail dominates in the following market spaces:

- Heavy haul (bulk commodities)
- High speed intercity (passengers)
- Heavy intermodal (double stack containers)

Tokody & Flammini [6] believe that rail has suffered from a lack of long-term strategic planning. Not only are there continuous changes in technological developments, but they also believe that the rail can benefit from the development of the smart technology (associated with the 4IR), which require long term-strategic planning. The 4IR technology can handle high volume data (big data) and it also provides real time data to make decisions quickly, which allows for decentralisation.

Figure 1 is a basic diagram of the integration of the rail systems for the smart rail. It shows different technologies that make up the smart rail system. This diagram shows systems that are generic to both commuter rail system and freight rail and it can be used for planning of Rail 4.0.

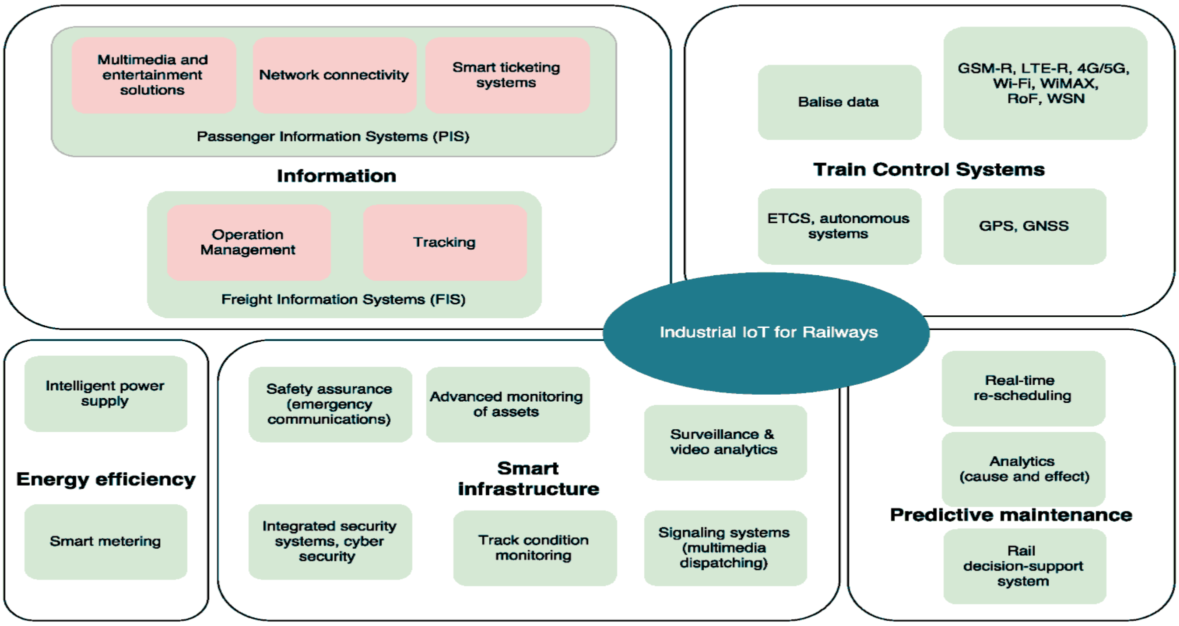

Figure 1: Industrial IoT Enabled Services Relevant for the Rail Operation [7]

Tokody & Flammini [6] and Pieriegud [8] believe that the development of intelligent and autonomous systems will have a positive effect in the rail, especially regarding the improved safety, infrastructure, and sustainability. The 4IR technologies will provide the following benefits [8]:

- Mobile Application
- E-ticketing.
- Digital train control.
- Signalling and traffic management.
- Digital platforms for predictive maintenance.

Some of the key characteristics of the 4IR are big data, cyber cloud, and artificial intelligence. These technologies are about being able to share information that is saved in the web;

however, the biggest problem with the web is security of information as well as the implementation of a new emerging technology.

Lee, Singh and Azamfar [9] propose a solution and refer to a step-by-step roadmap for the implementation of integrating physical systems (products) with cyber systems; it also touches on the block chain as technology that can significantly improve the cyber system. Block chain is also new technology and requires further research before it can be implemented. For the above solutions to be successful, proper planning is required. This is true with the implementation of emerging technologies of the 4IR. As organisations are planning for the implementation or development of 4IR technologies, cyber security is a factor that must be considered and planned for.

One of the biggest challenges of the 4IR is the investment required for new technologies. Some companies do not have funds to readily invest in more advanced technologies. There are also other costs, such as the cost of training. It will be required that employees must be trained, and these costs can hinder the plans towards the implementation of the 4IR. When speaking about the 4IR, most organisations only concentrate on the development of technology, and not the development of the whole value chain of the organisation, like the knowledge management of the organisation, business processes, etc.

People, or the 'human factor' of the organisation must be advanced into more creative roles and concentrate on activities that add value, while machines will do the repetitive and routine activities [10]. Organisations that fail to realise this will be met with challenges, especially from labour unions.

The planning of the 4IR must find a way to deal with challenges and barriers that may delay the implementation of its technologies; for example, how to develop or upskill the current workforce to adapt to the new technologies and new roles instead of letting employees go, as noted by Pessl, Sorko and Mayer [11]. Changes in workforce due to the introduction of the 4IR must be investigated and planned for, as suggested by Kazancoglu & Ozkan-Ozen [12]. This will assist the organisations in reducing the delays which may be due to Union Labours not approving the move towards the implementations of the new technologies.

Maynard [13] suggests teaching all stakeholders, from consumers to CEOs, about the benefits of the 4IR. This will help in reaching a consensus when planning for the development of new technologies. In the context of the South African rail sector, these stakeholders must also include the labour unions, as they also may cause delays in the development of the new technologies.

2.2 Technology Roadmap

Technology roadmap was developed as a tool for the planning of innovation [14] and it has been useful for the organisations that adopt the market-pull innovation mechanism (like the rail sector) as their aim is to improve the existing product lines in order to meet the needs of customers. It is for this reason that Hwang [15] suggested that manufacturing organisations should use technology roadmaps to plan for the 4IR, though she does not specify how it should be approached.

Roadmapping is a tool that also creates the knowledge to reach a specific vision of an organisation. It can be used as a backward planning process, through beginning with where the organisation wants to move to (the vision) and develop strategies to move towards the vision by determining the current status of the organisation and closing the gap [16]. Several scholars [17, 18, 19] agree that roadmapping is used to plan where organisations want to go, as it evaluates where the organisation is currently and analyses ways of closing the gap between the present and the future.

Muller & Phaal [19] state the following characteristics of the roadmap:

- Flexible
- Scalable and
- Can be customised to suite different strategy

While Centidamar, Phaal and Probert [17] list the following challenges or hurdles of roadmapping:

- Initiating the process (taking the first step): coordinating the team at the begin may prove to be difficult
- On-going maintenance (owning the process) of the roadmap: managing the process of roadmap may be a challenge
- Rolling out the roadmapping process within an organisation: taking the strategic plans to the departmental teams can also be a challenge

Phaal, Farrukh & Probert [1] found that keeping the roadmap alive is the biggest challenge of the technology roadmap. The breakdown of the findings based on the survey conducted and the biggest challenge is keeping the roadmap alive and on-going, which is almost 50% of the respondents' view. It is followed by the challenge of starting the process of technology roadmap at just over 30% of the respondent's view. The article does not include factors that affected the responses like the experience, qualification as well as the level of authority of the people who were in the positions of keeping the process alive and those who were involved in start-up as this information may assist with better planning going forward.

The strategic roadmap is regarded as the central artefact that serves three main purposes as noted by Erol, Schumacher & Sihn [10] in the context of the industry 4.0:

- As means to consistently analyse and plan the transformation of business models and assess the impact of technology
- As means to facilitate collaborative development of vision, strategy, and projects
- As a tool to manage and track all activities regarding the transformation process towards industry 4.0

The process flow of an example of technology roadmap based on the Figure 2 is as follows:

1. Vision- vision of the technology roadmap must be determined and agreed upon as the first step
2. Now- the current organisation's technology capabilities
3. Market
   3.1 The market requirements must be determined and known
   3.2 Plans to meet the market need must be made and plotted on the roadmap based on the planned progress of meeting them
4. Products
   4.1 Determination of products that can meet the customer needs must be demined
   4.2 Plans to acquire these products must then be made
5. Technology
   5.1 Technology required to develop and own the new product should be determined
   5.2 Then plans should be made on how and when to acquire the technology

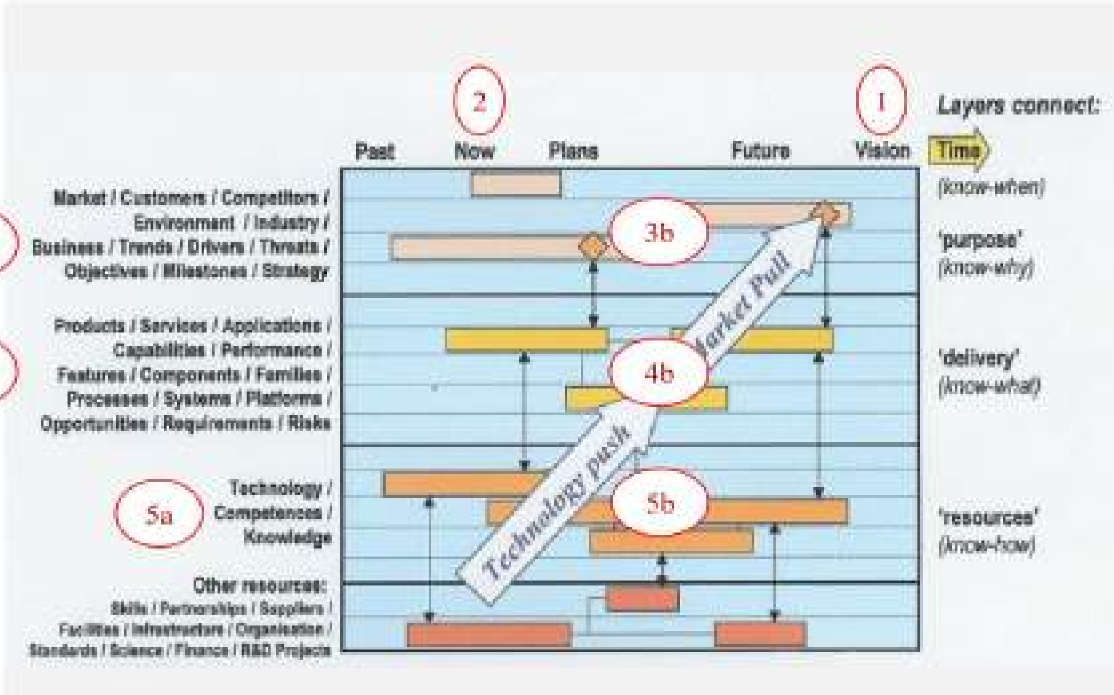

Figure 2: Example Process Step of Technology Roadmap [1]

Several scholars ([20], [18], [19]) agree that the technology roadmap must be customised to suit the culture of the organisation, or the new technology to be developed, as it will be effective. Kerr, Phaal and Thams [18] explain that the mere development of a technology roadmap is a customisation of the technology roadmap and that there is no guideline of how to customise it. Kerr, Phaal and Thams [18] further propose the use of the S-plan and customising it to the organisation. 'S- Plan' refers to the generic technology roadmap process, which can be customised to specific products or organisations, using the reference of the original generic process.

Amer and Daim [21] state that industrial or sectorial technology roadmaps require collaboration between organisations within the industry to form part of the planning process. Collaboration must thus be considered when developing the technology roadmap. When organisations collaborate on the development of the technology roadmap, stakeholders and statutory bodies must be included.

Hall [22] presented a list of stakeholders involved when developing the Roadmap for South African coal. The presenter does not say how the stakeholders were involved in the process and what benefit they brought by being involved. The participants and steering committee comprised of all 17 stakeholders. These were a collaboration of clients, private organisations, and governmental representatives.

Cetindamar et al. [20] have also come up with a strategy to customise a technology roadmap for product-service integration. This framework works differently for different technologies, depending on whether they are market pull products or technology push type of innovation.

Below (Figure 3) is the roadmap framework with the inclusion of partners as in the joint venture arrangement. This roadmap includes contribution from the different stakeholders, and this can benefit the rail industry to adopt for in the technology planning process.

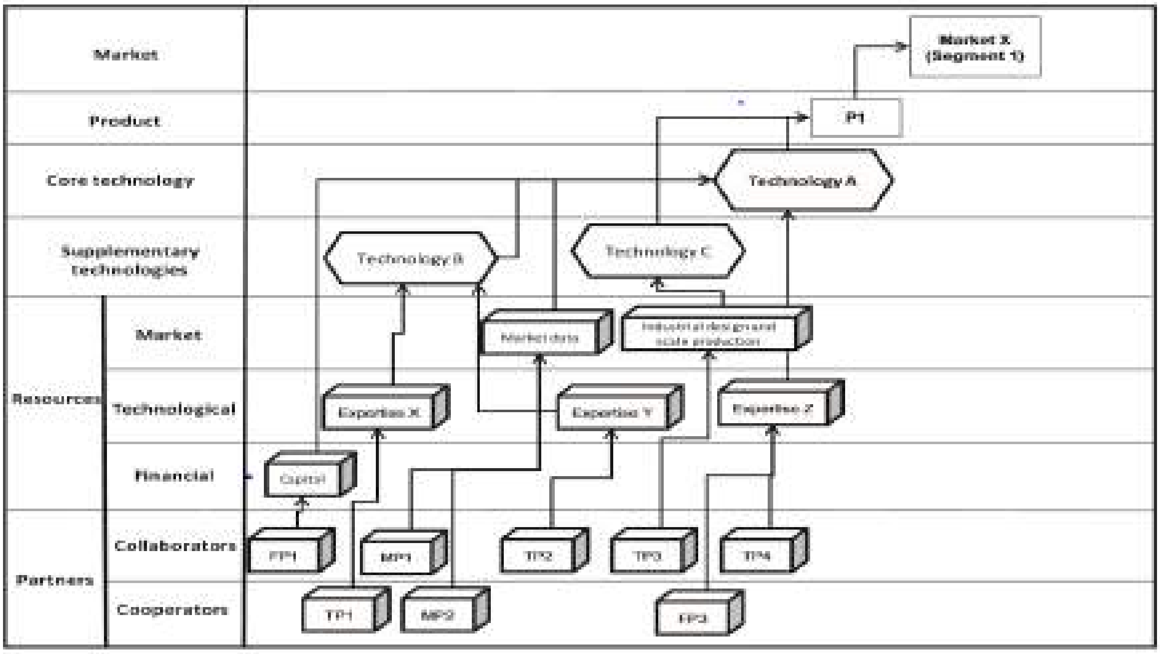

Figure 3: Multiple stakeholders technology roadmap [14]

Da Silva *et al*. [23] state that the rail sector can benefit from the use of a technology roadmap as a tool for strategic planning. Technology roadmaps are not only limited to use as a strategic process, but also for the following technology management activities, which may be on a departmental, company or sector level:

1. Identification: for technological development
2. Knowledge management: it can be used to map out the plan to follow for managing knowledge (learning activities)
3. Exploitation: the activity for commercialisation

Da Silva *et al*. [23] further identified four critical main points in developing the technology roadmap vision for the rail industry:

- Market.
- Public policies and investment.
- R&D and technology.
- People.

3 METHODOLOGY

The research methodology employed is a qualitative approach using semi-structured interviews designed to test and improve the theoretical model on technology roadmapping for the fourth industrial revolution. This theoretical model was derived through the literature review and the final model (enhanced through empirical data) is shown in the next section that discusses the results.

The questions for the qualitative interviews were divided into three categories: Category A (comprised of questions seeking the demographic information of the participants), Category B (was about the technology roadmap) and Category C (was about the fourth industrial revolution). Category A questions (used to attain the demographic data of the participants, which included data regarding the experience of the participant, experience in rail, number of years in rail, as well as the current roles and the number of years in that role). Categories B and C questions contributed to customising the planning process of the fourth industrial revolution in the South African rail sector.

This study adapted the snowball sampling technique. The years of experience of the 14 participants interviewed can be categorised as follows: more than nine participants have more than eight years' experience in their current positions, lowest experience in current experience is one year, longest experience in current position is 10 years, over nine participants have more than 14 years' experience in rail, the longest service in rail is 23 years and the least amount of experience in rail is nine years.

The respondents were drawn from the main two rail operators in South Africa and they are based in the following divisions: electrical (four), signals (three), perway (two), telecoms (one), human resources (one), ICT (one) and rolling stock (two).

The data analysis method used is a mixture of deductive and inductive quantitative analysis approaches. Therefore, the initial themes were directed by the theoretical model deduced and a more open-ended coding (grounded theory methodology) resulted with a modified technology roadmapping framework.

4 DISCUSION OF THE RESULTS

4.1 Emerging themes from the qualitative interviews

The following is a list of final themes that emerged from the interviews:

- Key stakeholders to be involved during roadmapping;
- Planning and/or technology roadmap managing team;
- Information to be discussed in planning;
- 4IR technologies in rail sector; and
- Unique features for South Africa's rail industry.

The interview responses led to a list of stakeholders that should be involved in technology roadmapping exercise and are unique to the South African rail industry. While most participants agreed on many stakeholders, there were a few who thought labour unions should be involved on planning for the technology roadmap. The idea of bringing labour representatives on board is supported by the literature of planning for the fourth industrial revolution [24]. As deduced from the interview responses, the following is a consolidated list of stakeholders who need to be involved in the planning stages of the rail industry roadmap: engineering bodies, government/ transport departments/ municipalities, consultants, rail network operators (e.g. Gautrain or TRANSNET), rail safety regulator (RSR), communities/commuters, labour unions, investors, board of directors and the security companies.

Table 1 shows the information to be gathered from stakeholders during the development of a technology roadmap and the ways to gather such information, as suggested by majority of the respondents interviewed.

Table 1: Methods and information to be gathering during technology roadmap development

Ways to gather information from the stakeholders	Information to gather during planning
• Group discussions • view sessions • Workshops • Research approach like surveys	• Opportunities of industry • Challenges of industry • Standards • Customer facing technology • Skills requirements • Funding • Specific political/ labour / stakeholders • Local manufacturing capabilities • Tools and process of sharing information

	• Integrated asset management

Some handful of the respondents believed that using artificial intelligence and automation may reduce the challenges/incidents faced by the rail organisations because they can reduce human interface. Over and above the automation and artificial intelligence, the rail industry can benefit from the technologies such as In Cab system, Electronic signaling system, Cloud based technology, big data management systems, Artificial intelligence, Digital twin/ digitalisation, Automation and Virtual reality of network.

When it comes to managing the technology roadmap for the fourth industrial revolution, some of respondents advised that there should be an information technology specialist as a member of the roadmapping committee; also, software tools should be used to make it easier for the committee and stakeholders to get information on the roadmap and progress.

The human resource (HR) manager also suggested that bringing new technology would mean there should be an upskilling of the employees and, if they (HR) can have information on products and type of technology being planned for, they can plan for the correct upskilling training.

The consolidated list of representatives who must be involved in the management of the technology roadmap development, as well as responses from participants on how to keep the team involved throughout the technology lifecycle is presented in Table 2.

Table 2: Managing Technology Roadmap

Members to be involved in technology roadmapping	**Ways to keep the technology roadmapping committee involved**
• ICT • HR • Train Operations • SCM • Legal • Finance • INFRA • Rolling Stock • Marketing • Safety • Security	• Continues review meeting • Communicate benefits of technology roadmap • Involve stakeholders through forums • Use software as a tool to manage technology roadmap

The unique features of the South African rail as listed by the respondents are the following items:

- Rail environment/ national rail policy and operator mandates
- Incorporate opportunities and challenges in the industry
- South African standards
- South African public policies
- Customer facing technologies
- Stakeholders
- Lack of technical capability of local manufactures
- Skills matrix
- Socioeconomic environment

4.2 The proposed customised framework for the rail sector technology roadmap

The following are some observations based on interaction with the participants in the rail industry on how to improve the development and usability of the roadmaps:

- There is a view that only the senior staff in organisations are often included in the development of technology roadmap; middle to senior management are included only in the implementation and the managing of technology roadmapping. As a result, some of the respondents only had an experience in the long-term strategic planning, rather than experience in the actual development of the technology roadmap. This led to missing information, as some questions were not answered, such as the question of the challenges and benefits of using the technology roadmaps.

- Most respondents were set on having private companies be involved in the planning, for the benefits of knowledge-sharing as well as on the funding of the roadmapping expected outputs.
- The skills or lack thereof, regarding the 4IR technologies, made knowledge management an important aspect, hence the recognition of involving HR at the very beginning of the planning of the technology roadmap.

The respondents introduced the activity of reviewing the roadmap but did not specify when there should be a review phase and whether it should be one review or more as well as the routine period of the reviews. This may be the point of discussion in future research.

Figure 4 shows the proposed customised technology roadmap for the planning of the fourth industrial revolution technologies in the rail sector (based on a theoretical model and the information derived from the interviews).

Roadmap Architecture		**Past**	**5yrs**	**10yrs**	**15yrs**	**20yrs**	**Information types**
Strategic goals			R1		R2		SWOT
Resources/ strategic objectives	Market						Resource plans
	Security						
	Safety						
	HR						
	Finance						
Support	Public partnership • Gov • Commuters • RSR						Partnership agreements
	Private partnership • Private rail operators • Manufactures						
Technology/ Product	Telecommunications	• In Cab system • Electronic signaling system • Cloud based technology • Big data management systems • Artificial Intelligence • Digital twin/ digitalisation • Automation • Virtual reality of network					Smart rail infrastructure system
	ICT						
	Rolling stock						
	Electrical (HC)						
	Signals						
	Perway						

Figure 4: Final Proposed Roadmapping Framework for the Rail Industry

Legend: R1- review phase 1; R2- review phase 2

This framework provides options in terms of which strategic objectives/ capability development should be pursued, a type of supporting structure that is required as well as the technology/ product options. Timelines suggested for the rail industry roadmap can range from 5 to 20 years, with the regular reviews (see R1 and R2) conducted as the roadmap is being implemented.

5 CONCLUSION

In response to the identified challenges within the South African rail industry, this paper has proposed a technology roadmapping framework for this industry. Proper long-term planning is necessary for this industry as the rail assets have a long lifecycle and the planning of acquiring these assets is also long. The technology changes faster than the assets can be changed, hence the suggestion to review the technological assets more frequently. The respondents suggested different technologies which might benefit the industry. The list is included in the final proposed framework. They also listed the type of private and public stakeholders who needs to be involved to make the technology roadmap effective.

The future research may also include private organisations, as the respondents have already listed them as the required stakeholders. Overall, this research has given more insight into the customisation of technology roadmap for the rail industry in South Africa.

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INVESTIGATING THE APPLICATION OF MATHEMATICAL PROGRAMMING MODELS FOR RETAIL PROMOTION PLANNING

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ABSTRACT

Retailers frequently underutilise promotions due to the complexity involved in promotion planning and demand forecasting. In response, researchers have proposed various mathematical models to assist retailers with these decision-making processes. This article identifies these existing mathematical models by conducting a systematic literature review (SLR). Sufficient background is provided on the variables that influence the profitability of retail promotions and the modelling techniques commonly deployed within the literature. This review aims to summarise and evaluate each study in terms of the modelling approaches followed and what combination of the variables, as mentioned above, are included within each model. The findings obtained from this review may serve as a basis for future researchers in developing a mathematical model that maximises promotional profit within a retail setting.

Keywords: Retail promotion planning, Optimisation modelling, Systematic literature review, Demand forecasting

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1 INTRODUCTION

Conducting retail promotions (the short-term reductions of a product's regular retail price [1]) offers many advantages to retailers. Amongst the known benefits, promotions boost short-term sales and increase store traffic [2, 3]. Additionally, an item sold at a discount induces the sale of complimentary items [4]. Finally, promotions allow retailers an additional revenue stream as vendors may offer retailers funding as an incentive for selling the vendor's items at a lower profit margin [1].

Concurrently, several adverse facets accompany promotions. To name a few:

- Customers react unfavourably to promotions if they believe their durations are restrictively short [5].
- The sale of a discounted item may prevent a substitute from being sold at a higher profit margin [6].
- Customers who stockpile items purchased during promotions are less likely to make repeat purchases. [7]. Therefore, repeat purchases that would have been sold at non-promotional margins compound losses. Designing profitable promotions over the long term is therefore complex.

Given that most retailers rely on informal heuristics to plan promotions [8], historical instances showcase the severe financial repercussions of poor promotion planning. Ailawadi et al. [7] found that 50% of promotions conducted at a large drug retailer in the USA over one year are not profitable because vendor funding does not sufficiently offset the lower profit margins on products. The authors estimate the retailer lost $52 million due to poor promotion planning. Jedidi et al. [9] come to a similar conclusion; the lower profit margins on three out of four promotional items sold at a specific retailer increase their sales but reduce overall profit by 5%. While the previous two studies showcase the profit impact of reduced margins, Kopalle et al. [10] describe a case study wherein overpromotion reduced retail profit by 7% to 31% over 124 weeks due to the stockpiling effect.

These instances of suboptimal promotion planning underscore the critical need for a more sophisticated and systematic approach to designing promotions. This is where mathematical modelling becomes pertinent. Mathematical models select the best variables with respect to some criterion amongst a set of alternatives [11]. Given mathematical models' effectiveness in finding optimal solutions to complex problems with large numbers of inter-related variables, this technique has been shown to be especially effective in outputting the optimal conditions at which to conduct promotions [12]. In response, researchers have proposed multiple mathematical models to aid retailers in designing profitable promotions. This paper identifies these models through a systematic literature review (SLR).

SLRs originated within the healthcare industry [13]. During the early 1990s, health practitioners adopted an evidence-based approach that emphasised incorporating the best available research into clinical practice [13]. A systematic review is a systematic approach to defining research questions and synthesising findings [14]. To this end, systematic reviews became popular for summarising evidence within a specific domain. Since then, many fields outside healthcare have adopted evidenced-based research practices and systematic reviews [15].

Considering the efficacy of Systematic Literature Reviews (SLRs) in synthesising evidence and the imperative of identifying how mathematical models assist retailers with designing promotions, conducting an SLR on this subject is warranted. This review's aim is threefold. Firstly, it aims to identify the mathematical models that assist retailers with promotion planning. Secondly, it evaluates them in terms of their modelling approaches. Thirdly, it evaluates them in terms of their scopes. In doing so, this paper contributes to the research by forming a basis for developing future mathematical models that ensure the effective application of retail promotions.

2 METHODOLOGY

An SLR is conducted according to the approach first described by Kitchenham [16]. Kitchenham's [16] review method is frequently followed in the literature. An inexhaustive list of reviews that follow this method includes the topics of stochastic programming models in the retail industry [17], how collaborative robots used on assembly lines impact manufacturing systems [18], and the use of deep learning approaches in detecting attributes within source code indicating underlying issues [19].

The approach divides the review into three stages. In the first stage, the need for a review is identified, and the review protocol is developed. The need for a review on the mathematical models that assist retailers with promotion planning is justified in this paper's introduction. The review protocol is defined as follows.

Five research questions are formulated to address the aim of this study. The research questions are listed in Section A of Table 1. Research Question (1) identifies the number of studies that can assist retailers with promotion planning. Research Questions (2) and –(3) evaluates the mathematical models in terms of their modelling approaches by summarising the optimisation- and demand modelling techniques deployed. Finally, Research Questions (4) and –(5) summarise the scopes of the models in terms of the retail variables that are included as well as identifying limitations within the models.

The databases Science Direct, Scopus, IEEE, and Web of Science are searched for studies that contain the words' retail', 'promotions', and 'optimisation' within the keywords, title, or abstract (hereafter referred to as metadata). Provision is made to include studies that use the US spelling of the word 'optimisation'. Section B of Table 1 denotes the keywords used to query the respective databases.

In the second stage of the methodology proposed by Kitchenham [16], studies of appropriate quality are identified, and data is extracted and synthesised. To this end, the inclusion and exclusion criteria are applied in a stepwise manner. In Step 1, the databases are searched for studies that contain the search terms within the metadata. In this step, non-English literature and literature published more than ten years ago are excluded. This ensures that the SLR only includes contemporary studies. This step identified 95 studies. Different databases may list the same studies. Duplicate studies are removed in Step 2. After this step, 66 studies remain. Given that promotions are temporary price discounts [1], a mathematical model must determine the optimal promotional price to be included in the review. In Step 3, the studies that do not use mathematical modelling to find the optimal promotional price are excluded. This step ensures the relevance of the retained studies. Ten studies remain after this step. The inclusion and exclusion criteria, as well as the number of studies each step identifies, are summarised in Section C of Table 1.

The review is reported in the final stage by evaluating them in terms of the review questions. The final stage of the methodology is covered in the subsequent section.

3 RESULTS

Table 2 lists the title, year of publication, and author of each identified study. Additionally, Table 2 summarises each of the identified studies according to its background, aim(s), and modelling approach followed.

Table 1: A summary of the review protocol

A. Research questions				
Question number		**Question**		
1		How many studies contain mathematical models that determine the promotional price that maximises retail profit?		
2		What optimisation approaches do these studies follow?		
3		How do the studies model retail demand?		
4		What combination of standard retail variables do the models include?		
5		What research gaps exist within the literature?		
B. Keywords and databases searched				
Keywords		'promotions' AND ('optimisation' OR 'optimisation') AND 'retail'		
Databases		• Science Direct • Scopus • IEEE Explore • Web of Science		
C. Inclusion- and Exclusion Criteria				
		Step 1	**Step 2**	**Step 3**
Inclusion criteria		• Studies that contain the keywords within the metadata • Studies that were published between 2013 and 2022 • English studies	• Studies that contain the keywords within the metadata • Studies that were published between 2013 and 2022 • English studies	• Studies that contain the keywords within the metadata • Studies that were published between 2013 and 2022 • English studies • Studies that use mathematical modelling to find the optimal promotional price
Exclusion criteria		• Non-English studies • Studies published before 2013 and after 2022.	• Duplicate studies	• Studies that do not use mathematical modelling to find the optimal promotional price
Number of studies from each database identied during this step	**Science direct**	15	15	3
	Scopus	44	39	5
	IEEE Explore	2	2	0
	Web of Science	34	10	2

Table 2: Summaries of identified studies:

No.	Study title	Year	Summary	Authors()
1	Optimising decisions of fresh-product members in daily and bourse markets considering the quantity and quality deterioration: a waste-reduction approach.	2021	Product waste is common within the fresh agricultural product supply chain (FAPSC). This study proposes a coordinated strategy between role players within the FAPSC that optimises retail promotions by minimising waste. Retail price is expressed as a function of price elasticity, tax rates, the number of wasted products, the selling price of wasted products within secondary markets, the stocking factor, and the wholesale-, shortage inventory-, and surplus inventory costs. The problem is modelled as **a Stackelberg game** wherein the vendor is the leader, and the retailer is the follower. The optimal retail price is obtained using backward induction.	Dolat-Abadi [20]
2	Promotion Optimisation for Multiple Items in Supermarkets	2021	This study is the successor of *The Impact of Linear Optimization on Promotion Planning* by Cohen et al. [24]. This study's predecessor focuses on the promotion of a single fast-moving consumer goods (FMCG). This study aims to optimise retail promotions by developing **a nonlinear integer programming model** that specifies the prices of multiple FMCGs that will maximise profit given specific business rules. The study inherently includes cross-item effects. Again, various demand models may be incorporated, allowing the inclusion of additional retail variables.	Cohen et al. [4]
3	Simultaneous use of customer, product and inventory information in dynamic product promotion	2018	Retailers can strongly influence customer buying behaviour by employing real-time personalised promotions. This study optimises retail promotions by specifying the optimal mix and pricing of vendor items to include within real-time promotions. The optimal mix and pricing maximise retail profit, given the retailer's inventory levels and the customer's inherent preference towards a particular profit. The authors model the problem as **a mixed-integer nonlinear programming model.**	Mahar et al. [21]

No.	Study title	Year	Summary	Authors()
4	The Impact of Linear Optimization on Promotion Planning	2017	FMCGs sell relatively quickly within retail settings. This study aims to optimise retail promotions by developing **a nonlinear integer programming model** that specifies a single FMCG's price that will maximise profit given specific business rules. The model is modular, as various demand models may be incorporated. A suitable demand model allows retailers to add additional retail variables.	Cohen et al. [8]
5	A retail store SKU promotions optimisation model for category multi-period profit maximisation	2017	This study proposes **a nonlinear integer programming model** that optimises retail promotions at a stock-keeping-unit (SKU) level. The model's goal is to maximise promotional profit over a specific period. The authors show that the level of display and discount depth influence the profitability of retail promotions. As such, the decision variables of the model are whether and how to promote an item and discount depth.	Ma and Fildes [22]
6	Price promotion with reference price effects in the supply chain	2016	Trade promotions are offered by vendors to retailers, vendors offer consumer promotions to customers, and retail promotions are offered by retailers to customers. This study aims to find the discount depth that maximises retail profit, given the effects of trade, consumer, and vendor promotions within retail settings. **A Stackelberg competition** is developed wherein the vendor is the leader, and the retailer is the follower. The optimal discount depth is obtained using backward induction.	Lin [23]
7	Modelling of Product Sales Promotion and Price Discounting Strategy using Fuzzy Logic in a Retail Organization	2016	This study proposes a holistic strategy that maximises the profit obtained by retailers through promotions. **A nonlinear programming model** is developed that specifies the optimal order quantity of a retailer, given the effects of trade rebates. Finally, the authors deploy heuristic methods to determine the discount rate of a retailer to maximise profit.	Kumar et al. [24]

No.	Study title	Year	Summary	Authors()
8	Pricing and Ordering under Trade Promotion, Brand Competition and Demand Uncertainty	2016	Off-invoice-, scan-back-, and buy-back policies are common forms of vendor funding. Off-invoice policies are discounts vendors offer to retailers' orders in return for meeting purchasing targets. Scan-back policies are discounts vendors offer retailers in return for meeting sale targets. Buy-back policies allow retailers to resell unsold stock back to vendors. This study incorporates the effects of these policies within **a nonlinear programming model**. This model aims to find the product price that maximises retail profit from promotions.	Tsao [25]
9	Redesigning promotion strategy for e-commerce competitiveness through pricing and recommendation	2015	Electronic retailing (e-tailing) platforms often recommend products other than those listed to customers during promotions, as customers are more likely to purchase these when the listed item is discounted. This study proposes **a nonlinear programming model** that maximises overall e-tailer profit by specifying the optimal discount depth of the listed product and the mix of other products to recommend during promotions.	Jiang et al. [26]
10	Enhanced joint pricing and lot-sizing problem in a two-echelon supply chain with a logit demand function	2014	The frequency- and size of orders and the retail price significantly influence the combined profit of a vendor and a retailer. This study proposes **a nonlinear integer programming model** wherein these factors are decision variables. The model's objective is to maximise the combined profit of the two-echelon supply chain. The model allows retailers to set prices below cost. In doing so, the model optimises retail promotions.	Yaghin et al. [27]

3.1 Research question 1: How many studies aim to optimise retail promotions using mathematical modelling?

The review protocol identified ten studies published between 01 January 2013 and 6 November 2022 that aim to optimise promotions using mathematical modelling.

3.2 Research question 2: What optimisation approaches do the studies follow?

Table 3 lists the optimisation modelling- and solving approaches used within each identified study.

Table 3: Modelling approaches deployed within the identified studies

No.	Author(s)	Modelling approach	Solving approach
1	Dolat-Abadi [20]	Stackelberg competition	Backward induction
2	Cohen et al. [4]	Nonlinear programming model	Linearisation
3	Mahar et al. [21]	Nonlinear programming model	Metaheuristic
4	Cohen et al. [8]	Nonlinear programming model	Linearisation
5	Ma and Fildes [22]	Nonlinear programming model	Metaheuristic
6	Lin [23]	Stackelberg competition	Backward induction
7	Kumar et al. [24]	Nonlinear programming model	Heuristic
8	Tsao [25]	Nonlinear programming model	Heuristic
9	Jiang et al. [26]	Nonlinear programming model	Heuristic
10	Yaghin et al. [27]	Nonlinear programming model	Metaheuristic

The studies by Dolat-Abadi [20] and Lin [23] model the problem as a Stackelberg competition. Simaan and Cruz [28] describe a Stackelberg competition as an economic game wherein one player, the leader, decides first. In response, another player, the follower, makes their decision. The leader is aware of the follower's decision-making process and can influence it. The optimal strategies for Stackelberg competitions are commonly determined using backward induction. Backward induction involves evaluating each optimal decision from the final to the starting decision node. An action is eliminated if the node's alternatives dominate its terminal node [29]. Dolat-Abadi [20] and Lin [23] follow the backwards induction solving approach.

The remaining studies model the problem as nonlinear programming models, i.e., optimisation problems wherein the objective function or at least one of the constraints is nonlinear [11]. Nonlinear programming problems are generally NP-hard and, thus, difficult to solve [30]. Historically, a popular approach has been approximating a linear equivalent to the problem [31]. Linearisation allows the problems to be solved effectively using algorithms such as the Simplex-, Khachiyan's, Affine Scaling, and Karmakar's method [11]. Cohen et al. [8] and Cohen et al. [4] follow a linearisation approach to solve the problem.

Alternatively, heuristic and metaheuristic methods often provide sufficiently good solutions to nonlinear programs [32]. These methods do not necessarily provide exact solutions. However, heuristics can provide high-quality solutions in a reasonable amount of time by algorithmically exploring the accumulated search experience- and space [33]. Kumar et al. [24] deploy a heuristic based on the Fordyce-Webster Algorithm. Yaghin et al. [27] deploy a particle swarm metaheuristic. Tsao [25] develops a custom heuristic algorithm. Ma and Fildes

[22] deploy a genetic algorithm. Several open-source and commercial solvers are available for solving nonlinear programming problems using autoselected metaheuristic methods [34, 35]. In this regards, Mahar [21] deploys BARON and Jiang et al. [26] deploy the NMaximise routine included in Wolfram's Mathematica software.

3.3 Research question 3: How do these studies model retail demand?

To effectively assist retailers with promotion planning, mathematical models need some framework to forecast customer response to promotional activities. Table 4 summarises how each study accounts for retail demand, given the effects of promotions.

Table 4: Demand modelling techniques deployed within studies.

No.	Study	Modelling technique	Predictors within the demand model
1	Dolat-Abadi [20]	Random demand	N/A
2	Cohen et al. [4]	General nonlinear function	Item price, past prices of items, past prices of substitutes
3	Mahar et al. [21]	General nonlinear function	Discount depth, level of advertising, customers' valuation of an item
4	Cohen et al. [8]	General nonlinear function	Item price, past prices of item
5	Ma and Fildes [22]	Autoregressive distributed lag model	Discount depth, level of advertising, past sales, and whether a special occasion is taking place.
6	Lin [23]	Linear function	Item price
7	Kumar et al. [24]	Moving average model	Past sales
8	Tsao [25]	Linear model	Item price, customers' brand loyalty
9	Jiang et al. [26]	General nonlinear function	Item price, discount depth, customers' valuation of item and substitutes
10	Yaghin et al. [27]	Logistic regression model	Item price, price sensitivity of item, market size

The techniques that are deployed vary in complexity. The study by Dolat-Abadi [20] assumes that demand is random. The studies by Lin [23] and Tsao [25] deploy linear regression. More advanced statistical learning methods, such as the autoregressive distributed lag model developed by Ma and Fildes [22], are also used. The study conducted by Yaghin, et al. [27] uses a logistic regression model as the primary demand forecasting tool, while Mahar, et al. [21] include logistic regression predictions within a more advanced nonlinear function.

The label *general nonlinear function* is given to all miscellaneous modelling techniques. Jiang, et al. [26] and Mahar, et al. [21] use mathematical analysis to arrive at custom equations to express the probability of customers purchasing an item. Other studies that fall under this label exploit widely accepted retail equations. The studies conducted by Cohen, et al. [36] and Cohen, et al. [4] use the log-log relationship to reflect the relationship between sale price and demand. Kumar, et al. [24] use a moving average forecasting method to predict sales.

The demand models used within the literature also vary in the predictors included. The pie chart in Figure 1 indicates how often each predictor was included within the demand models.

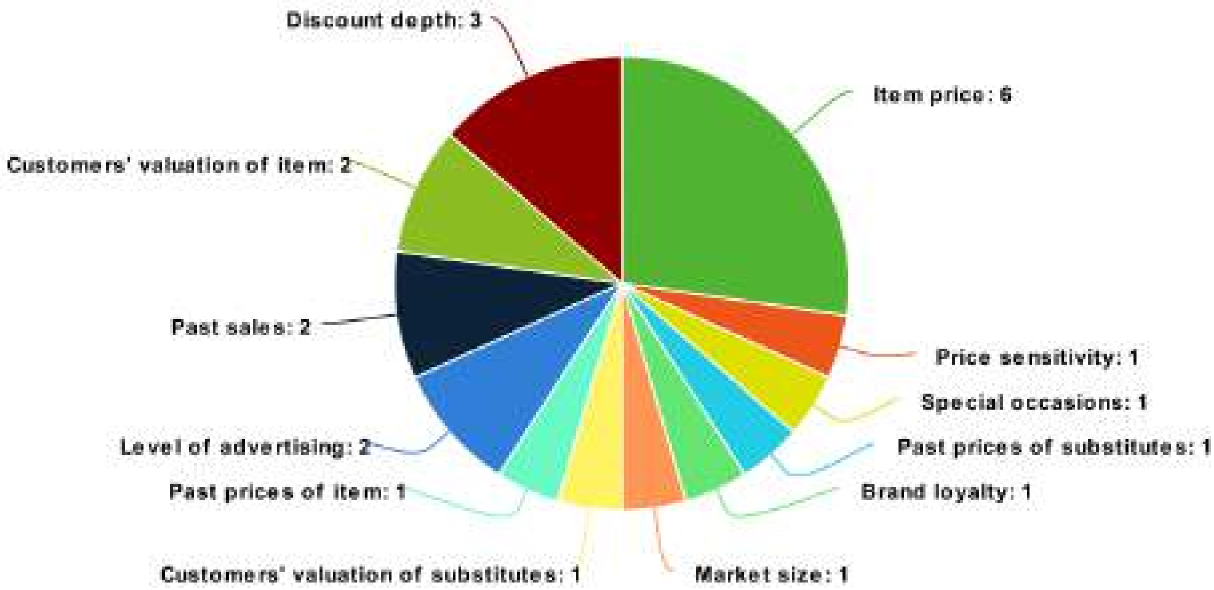

Figure 1: Pie chart of predictors within the demand model

Item price was the most common predictor, occurring in six out of ten studies. The reason for this inclusion is evident, given the strong relationship between item price and demand [32]. For the same reason, discount depth is the second most common predictor within the demand models, occurring in three out of ten studies. Other predictors occurring in multiple studies are the customers' valuation of an item, past sales, and the level of advertising. Seven out of the twelve predictors occur in only one study.

This diversity in demand modelling techniques and the predictors indicates that there is no universally applicable method to incorporate customer demand into mathematical models that assist retailers with promotion planning.

3.4 Research question 4: What common retail effects do these studies address?

Table 5 summarises the retail variables the models include, as identified in this paper's introduction. Own-promotional effects refer to the effect that its promotion has on its sales. Cross-promotional effects refer to the effect that the promotion of an item has on the sale of other items. Stockpiling effects refer to the effect that the promotion of an item has on its long-term sales. Vendor funding refers to additional revenue streams a vendor provides to a retailer in return for promoting their items.

Table 5: The occurrence of common retail effects within the studies

		Effects			
No.	**Authors(s)**	**Own-promotional**	**Cross-promotional**	**Stockpiling**	**Vendor funding**
1	Dolat-Abadi [20]	✓	×	×	×
2	Cohen et al. [4]	✓	✓	✓	×
3	Mahar et al. [21]	✓	✓	×	✓
4	Cohen et al. [8]	✓	×	✓	×
5	Ma and Fildes [22]	✓	✓	✓	×
6	Lin [23]	✓	×	×	✓
7	Kumar et al. [24]	✓	×	×	✓
8	Tsao [25]	✓	✓	×	✓
9	Jiang et al. [26]	✓	✓	×	×
10	Yaghin et al. [27]	✓	×	×	✓

To be included in this review, a mathematical model must determine the optimal promotional price at which to sell an item. All mathematical models under investigation, therefore, include the effects of own-promotion. Following this effect, cross-promotional- and vendor funding effects are most included, appearing in half of the identified studies. Only three studies include the effects of stockpiling. While the mathematical models each address some combination of these effects, no single model simultaneously addresses own-promotional, cross-promotional, stockpiling, and vendor funding effects.

3.5 Research question 5: What gaps exist within the literature?

Table 6 lists the limitations and future recommendations of each identified study. Most of the recommendations are study specific. Multiple authors, however, recognise the accuracy of the demand models as a shortcoming. This is the case for the studies by Yaghin, et al. [27], Ma and Fildes [22], Jiang, et al. [26], and Mahar, et al. [21].

Table 6: Future recommendations identified by study authors

No.	Author(s)	Self-identified research gaps
1	Dolat-Abadi [20]	The study can be expanded to include multiple vendors who compete with each other in terms of investment. Industry mechanisms such as payment delays and vendor funding effects could be included. Retailers may invest in fresh-keeping activities as well. The model can be expanded to include this variable.
2	Cohen et al. [4]	Not stated.
3	Mahar et al. [21]	The cost of changing the active promotion may be incorporated as a model parameter. The assumption that the customer only purchases a single product could be dropped. The demand model can be enhanced to include price sensitivity effects.
4	Cohen et al. [8]	The model should be validated by conducting a pilot expiring where the model is applied to a real-world retail setting.
5	Ma and Fildes [22]	The model can be expanded to include additional retailers. The effects of ordering- and stocking costs can be included. The demand model can function even in the presence of limited input data. Computational issues concerning the use of the genetic algorithm can be resolved.
6	Lin [23]	The retailer and vendor's joint pricing and promotion decisions may be explored. Promotion duration can be incorporated as a decision variable.
7	Kumar et al. [24]	The model may include multiple suppliers, retailers, and product categories. Additional parameters may be incorporated, such as back-orders and transportation costs. The computability of the model can be improved.
8	Tsao [25]	The model can be expanded to include brand and retail competitions. The effect of other forms of trade promotions can be investigated.
9	Jiang et al. [26]	The model can be enhanced to cater specifically to brick-and-mortar retailers. The model can be made to consider the impact of network congestion on profitability. Additionally, it can incorporate the influence of product quality on service duration. Moreover, there is room to enhance the demand model.
10	Yaghin et al. [27]	The model can include multiple demand classes and vendors. The model can incorporate stochastic elements. Other convexification and modelling strategies may be explored to improve the computability of the model.

Additionally, multiple authors recognise computability issues with nonlinear programming models, even when using heuristics and metaheuristics in their solving. This is the case for the studies by Yaghin, et al. [27], Ma and Fildes [22], and Kumar, et al. [24].

However, the central gap within the literature is apparent, considering that the effects of cross-promotional, stockpiling, and vendor funding are significant to profitability. The previous research question indicates that no mathematical model within the scope of this SLR simultaneously accounts for these effects.

With this said, depending on the mathematical model's objective, excluding some combination of the abovementioned effects may be appropriate. For example, the goal of the mathematical model by Dolat-Abadi [20] is to minimise fresh agricultural product waste. The effect stockpiling has on this goal may be insignificant. This study does not posit the ineffectuality of a mathematical model that disregards some of the effects. Instead, it advances the notion that to maximise promotional profit, the incorporation of all the effects is imperative.

4 FINDINGS AND CONCLUSIONS

Promotions can be highly beneficial to retailers; however, the contrary may also be true in some instances, as several adverse effects accompany them. This makes the planning of profitable promotions complex. In response, multiple mathematical models have been developed to assist retailers with promotion planning.

An SLR is conducted following an established methodology to identify these studies and to evaluate them in terms of the modelling approaches deployed and their limitations. In doing so, this paper provides a valuable contribution to research by providing a comprehensive summary of the existing mathematical models used in retail promotion planning.

The SLR indicates that ten studies have been published since 2013 that aim to optimise retail promotions. These studies exclusively model the promotion optimisation problem as either a Stackelberg competition or a nonlinear programming model. The Stackelberg competitions are solved using backward induction. The nonlinear programs are solved using heuristics and metaheuristics or linearised and solved using conventional methods. The demand modelling approaches deployed vary in complexity and the included predictors.

Multiple authors report, however, that their demand models' applicability limits the optimisation models' usefulness. Multiple authors also express difficulty in solving nonlinear programming models. Finally, none of the identified studies address the combination of variables significantly influencing retail promotion profitability.

5 FUTURE WORK

This study reveals a research gap where no model has been identified that simultaneously addresses cross-promotional, stockpiling, and vendor funding effects. In addition, solvability issues and shortcomings within the demand models deployed by multiple existing promotion optimisation models limit their usefulness.

This means that within the scope of this study and to the authors' best knowledge, no existing mathematical model can fully optimise promotions. It is recommended that future research focuses on the development of mathematical models that simultaneously includes the effects of cross-promotion, stockpiling and vendor funding. Concurrently future models must accurately account for retail demand whilst retaining solvability. Developing mathematical models that meet these requirements provides a challenging task for future researchers but is crucial for enhancing the promotion planning strategies of retailers.

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IMPACT OF ADMINISTRATIVE DELAYS ON THE OVERALL DOWNTIME IN LOCAL GOVERNMENT VEHICLE FLEETS IN SOUTH AFRICA

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ABSTRACT

Local Government Vehicle Fleets (LGVFs) are an essential component in the running of municipalities. Their asset portfolio is well over hundreds of millions to billions of Rand, making them critical assets in the running of municipalities. The purpose of this study is to assess the impact of administrative delays on the overall downtime experienced in LGVFs. The scope of downtime for this study is for activities related to services and repairs. A review of literature focused on the LGVFs usage as well as unpacking the business processes associated with the flow of work management activities. Potential areas where delays could be experienced were identified while the impact of downtime was also elucidated in terms of cost, fleet size and other metrics. The conclusion is that there is a need to equip policy makers with a framework that will balance statutory and policy compliance and running the LGVFs optimally.

Keywords: Vehicle Fleets, Downtime, Municipalities

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1 INTRODUCTION

Vehicle fleets in local governments are vital assets by which municipal services such as electricity, water and transportation are delivered. Various municipalities and cities in South Africa manage thousands of vehicles such as City of Cape Town (CoCT) which has an active fleet of approximately 7 000 vehicles [1] worth billions of Rand. This makes vehicle fleet assets a critical asset portfolio which must be managed optimally if maximum value is to be derived from them.

In the management of vehicle fleets, downtime can be divided into two categories: scheduled downtime, which includes planned services and repairs, and unscheduled downtime, resulting from unforeseen circumstances like breakdowns and accidents. Fleet downtime can be attributed to many factors and some experts in Local Government Vehicle Fleets (LGVFs) postulate that administration delays contribute a significant portion to downtime compared to the actual repair time [2]. However, no study has definitively determined the extent of this contribution. Other studies have shown that in fleets, unscheduled downtime can also be attributed to other extreme factors such as climate and natural conditions which human intervention can hardly control [3].

LGVFs play a crucial role in providing essential services to residents and employees of municipalities, including transportation, security and law enforcement, emergency services, water, electricity, and waste collection. These fleets serve various core functions such as refuse removal from residential areas and industrial sites, transporting people to their places of residence, work, or business, providing emergency services like fire engines, facilitating law enforcement activities, and enabling service delivery such as water and electricity projects, servicing, and repairs. Municipal environments often require specialized vehicles to perform these functions [4].

The availability of LGVFs is crucial for municipalities and cities. When these assets experience downtime, there can be significant consequences. Residents may struggle with commuting and waste accumulation and interruptions in essential services like electricity, water, and sanitation can raise security and health risks. Delayed emergency responses can lead to property damage and loss of life, while insufficient law enforcement visibility may lead to increased crime. Idleness among municipal employees and a backlog of service requests can occur without access to vehicles. Fleet managers may face pressure to acquire additional vehicles to compensate for downtime.

Managing the downtime of LGVFs and the repairs and maintenance (R&M) process is thus necessary to ensure reduction in downtime related costs and optimising vehicle fleet size. Some municipal managers have argued that in trying to mitigate effects of downtime, municipalities end up being inefficient by mitigating effects of downtime through purchase of extra vehicles [2]. For example, for a fleet of 7 000 vehicles, a fleet operational availability of 75% translates to an average of 1 750 vehicles off the road every day, which would be costly to the municipality and the residents.

The importance of functionally available fleets cannot be overemphasized. Therefore, this study puts focus on reviewing elements that affect LGVFs downtime and ways in which this impact can be reduced using available literature. This research will contribute value adding literature for analysing downtime categories. Most importantly, it will unpack administrative bottlenecks in procuring R&M services for LGFVs and review all elements that exacerbate downtime.

2 DOWNTIME

Downtime is the state in which an asset is unavailable to perform any work. This can be through planned downtime for scheduled services or unplanned downtime in which an unexpected undesirable condition or breakdown forces a maintenance intervention to be executed.

2.1 Downtime in Vehicle Fleets

In vehicle fleet management, downtime can be categorised into scheduled downtime for planned services and repairs, as well as unscheduled downtime due to unforeseen circumstances. Fleet downtime can be attributed to many factors and some who have experience in LGVFs postulate that administrative delays contribute a significant portion [2], however there is no study that clearly determines to what extent this is. Another study has shown that in fleets, unscheduled downtime can also be attributed to other factors such as climate and natural conditions which human intervention can hardly control [3].

2.2 Factors affecting Downtime

There are several challenges that contribute to prolonged downtime in vehicle fleets [3], [5], [6].Some of the issues are listed below:

2.2.1 Vehicle age – generally older vehicles experience prolonged downtime periods and fail more frequent than newer vehicles.

2.2.2 Vehicle usage such as running hours or mileage – high mileage vehicles tend to experience more downtime than those that have low usage because of the frequency with which original equipment manufacturer (OEM)'s usage-based maintenance requirements are reached.

2.2.3 Operating conditions such as weather and climate – in environments that experience harsh conditions such as extreme cold, heat or humidity, some vehicles become inoperable.

2.2.4 Administrative delays in authorisation of repair or servicing work – downtime can be prolonged due to compliance to policy or statutory requirements. Some of these requirements make it mandatory to advertise for services to be rendered for a certain minimum period.

2.2.5 Outsourced service providers' inefficient processes – service providers can prolong downtime due to their inefficient process such as delays in purchasing spare parts to execute the repair work.

2.2.6 Lack of real time status updates and feedback from service providers – LGVFs can experience prolonged downtime because of poor communication. A service may have been completed but if local government officials are not notified on time, the downtime will be extended.

2.2.7 Information not readily available when required such as vehicle model and warranty information can cause delays in getting quotations and procurement of parts.

3 WORK MANAGEMENT PROCESS

Maintenance Work Management is the process of properly managing the maintenance work using work orders from planning to receiving the feedback of completed work.

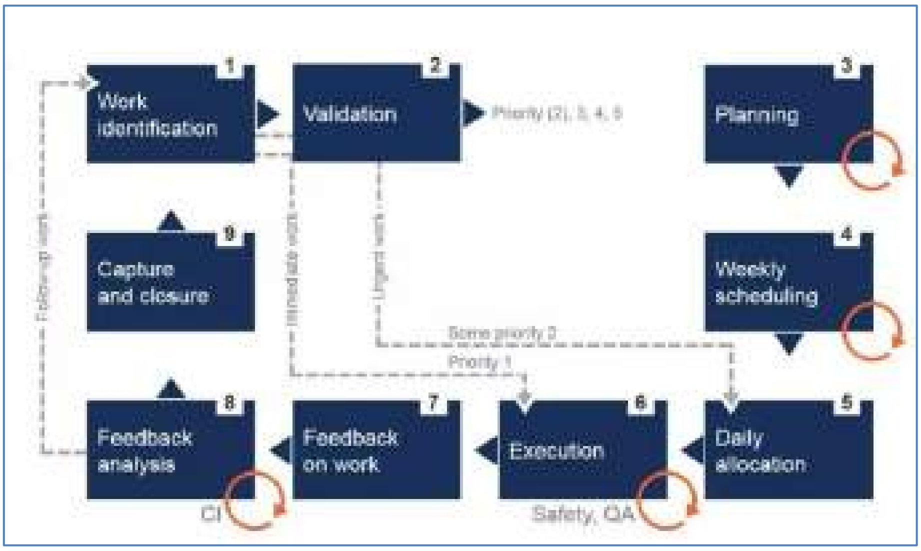

Figure 1: Work Management Process: Adopted from Pragma [8]

Pragma, a leader in the Physical Asset Management (PAM) field, recommends a work management process detailed in Figure 1. When one applies this process to a fleet environment, downtime can be prolonged in certain steps as discussed below.

3.1 Work Identification[1] – LGVFs are complex in the sense that work can only be identified after diagnostic tests are done to find out what work will be required. However, a high-level work identification process is imperative to determine which service providers should be used for different requirements such as engine, body, tyres, auto-electrical system, and ancillary equipment such as hydraulic system.

3.2 Validation[2] – for the work process to be initiated there must be a work order from a requester. This work is then validated by a designated official to determine if the work is indeed what is required.

3.3 Planning[3] – this process is important to determine which (trade) does the work, when the work is to be done, spare parts required, tools required and estimated cost of the work. In LGVFs this process is where downtime may be prolonged as certain policy steps and compliance to statutory and legal requirements must be adhered to. For example, according to City of Cape Town's SCM policy section 299 [12], for any transaction value between R10 000 and R200 000, a minimum of 3 quotations must be supplied. Section 302 of the same policy also demands that quotations which are likely to be above R30 000 must be advertised for at least seven days. These processes inherently prolong downtime periods, and thus it is important to investigate to what extent they are affecting LGVFs availability.

3.4 Scheduling[4] - In vehicle fleets, maintenance scheduling is the process of organising when a vehicle is to be sent for a maintenance intervention. This works hand in hand with the planning function which determines who will perform the maintenance intervention, what parts they will require, the estimated costs and durations [11]. The challenge which comes with this is that different components of the vehicle such as tyres and brake pads deteriorate at different intervals [17].It is thus important to find an optimum period that ensures that all components are checked and repaired in order to reduce downtime.

R&M process for LGVFs involves administrative checks and controls to ensure that the repairs are done within the statutory frameworks. It can take up to weeks for authorisation of minor repairs or purchase of spares for major repairs and more delays are incurred in the process due to the additional administrative processes that must be followed [2]. Extra levels of authorisations are required for associated or additional costs to conform to the Municipal Finance Management Act (MFMA) which all municipalities must adhere to [7]. A study showed that more than 80% of downtime of vehicles undergoing a service or repair, is not related to the actual time spent servicing, or repairing a fleet vehicle [5] and it is imperative to get an accurate perspective for LGVFs. LGVFs also have their own workshops for internal repairs of vehicles. These facilities are sometimes not viable because of the mix of vehicle types and or low volumes of vehicles brought in for repairs [2]. In conclusion the work management process has elements that are prone to extend LGVFs downtime if no proper controls are in place,

4 PROCUREMENT AND ASSET MANAGEMENT

The Municipal Finance Management Act 56 of 2003 (MFMA) "intends to secure sound and sustainable management of the financial affairs of the municipalities and other institutions in the local sphere of government…" [7]. The Act sets out a framework of how financial processes are managed in the local government environment including managing the R&M of LGVFs. The procurement process can be summarised into 8 stages of which LGVFs are aligned to for procuring services for R&M. In between these processes, potential delays exist especially when managing fleet sizes of up to thousands of vehicles.

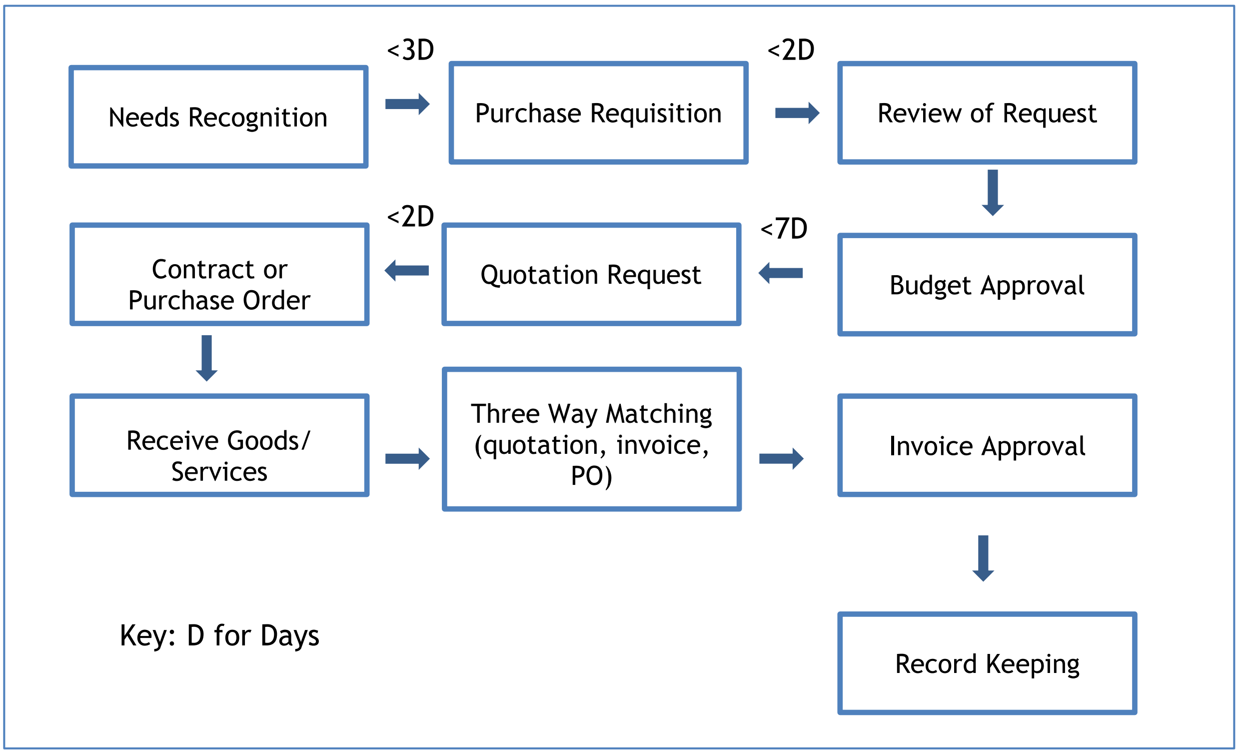

Figure 2: Procurement Process: Adopted from Kissflow Procurement Cloud [13]

The procurement process has different role players that are involved from initiating a maintenance activity to execution as shown above. There are certain processes that must be completed within benchmarks set in days as shown in Figure 2, however enforcement of such benchmarks can be challenging for municipal environments processing thousands of work requests per month. Depending on the estimate cost of a work request, budget approval and purchase order issuance can be prolonged to conform to certain policy guidelines.

4.1 Unauthorised, irregular, or fruitless and wasteful expenditure

Section 32 of the MFMA puts liability on municipal officials for any subsequent “Unauthorised, irregular or fruitless and wasteful expenditure” [7]. This liability results in checks and balances being implemented within the local government to ensure all expenditure is duly authorised and analysed to be not fruitless or wasteful.

Fleet assets are not spared in that whenever services are needed for R&M of the vehicles, the same process applies regardless of urgency. In effect a repair for R3 000 will undergo the same administrative processes and authorisation as that for R50 000.

4.2 Goods and services procurement

Local governments have policies that should align to the Section 111 of the MFMA [7]. These policies govern the processes of tendering, quotations, auctions etc. which in this study, affects the execution of repairs and maintenance work on Fleet Assets [12].

4.3 Supply chain management (SCM) policies

To align with the MFMA legislation councils have adopted SCM policies for the implementation of procurement processes [7]. Written price quotations are required for transaction values between R2000 and R10 000 [12]. For transactions between R10 000 and R200 000 formal written price quotations are required and for transaction values that are more than R200 000 competitive bidding processes are required [12]. All these processes add layers of administrative processes that can potentially cause delays for large fleets, as hundreds of quotations and requisitions are potentially handled daily.

4.4 General conditions of contract

All the SCM policies have a section on the general conditions that a bidder must meet to be considered to offer any services to municipalities. The following are some of the critical things mentioned by the policy [12].

- Tax reference number
- VAT registration number
- Valid tax clearance certificate

If a service provider is the sole supplier for a particular service and their tax affairs are not in order, this can result in unnecessary downtime being incurred. These requirements are checked every time work is allocated to a particular contractor.

5 LIFECYCLE VALUE REALISATION

Lifecycle value realisation (LVR) has to do with different methodologies that are utilised in making sure that the “best total value” is released throughout the lifecycle of an asset [14]. This begins from the acquisition of the asset, utilisation of the asset, maintenance etc. in realisation of the objectives of an organisation [14]. The study aims to ensure that value is realised from LGVFs assets during their lifecycle by cutting down maintenance cost in terms of the downtime period [11].

5.1 Asset management decision making

The importance of asset management decision making is to maximise the value realised from an asset during its life [15]. This study focused on the challenges faced during the operation and maintenance of an asset and the associated decision making. The way an asset is operated and maintained affects the costs associated with that asset [15] and achievement of an organisation’s objectives. Therefore, this study was well within the scope of the Group 2 of the 39 GFMAM subjects.

5.2 Benchmarks

There seems to be NO industry standards on availability levels for fleet assets, however an online article pegged a benchmark of 95% [16]. Several issues affect attainment of high levels of fleet availability including vehicle types mix, spare part management, vehicle age and condition and other factors. Some of the benchmarks related to fleets include schedule attainment for planned scheduled tasks, tactical work (planned) vs non-tactical work (unplanned) ratio, technician productivity and other metrics [18]. These benchmarks help gauge the performance of the fleet and the management practices.

6 COSTS ASSOCIATED WITH DOWNTIME

LGVFs are diverse fleets and certain vehicle types are more challenging to manage than others. These include vehicles with hydraulic systems mounted on them such as aerial platforms, cranes and waste compactors. When these vehicles are unavailable, there are direct and indirect costs associated with their downtime [17][5] such as;

- towing fees in the event of breakdowns,
- rental of substitute vehicles,
- overtime for technicians for cases of internal workshops,
- service delivery compromised
- If short term rentals are not available, work crews will be underutilised
- Inflating fleet size to compensate for downtime
- Insurance, licensing and R&M costs.

It is important to explore the contribution of the workmanship of the service providers to the overall downtime of the vehicles. If the workmanship of the repair work or servicing of the vehicles is poor, then it will lead to more frequent breakdowns and hence an increase in downtime.

6.1 Total downtime cost

The impact of downtime can be quantified in terms of downtime cost which will be discussed in this section. For one to truly be able to determine this cost, certain information must be available and accurate. Tabikh carried out a survey on manufacturing companies in Sweden and the conclusion was that 87% of the surveyed companies did not have a model of quantifying the downtime cost [9]. Fitchett emphasizes the importance of recording the actual times of a downtime occurrence [10]. This is done through the work order management process, and often the “started on” and “completed on” dates and times must be populated to give the accurate downtime period. However, there is research that shows that most organisations do not fully utilise their work order systems or enterprise resource planning (ERP) systems with the procedures being by-passed sometimes [10]. To accurately track downtime, it is important to put in place and follow procedures to ensure the ERP systems have adequate information. When this is done, downtime can be accurately tracked with the end goal being to reduce it.

A lot of methods utilised for reporting, describe downtime as the period when a maintenance intervention take place [10]. However, this is not the true reflection of the downtime period; the downtime starts from when the failure occurs and the asset cannot be utilised. Applying this to LGVFS, downtime is from when a vehicle is unable to function as desired rather than when it is taken for service or repair, or dropped at a service provider’s premises. Due to delays of procuring parts and or getting authorisations from delegated local government officials, “started on” date of the maintenance intervention is not necessarily the date the vehicle is brought in for maintenance intervention or when the vehicle became inoperable.

Depending on the industry, a downtime cost is calculated based on certain criterion such as production cost, amount of scrap due to the downtime, cost of reduced production and other measures [10]. In LGVFS the downtime cost can be best calculated by the following factors

6.1.1 Hiring costs of vehicle in the same class: For continuity of business the department may be forced to hire another vehicle of the same class. This extra cost then becomes part of the downtime cost, and as the downtime is prolonged, the greater this cost becomes.

6.1.2 Unutilised Labour: In the event of no alternative hiring arrangements available, it can be calculated in terms of cost of labour that becomes idle for that downtime duration. For example, a vehicle utilised by two people and is unavailable for 8 hours; one can quantify downtime cost in terms of 16 labour hours multiplied by the labour rate of the corresponding employees who become idle.

6.1.3 Lost Revenue: If a particular vehicle is used for economic activity that directly brings income to the municipality such as My-Citi buses which transport personnel every day, the downtime cost can be quantified in terms of opportunity cost of potential revenue. For example, if the bus transports on average 30 people per hour and is down for 10 days, the cost can be estimated by multiplying these variables by the cost per trip minus the running costs.

6.1.4 Overtime: Other LGVFs vehicles are used for essential services that must be provided regardless of status of the availability of vehicles. For water and sanitation services such as solid waste management, refuse must still be collected even when fleets are facing challenges. In such circumstances overtime is accrued to cater for delays caused by downtime and this can then be categorised as part of downtime cost.

6.1.5 Oversized fleet size: The greatest downtime cost is manifested on the fleet size for fleets experiencing high downtime percentages. To mitigate effects of downtime, the fleet is oversized to compensate for inefficiencies. For example, a fleet of 1 000 vehicles operating at 60% availability without any need for outsourcing may be said to be oversized. If an availability target of 85% is achieved this can result in fleet size being optimised to for example 850 rendering the other 150 of no use. One can argue in this case the downtime cost to be the replacement costs of the 150 ‘extra’ vehicles which can approximate more than R200 million for specialised vehicles.

The intent of knowing and quantifying downtime costs is to mitigate its effects through reduction of downtime. Significant savings can be accrued from knowing all factors contributing to downtime and dealing with them decisively. Due to interventions that were instituted at one manufacturing facility, savings of 10 minutes per day could be realised which translates to up to 50 hours a year and a cost of more than R5,4 million [9]. Applying the same principles to LGVFs can result in significant savings to local governments through reduced downtime, optimising fleets size and deferring capital expenditure.

7 METHODOLOGY

In the literature review, four major topics were covered which are downtime, work management, procurement process and the downtime costs. An integrative literature review method was used with the aim of assessing the literature on the topic of downtime, specifically in LGVFs [19].

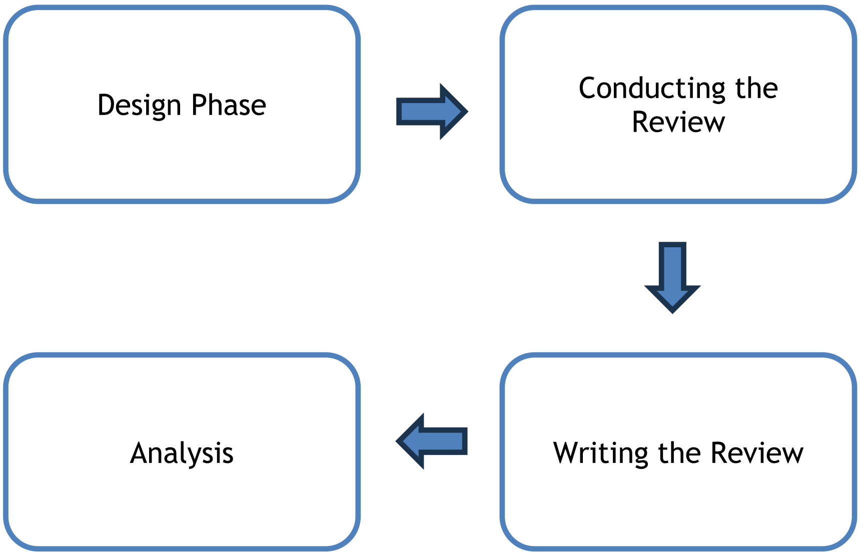

Figure 3: Integrative Review Process

The aim of the study was to gain insights into what constitutes downtime in LGVFs and how the environment they operate in, affect the downtime they experience. The approach was to review literature on the major topics as stated and those were the terms used in searching for articles. For downtime, a different variation of unavailability was used as well as searching for articles related to availability. Other search terms that were used are downtime cost, cost of downtime, vehicle fleets, procurement process and fleets.

More than 100 papers were reviewed on two search engines, google scholar and sun scholar which gave access to different journal and conference publications. However less than 20 articles were used as there is limited information in this research area. It must be noted that outside this review, a case study will be conducted on one of the major municipalities in South Africa to assess quantitatively the impact of administrative delays on the downtime experienced in their LGVFs and to quantify the downtime costs associated.

8 DISCUSSION

After a comprehensive review of literature relating to downtime, the conclusion is to a large extent, administrative processes prolong the downtime experienced in LGVF, to a degree that will be determined in a case study. Webb [2] an experienced manager in the local government industry has claimed that in fact, the portion of downtime related to administrative processes is greater than 50%, however this was not backed by any data but mere experience. In as much as this may be true it is important that a scientific method is followed to make this claim.

However, from the review of the MFMA legislation and certain supply chain policies of some municipalities, there are inherent procedural delays that cause downtime to be exacerbated. If the policy states that an advertisement requesting for quotations should be seven days, then the LGVFs assets will have to stand for that period, thereby increasing downtime. In such cases downtime will tend to increase, however this must also be backed up by scientific data to verify what percentage of work request get advertised for such long periods and what impact it has on the downtime.

The work management process must also be streamlined to ensure that planning and execution is optimised thereby reducing downtime. Downtime is influenced by the planning process with delays or inefficient planning having a negative impact on the availability of the LGVFs assets. A case study will give insights into how efficient the planning process is in LGVFs and how other role players responsible for administrative processes are effectively performing their functions.

To make a case to policy makers to adjust policy or legislation, it was important that downtime cost be expanded on. The literature provided different ways in which downtime costs can be quantified in relation to hiring cost, unutilised labour, bloated fleet size and other costs. This is imperative to make a comparative analysis of average downtime cost incurred against the thresholds set out in policies. For example, incurring a downtime cost of R18 000 for an approval of R10 000 is not economical and hence a case can be made either to adjust advertising periods or increase thresholds that require prolonged advertising periods, to reduce the downtime incurred.

9 CONCLUSION

Review of literature has established that there are administrative processes that have an influence in the downtime that is experienced in LGVFs. The MFMA set up a legislative framework that must be adhered to in procuring goods and services while the SCM policies also set out the process to be followed in this regard. As discussed, it is to a large extent inherent in the process that delays will take place to an extent which will be investigated in a case study. The policies that are enforced are meant to ensure that municipal resources are not wasted, however the hidden costs associated with downtime do not seem to have been considered in coming up with policies, which could result in more costs being incurred due to downtime, than what is intended to be saved.

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A CONCEPTUAL FRAMEWORK FOR THE IMPLEMENTATION OF QUALITY MANAGEMENT PRACTICES FOR SUSTAINABLE WHEAT FLOUR MILLING

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ABSTRACT

Goal-12 of the 17-sustainable development goals is focused on responsible consumption and production of products and services, and its targets include reducing waste generation through prevention, sustainable management and efficient use of natural resources. This study aims to explore the impact of quality management practices on sustainable wheat-flour milling. A quantitative research approach was collected through a self-distributed and online questionnaire. QMPs, such as 6-sigma practices, 5S practices, quality management system implementation and process management, were found to be affected by factors, such as organisational culture, workforce management and leadership support and commitment thereby affecting product quality and financial sustainability of the organisation. The results of the study indicate that organisational culture, workforce management and leadership support and commitment in the wheat-flour milling organisation are indeed factors that management should consider when QMPs are being considered.

Keywords: Total quality management, organisational performance, customer satisfaction, customer focus, continuous improvement

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1. INTRODUCTION

The heart of the matter is that the sustainability of all organisations depends on their ability to deliver high quality products to meet and exceed customer expectations. Therefore, organisations adopt strategies such as quality management to achieve that. The Wheat-Milling industry contributes greatly to the global economy and thus QMPs are of high importance in the wheat milling industry. The focus of this study is to examine the impact of QMPs on the sustainability of wheat-flour milling business. This paper will lay down the background of the study, research problem, research questions, research objectives, population and sample framework, data collection and analysis, as well as the ethical considerations in the study. This study is important, as it exposes the factors that affect QMPs and more importantly identifies the most significant quality management practice that influences rework. Lastly, it provides recommendations on how to improve QMPs.

2. BACKGROUND TO THE STUDY

One of the major global bottlenecks to sustainability in the manufacturing industry is product waste that requires reworking [1]. Most manufacturing organisations throw away non-conforming products to avoid the rework process, as rework costs are high [1]. This is a global challenge, as waste not only has a great impact on the environment but also on the economic and social aspects of the triple-bottom-line. In the South African wheat-milling industry, most of the waste goes back to rework and very small quantities of this waste go to animal feed. Even though wheat flour can be reworked, the rework costs are high. There is a growing engrossment in the flour milling industry because of its great impact on global economic changes, as well as its great role in boosting the South African economy. Moreover, South African wheat-flour milling organisations have opted to utilise quality management programme to strengthen their competitive advantage so as to overcome unexpected business difficulties and threats that may arise. Nevertheless, the execution of quality management for most organisations is lower than the expected level, and this has a great negative impact on the sustainability of organisations [2].

3. RESEARCH PROBLEM

The research organisation is faced with problems of high non-conformances and defects due to poor quality products, contamination and infestation. Defects can result in severe loss in terms of costs, reputation or project failure. [3] agree with [2] by saying that defects harm delivery times, costs and quality of products and by deleting these wastes, organisations in the manufacturing industry can increase their profits. However, [4] believe that defects not only impact costs but also production throughput. Higher defects lower manufacturing yields and the quality of products and lead to reliability problems. The failure of organisations to get to the root causes of these defects results in high costs for rework [5].

3.1 Problem statement

QMPs are an essential part of any organisation. High rework volumes due to defects impacts organisational financials and sustainability. The triple bottom-line aspects of sustainability cannot be achieved without successful implementation of these practices. The organisation has been experiencing high rates of rework and losses leading to poor financial results. Therefore, which QMPs are most relevant in the wheat flour milling organisation.

3.2 Research questions

- What are the factors that influence QMPs in the wheat-flour milling organisation?
- What is the most significant quality management practice that influences rework at the wheat-flour organisation?
- Which recommendations can be provided to improve QMPs at the wheat-flour milling organisation?

3.3 Hypotheses developed for the study.

The following hypotheses have been developed for this study:

Table 1: research questions related to hypotheses.

Research question	Hypothesis
What are the factors that influence QMPs in the wheat-flour milling organisation?	• H_1 QMPs have a direct impact on organisational performance.
What are the factors that influence QMPs in the wheat-flour milling organisation?	• H_2 QMPs have an impact on product quality.
What is the most significant quality management practice that influences rework at the wheat-flour organisation?	• H_3 Leadership commitment and support have an impact on the implementation of QMPs .
What is the most significant quality management practice that influences rework at the wheat-flour organisation?	• H_4 Organisational culture has an impact on QM practices.
What is the most significant quality management practice that influences rework at the wheat-flour organisation?	• H_5 QMPs have an impact on business sustainability.

4. LITERATURE REVIEW

4.1 Introduction

Despite several publications evidenced by [6,7,8,9,10] the correlation between QMPs and organisational performance in the manufacturing industry is well researched, however there is very little research on the impact of waste on business sustainability [3,4,5]. Not only does the milling industry contributes largely to the South African economy but also globally. Goal 12 of the 17 sustainable development goals to transform the world [5] is focused on responsible consumption and production, and its targets include substantially reducing waste generation through prevention, sustainable management and efficient use of natural resources [11]. Product-rework involves the use of energy and water. Considering water scarcity in South Africa and the fact that wheat-milling organisations, including the organisation under study, do not use renewable energy sources but rely on non-renewable energy sources, the impact of product waste on business sustainability should be investigated. The first part of this study will show the literature that exists on QMPs and the relationships that have been studied. A conceptual framework will then be developed to reflect the relationship between QMPs, product-waste that results in reworks and business sustainability. Quality management as an essential routine activity that is there to prevent defects that have an impact on customers and plays an important role in improving operations and believe that it is the main driver for improvement [12]. QMPs are the crucial and integral activities that organisations practice to oversee and control quality of products. This results in enhanced quality performance and puts the organisation at competitive advantage [13]. QMPs is defined as continuous improvement tools, techniques, and strategies for quality improvement, typically driven by the need to satisfy customers, listing practices such as management Total Quality Monitoring (TQM), statistical techniques of quality, quality assurance, education and training, senior management support, employee involvement, customer orientation and quality systems [14]. The implementation and importance of the full participation of all members of the organisation, including senior management, who help ensure that practices are implemented effectively in various aspects of products, processes and services. Quality management can only be fully implemented with management leadership that can share the quality values with all members of the organisation and that enables employees to carry out the physical and mental activities of the organisation [15].

4.2 Quality management supporting standards and quality management strategies.

4.2.1 ISO9001

One of the systems in place to support the implementation of quality management is ISO 9001:2015, an internationally recognised standard for quality management systems that has two objectives, namely reliability and flexibility. According to [16] , it consists of approaches that enable managers' leadership at all levels of the organisation, reinforced integration of organisational business and other management systems, consideration of all stakeholders and risk-based thinking. Among its benefits are organisational and operational improvements, better brand image, improved customer relationships, better quality and customer satisfaction.

4.2.2 Six Sigma practises

Six sigma as a business strategy and science combining statistical and managerial methods aimed at continuously improving processes by reducing manufacturing costs, which results in better customer satisfaction [17]. Adoption of six sigma practices for quality improvement is focused on reducing variations in the process, resulting in profitability, sales growth and reduced indirect costs [2]. This is achieved through applying sophisticated root cause techniques to be able to control and explore problems [18].

4.2.3 5S Practices

Sustained customer satisfaction and organisational competitiveness could be achieved through lean manufacturing which continually improves processes through cost optimisation, safety, enhanced productivity through waste reduction and full use of resources, thereby improving product quality [19]. One of the building blocks of lean manufacturing is the Japanese philosophy, 5S, which emphasises cleanliness, orderliness and self-discipline. This philosophy advocates the values of trust in the organisation, self-restraint, team-working and organisational commitment. The framework is based on 5 pillars in the Japanese acronym for Seri (organise), Setion (neatness), Sesio (cleaning), Seiketsu (standardisation) and Shitsuke (discipline). The 5 steps of 5S are sort, set, shine, standardise and sustain. When integrated with safety, the philosophy becomes 6S. [19] also state that when 5S is integrated with other quality management initiatives, such as ISO 9001, it helps accrue higher productivity and higher product quality.

4.3 Factors affecting quality management adoption.

Quality management is as an approach or an essential routine activity that is there to prevent defects that have an impact on customers and plays an important role in improving operations [12]. Quality management is also defined as an approach that realises organisational objectives through support from top management, customer relationship, supplier relationship, employee management, product design and process management [2]. Information technology, organisational size, the extent of market competition, product diversity, leadership competencies, organisational culture, manufacturing strategy and organisational structure have been identified and examined in literature as factors that are associated with the adoption of quality management [13].

4.4 Leadership in quality management

Leadership can be defined as “personality characteristics that influence others to pursue the organisation’s goals by attending to their customer’s needs and expectations” [20]. Leadership as one that provides a good work environment for empowerment, innovation and improvement and is always striving to improve performance and communication among project parties [21].

According to [20], not only is leadership fundamental in implementing quality management systems but also in developing an effective organisational environment that involves all employees to pursue quality goals. Leaders have a responsibility to create a connection of trust with employees using effective communication to lead in order to achieve the goals of the organisation while possessing self-confidence and firmly believing in their vision [23]. This is achieved through openness, fairness and honesty to staff and encouraging them to be independent in their decision making [23]. [24] support this by also saying that managers and leaders should possess independence, trustfulness and fairness. This argument is supported by [25] report which promotes ethical and effective leadership and encourages qualities, such as integrity, competence, responsibility, accountability, fairness and transparency.

4.5 Organisational culture

Organisational culture as mutual motives, values, beliefs, identities and interpretations or meanings of significant events that arise from common experiences of members of collectives that are passed down from generation to generation [13]. In a study carried out to investigate the impact of organisational culture on QMPs, a list of reasons for the pattern of failure for successful execution of QMPs as partial deployment and a lack of understanding of organisational culture were presented [26]. The organisational culture of quality begins with a leadership that understands and believes in the implication of systems visions and knows that it is necessary to serve the customer to be successful.

4.6 Relationship between quality management and organisational culture

An existing relationship between organisational culture and the adoption of TQM (one of the quality managements practices) was pointed out by [13]. Teamwork and collaboration, risk taking and open communication, continuous improvement, customer focus, partnership with suppliers, quality monitoring and evaluation. QMPs can contribute to and strengthen the generation of a culture that promotes change and innovation with its teamwork practices that allow employees greater autonomy and power of decision [15]. Organisational culture has been considered as an essential element in the successful implementation of quality improvement programs [27].

4.7 Sustainability

Sustainability is a concept that consists of three perspectives that form the three bottom-line, that is, social, environmental and economic perspectives. There needs to be a balance of the three components, as harmony and integration of these will ensure that sustainability goals are established in an organisation [28]. With a successful implementation of QMPs, business' sustainability is attainable. Tight competition, lack of resources, more informed and demanding consumers, continuous technological innovations, climate change and stakeholders' pressure are challenges that are faced by management to ensure business sustainability. It is essential to integrate sustainability at different management levels, such as strategic and operational levels, considering stakeholders' current and future needs [28]. Sustainable manufacturing is the manufacturing of products with a minimum negative impact on the environment, with conservation of natural resources with economic viability maintaining the safety of employees, community and consumers [2]. Goal 12 of the Sustainable Development Goals [3] is to ensure sustainable consumption and production patterns. This is achieved through making fundamental changes in the way societies produce and consume goods and services [29]. Unsustainable patterns of consumption and production are the root cause of the triple planetary crises, that is, climate change, biodiversity loss and pollution [30]. Rework requires the use of water and electricity. Generally, South Africa is faced with the challenge of water scarcity and power outages. The organisation under study is affected by both these factors and does not use electricity from renewable sources. When there is load-shedding, the mill stands. For the organisation to be able to contribute to Goal 12 of sustainable consumption and production, it means that the mill must use resources responsibly to avoid defects, both those that lead to rework and those that will end up in landfills.

4.8 Integration of sustainability into QMPs

According to [20], "The integration of sustainability into QMS has been defended as a path to the improvement of the organisation's performance and, therefore, can increase its competitive advantage by accomplishing its economic, social and environmental goals". Sustainability goals can be achieved by the implementation of quality management systems, which is a more co-ordinated management process and can meet all stakeholders' needs and expectations [20]. In a study by [31] that aimed to unfold the impact of supply chain QMPs on sustainability performance, the findings were that customer focus has the greatest impact on sustainability performance, with 100% relative importance, followed by quality leadership (75%), information sharing (61.5%) and supplier focus (57.30%).

In a study by [32] that attempted to identify an adequate model that can improve financial performance, the findings were that quality management can improve financial performance. One of the quality management goals is to attain higher profits, and this is achieved through improved QMPs, enhancing process efficiency and cost reduction [28]. This clearly shows a relationship between QMPs and the economic aspect of the triple bottom-line. The results of a quality paper investigating sustainability through QM practices in the food and beverage industry revealed that effective QM implementation has a positive and significant effect on sustainability, and a framework Figure 1 was developed [33]. The conceptual framework was derived from the literature and is represented through the various constructs in Figure 1.

4.6 Conceptual framework

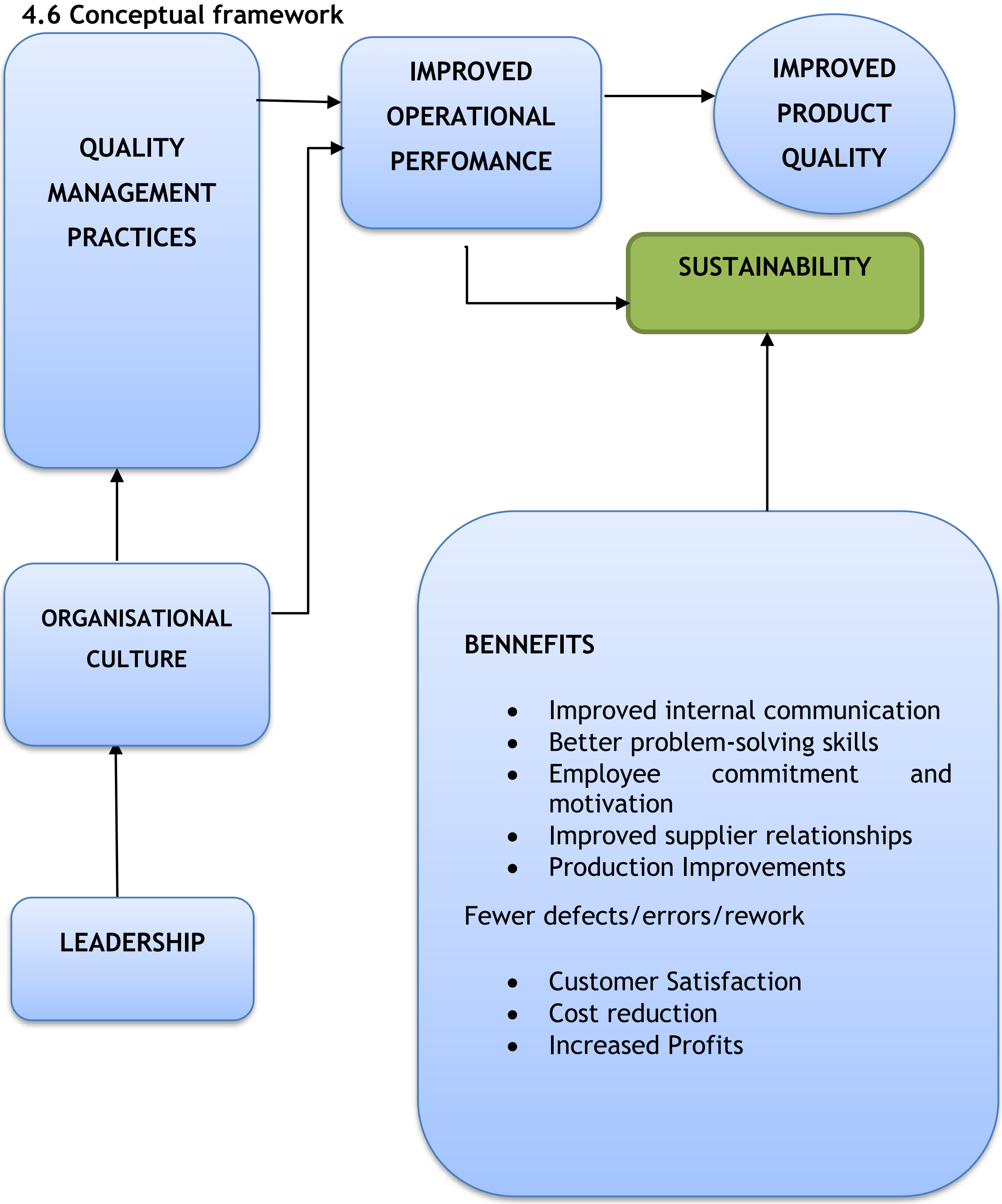

Figure 1: A conceptual framework drawn from literature.

5. RESEARCH METHOD

The research paradigm of this study is explained using the research onion adopted from [39]. The researcher adopted the positivism philosophy, which largely mirrors the philosophical stance of a natural scientist [39]. A deductive approach was taken where the research began on existing theory, hypotheses were developed, and data were collected to confirm or reject a hypothesis. The objective was to test a theory with different groups and contexts to help confirm the theory.

A survey strategy was used to collect data. The timeframe of this study was a cross-section; it involved the collection of data at a specific point in time [39]. Unlike the longitudinal approach, where data are collected repeatedly over a long period, data collection for this study was short-term. This study was based on non-experimental research designs, which are termed as descriptive and correlational.

5.1 Population and sample size

This study adopted census sampling methods, as it is preferrable if the population size is small, as reflected in the sampling frame [40]. In a census sample, all elements of the population are included [41]. A census-based sampling attempts to acquire data from an entire population systematically [42]. This study used primary data, using a census sample method and the chosen sample groups from a population of 219 employees, and included the management, packing, production, quality, SHE (environmental, health and safety), administration and the maintenance departments. A pilot test was conducted on three-management team members. The responses were not added to the sample. The pilot test determined whether the sample population clearly understood the instructions of the questionnaire [46].

Table 2: Population and sample size

Operational Unit	*Total Population*	*Sample size*	*Population %*	*Sample method*
Management	*21*	*21*	*100*	*Census*
Packing	*45*	*45*	*100*	*Census*
Production	*72*	*72*	*100*	*Census*
Quality+ SHE	*15*	*15*	*100*	*Census*
SILO	*15*	*15*	*100*	*Census*
Administration	*15*	*15*	*100*	*Census*
Maintenance	*36*	*36*	*100*	*Census*
Total	***219***	***219***	*100*	*100%*

5.2 Data collection

Primary data were collected through a self-distributed and online questionnaire, which had been chosen because it was efficient and affordable and easily available to every employee who wished to participate.

5.3 Pilot test

The pilot test was conducted on three management team members and thereafter, adjustments were made to the questionnaire before it was distributed to the sample population. The questionnaire covered aspects such as QMPs, organisational culture and leadership and business sustainability. The questionnaire was structured in a manner that the instructions were easy to understand and the language and wording were simple to understand. Also, the questionnaire answered the research questions for the study. The questionnaire used a five-point Likert scale: (1= Strongly disagree, 2=disagree, 3=neutral, 4= agree, 5= strongly agree)

5.4 Vaidity and reliabilty

The scales used in research must be valid and reliable, as these factors will ensure beneficial results.

5.4.1 Validity

Data are termed valid when they are meaningful and can be appropriately interpreted [46]. The instrument's validity was tested using content validity in this study. The content validity was evaluated using statistical methods, specifically factor analysis.

5.4.2 Reliability

Reliability indicates how stable the measured values are when measurements are repeated with the same instrument under the same condition [47]. In this study, reliability was determined by internal consistency. Internal consistency is related reliability of expressions contained in the measuring instrument [46]. Cronbach's coefficient was used to measure internal consistency, and the higher the value or the closer the reliability coefficient to 1.0, the higher the measurement of the items. In this study, Cronbach's alpha values greater than 0.7 represented acceptable reliability, while values greater than 0.8 were considered excellent [46].

6. DATA ANALYSIS AND FINDINGS OF THE STUDY

6.1 Sample analysis

The response rate of this study was 54.8%, meaning that 120 of the initially targeted 219 participants responded. While the sample was significantly lower than the target sample, it was in line with the average response rates of 55.6% for management and leadership studies, as reported by [44].

6.2 Instrument reliability analysis

This section discusses the reliability of the results of the research instruments. The Cronbach's Alpha (α) coefficient was used to measure the reliability of the research instrument. The results are presented in Table 3.

Table 3: Instrument reliability analysis

Instrument	Mean	Variance	SD	α
QMPs	**Six Sigma**			
	16.43	9.00	3.00	0.80
	5Ss			
	16.20	12.12	3.48	0.87
	Quality Management System			
	20.70	18.07	4.25	0.91
	Leadership commitment and support			
	20.84	20.51	4.53	0.94
	Workforce Management			
	25.73	42.71	6.54	0.91
	Organisational Culture			
	7.34	4.42	2.10	0.93

Instrument	Mean	Variance	SD	α
Sustainability	Operational Performance			
	12.23	7.30	2.70	0.84
	Business Financial Sustainability			
	46.45	92.30	9.61	0.92
	Quality Performance			
	25.20	29.24	5.41	0.84
	Business Performance			
	21.25	22.42	4.74	0.89

6.3 Regression analysis

To test the impact of QMPs on organisational sustainability, the regression model was developed. The results of the regression analysis are presented in this section. The discussion is done for each of the research hypotheses as presented in the literature review.

6.3.1 QMPs on organisational performance

The first hypothesis (H_1) was stated as:

H_1 QM practices have a direct impact on organisational performance.

Table 4 presents the results of regression modelling to prove the hypothesis.

Table 4: Impact of QMPs on organisational performance

Model Summary									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.716[a]	.513	.501/t5r01	3.34448	.513	44.205	1	42	.000
a. Predictors: (Constant), QM									

The results in Table 4 show that QMPs accounted for 51.3% of the variations in organisational performance (r square = 0.501, $p < 0.01$). It can be concluded that QMPs have a statistically significant positive impact on organisational performance. Thus, the results confirm and support H_1.

6.3.2 QMP on product quality

The second hypothesis was: H_2 QMPs have an impact on product quality. Regression analysis results to prove the hypothesis are presented in Table 5.

Table 5: Impact of QMPs on product quality

Model Summary									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.844[a]	.712	.705	2.93506	.712	103.934	1	42	.000
a. Predictors: (Constant), QMP									

The results in Table 5 show that 71.2% of variations in quality performance can be explained by variations in QMPs (r square = 0.712, $p < 0.01$). Based on these results, it can be concluded that QMPs have a statistically significant positive impact on product quality. Thus, the results confirm and support H2, which proposes that QMPs have a positive impact on product quality.

6.3.3 Influence of leadership commitment and support on QM practices

The third research hypothesis was stated as:

H_3 Leadership commitment and support have an impact on the implementation of QM practices.

The results to prove the hypothesis are presented in Table 6.

Table 6: Influence of leadership commitment and support on QM practices

Model Summary									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.932[a]	.869	.866	5.97538	.869	278.980	1	42	.000
a. Predictors: (Constant), Lcs									

The results in Table 6 show that 86.9% of variations in QMPs can be explained by variations in leadership commitment and s (r square = 0.869, $p < 0.01$). Based on these results, it can be concluded that leadership commitment and support have a statistically significant positive impact on QMPs. Thus, the results confirm and support H3, which proposes that leadership commitment and support have a positive impact on QMPs.

6.3.4 Organisational culture on QM practices

This section presents results to test the fourth hypothesis: H_4 Organisational culture has an impact on QM practices. The results are presented in Table 7.

Table 7: Organisational culture on QM practices

Model Summary									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.778[a]	.605	.596	10.37602	.605	64.450	1	42	.000
a. Predictors: (Constant), Ogc									

The results in Table 7 show that 60.5% of variations in QMPs can be explained by variations in organisational culture (r square = 0.605, p < 0.01). Based on these results, it can be concluded that organisational culture has a statistically significant positive impact on QMPs. Thus, the results confirm and support H4, which proposes that organisational culture has a positive impact on QMPs.

6.3.5 QMP on business sustainability

Table 8: QMP on business sustainability

Model Summary									
Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics				
					R Square Change	F Change	df1	df2	Sig. F Change
1	.865[a]	.749	.743	10.72223	.749	125.138	1	42	.000
a. Predictors: (Constant), Qmp									

The final hypothesis of the study was that QMPs have an impact on business sustainability: H5 QMPs have an impact on business sustainability. The results to test that hypothesis are presented in Table 8.

The results in Table 8 show that 74.9% of variations in business sustainability can be explained by variations in QMPs (r square = 0.749, p < 0.01). Based on these results, it can be concluded that QMPs have a statistically significant positive impact on business sustainability. Thus, the results confirm and support H_5 which proposes that QMPs have an impact on business sustainability.

7. KEY RESEARCH FINDINGS

The study adopted a quantitative approach method to study the perceptions of QMPs on the sustainable wheat-flour milling business.

7.1 Descriptive statistical analysis results

7.1.1 QMPs

The results conclude that the organisation under study practises 5S practices [12,14]. According to [19], 5S practices lead to improved quality performance. Quality management system also had high means scores, showing that the quality management system in the organisation is effective. Process management was also perceived to be functioning by the participants.

7.1.2 Sustainability

Organisational sustainability was broken done into two factors namely, quality performance and business performance. The quality performance factor gave high mean scores. Thus, participants, on average, felt that the quality performance has been above average. The mean scores for organisational performance were higher than the 2.50 threshold; they were relatively lower than those of other factors and were all less than 4.00 (3.07-3.82). This implies that there is still room for improvement on the organisation's overall business and sustainability performance.

7.2 Correlational analysis

Sustainability was found to be positively correlated with QMPs. Thus, all the factors of QMPs were found to be positively correlated to sustainability namely, Six Sigma, 5Ss, quality management system, leadership commitment and support, workforce management and organisational culture. It can, therefore, be concluded that QMPs, together with their respective factors, as measured in this study, have a positive effect on business sustainability. The results in this study support those earlier studies, such as [10], [20], and [44] who all found that QMPs influence organisational performance.

7.3 Regression analysis

The results have proved that QMPs have a statistically significant positive impact on organisational performance. Thus, the results confirm and support hypotheses that were identified for this study.

8. RECOMMENDATIONS

Based on the results of this study, the work force management system needs to be improved in the organisation, as the mean scores were lower than those of other factors, and there was high variability in respondents' responses. This could be achieved by using Artificial Intelligence (Al) and machine learning to improve employee experiences and engagements. The Al strategies will also help measure employee productivity and efficiency. The overall business' sustainability performance needs some improvement. Organisational sustainability was broken done into two factors: quality performance and business performance. Participants, on overage, felt that the Miller's quality performance has been above average. On the other hand, the business performance factor had mean scores that were relatively lower than those of other factors and were all less than 4.00. This implies that there is still room for improvement on the Miller's overall business and sustainability performance. There is a weak link in the value chain that affects quality performance, and the management needs to draw up strategies to get to its root.

9. CONCLUSION

This study investigated The Impact of QMPs on Sustainable Wheat-Flour Milling. The aim was to expose the factors that affect QMPs in the wheat-flour milling organisation, the most significant QMPs that influence rework in the wheat-flour milling organisation and lastly, provide recommendations on how to improve QMPs in wheat-flour milling organisations. The study initially targeted 219 participants and the response rate was 54.8%, which was lower than expected. This could have been due to the limited time the researcher had to collect data. A similar study at the company could be conducted in the future and the researchers should give themselves enough time to collect data to ensure a high rate of responses. The study focused exclusively on wheat-flour mills in one organisation. The results may not be reflective of other milling organisations. While the sample size was adequate, valid, future studies could be extended and expanded to other wheat-milling organisations facing a similar challenge as the company under study to draw more definitive statistical conclusions on the target population. All the objectives of the study were achieved. QMPs, such as six sigma practices, 5S practices, quality management system implementation and process management, were found to be affected by factors, such as organisational culture, workforce management and leadership support and commitment in the wheat-flour milling organisation. Workforce management was found to be the most significant factor that affects the implementation of QMPs. All QMPs factors studied do have an impact on product quality. Poor implementation of these practices results in poor product quality, leading to high volumes of rework. Workforce management needs some improvement, as it could be affecting quality performance. On average, participants felt that quality performance was just above average in the last three years thereby leading to low mean scores for business performance compared to other factors. It was, therefore, proposed by the researcher that for future studies, a more in-depth feedback approach from the respondents be used through a qualitative or a mixed methods approach.

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APPENDIX 1

SURVEY QUESTIONAIRE

THE IMPACT OF QUALITY MANAGEMENT PRACTICES ON SUSTAINABLE WHEAT-FLOUR MILLING

Please take time to read the following information. If at any point you have questions please do contact the researcher, Andisiwe Nwabisa Mdoda at 65102959@mylife.unisa.ac.za

Overview

You are herewith invited to participate in an academic research study conducted by Andisiwe Mdoda, a student in the Master of Business Administration at UNISA's Graduate School of Business Leadership (SBL).

The purpose of the study is to explore the impact of Quality Management Practices on sustainability of Wheat-Flour milling business as the Wheat-Milling industry is a major contributor to the global economy and thus Quality Management Practices are of high importance in the wheat-milling industry. This study will expose the factors that affect Quality Management Practices, the most significant Quality Management practice that influences rework and lastly provide recommendations on how to improve Quality Management Practices in wheat milling organisations.

All your answers will be treated as confidential, and you will not be identified in any of the research reports emanating from this research. Your participation in this study is very important to us. You may however choose not to participate and you may also withdraw from the study at any time without any negative consequences.

The questions consist of 3 sections, namely; Informed Consent, Demographic Information and the last section is made up of questions pertaining to the research problem. You will not be expected to make any financial contributions as a participant in this study. There will be no financial benefits, gifts or compensation in exchange for completing this questionnaire.

Please answer the questions in the attached questionnaire as completely and honestly as possible and please return the questionnaire to the researcher not later than 25 November 2022. This should not take more than 30 minutes of your time. The results of the study will be used for academic purposes only and may be published in an academic journal. We will provide you with a summary of our findings on request.

Please contact my supervisor, Prof Sugandren Naidoo by email at naidoosu@unisa.ac.za if you have any questions or comments regarding the study. Please continue to the next section to start with the survey.

1. INFORMED CONSENT

By continuing with the sections below, you as the participant acknowledge that you have read and signed the participants informed consent form and that you are willing to participate.

After section 1 Continue to next section

Section 2 of 9

2. DEMOGRAPGIC INFORMATION

Please select an appropriate answer

2.1 Gender *

- ◯ Female
- ◯ Male

2.2 Please enter your age in the space provided below *

Short answer text

2.3 Highest level of education *

- ◯ Other
- ◯ Diploma
- ◯ Graduate degree
- ◯ Post-graduate degree
- ◯ Master's degree
- ◯ Doctoral degree

2.4 Please enter years of service in the company in the space provided below. *

Short answer text

Section 3 of 9

3. QUALITY MANAGEMENT PRACTICES

This section contains questions about Quality Management Practices in your organisation. State your level of agreement or disagreement with the given statements by selecting the responses which best describe your organisation.

Please select your answer on the scale from (1 = Strongly disagree 2=Disagree 3=Neutral 4= agree 5= strongly agree)

Six Sigma

Description (optional)

3.1 Green belt/black belt are able to measure processes (defects per million opportunities, sigma level, process capability indices, defects per unit and yield) to evaluate process improvements.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

3.2 Green/black belts are encouraged to take up case studies to be solved through 6S

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

3.3 The organisation pursues a formal planning to improve the business processes.

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

3.4 The organisation measures performance of processes against customers' requirements

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

After section 3 Continue to next section

Section 4 of 9

4. 5S PRACTICES

Description (optional)

4.1 All 5S steps are deployed

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

4.2 There is improved housekeeping in the workplace of the organisation

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

4.3 Visual indicators are deployed to identify proper location

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

4.4 Place for everything, everything in its place is practiced

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

After section 4 Continue to next section

Section 5 of 9

5. QUALITY MANAGEMENT SYSTEM

5.1 The PDCA (Plan-Do-Check-Act) cycle in my organisation is used as a standard operating procedure for continuous quality improvement efforts.

1	2	3	4	5
○	○	○	○	○

5.2 Quality objectives are clearly and specifically defined in the organisation

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

5.3 Product's specification provided by the customers are verified and validated

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

5.4 Clear work instruction exists for all business processes

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

5.5 Internal/external audits are effective in terms of reduction of non-conformity

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

After section 5 Continue to next section

Section 6 of 9

6. OPERATIONAL PERFOMANCE

Description (optional)

6.1 In your organisation, production is stopped immediately for quality problems

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly Agree

6.2 Your organisation conducts preventive equipment maintenance

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly Agree

6.3 In your organisation, shop floors are well organised and clean

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly Agree

After section 6 Continue to next section

Section 7 of 9

7. LEADERSHIP COMMITMENT & SUPPORT

Description (optional)

7.1 Your organisation's top management is evaluated for quality performance

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

7.2 In your organisation, major department heads participate in the quality improvement process

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

7.3 In your organisation, "Quality issues" are reviewed in top management meetings

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

7.4 In your organisation, top management views quality performance as a major objective

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

7.5 In your organisation, quality policy is developed by top management

	1	2	3	4	5	
Strongly disagree	○	○	○	○	○	Strongly agree

After section 7 Continue to next section

Section 8 of 9

8. ORGANISATIONAL CULTURE AND WORKFORCE MANAGEMENT

8.1 WORK FORCE MANAGEMENT

8.1.1 Your organisation provides feedback to employees on their quality performance

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

8.1.2 Contractual employees are also involved in quality decisions in your organisation

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

8.1.3 Quality-related training is given to contractual employees

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

8.1.4 Quality-related training is given to managers and supervisors in your organisation

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

8.1.5 Your organisation provides quality Training as "total quality concept" (i.e., philosophy of company-wide responsibility for quality)

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

8.2 ORGANIZATIONAL CULTURE

Description (optional)

8.2.1 In your organisation group culture is encouraged in terms of participation, open discussion, empowerment of employees to act, assessing employee concerns and ideas, human relations, teamwork, and cohesion

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

8.2.2 In your organisation development culture is driven in terms of flexibility, decentralization, expansion, growth, and development, innovation and change and creative problem-solving processes

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

After section 8 Continue to next section

Section 9 of 9

9. BUSINESS FINANCIAL SUSTAINABILITY

9.1 QUALITY PERFOMANCE

9.1.1 Quality of your organisation products and services has been improved over the past 3 years

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

9.1.2 Process variability in your organisation has decreased over the past 3 years

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

9.1.3 Delivery of your products and services has been improved over the past 3 years in your organisation

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

9.1.4 Cost of scrap and rework as a percentage (%) of sales has decreased over the past 3 years in your organisation

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

9.1.5 Over the past 3 years, cycle time (from receipt of raw materials to shipment of finished products) has decreased in your organisation

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

9.1.6 Customer satisfaction with the quality of products and services has increased over the past 3 years in your organisation

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

9.1.7 Equipment downtime in your organisation has decreased over the past 3 years

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

9.2 BUSINESS PERFOMANCE

Description (optional)

9.2.1 Your organisation sales have grown over the past 3 years

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

9.2.2 Your organisation's market share has grown over the past 3 years

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

9.2.3 Unit cost of manufacturing has decreased over the past 3 years in your organisation

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

9.2.4 Your organisation's operating income has grown over the past 3 years

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

9.2.5 Your organisation's profits have grown over the past 3 years

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

9.2.6 Return on assets of your organisation has increased over the past 3 years

	1	2	3	4	5	
Strongly Disagree	○	○	○	○	○	Strongly Agree

Thank you for taking part in this survey.

Short answer

Short answer text

THE IMPACT OF TOTAL QUALITY MANAGEMENT ON ORGANISATIONAL PERFORMANCE IN A FINANCIAL SERVICES ORGANISATION

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ABSTRACT

The survival of all organisations that operate in a global economy depends on delivering quality products and services with a focus on exceeding customer expectations. A quantitative research approach was employed in this study. An online survey questionnaire was deployed to gather data from a sample of at least 100 employees of business support employees of a financial service organisation in South Africa. Analysis of the data was done using descriptive statistics and inferential statistics. Results of the study revealed that TQM positively influences organisational performance. This implies that if there is any improvement or deterioration in any of these factors it will have an influence on organisational performance. Further, the results of the have managerial implications when it comes to strategies for improving the quality-of-service delivery of the financial service organisation.

Keywords: Total quality management, organisational performance, customer satisfaction, customer focus, continuous improvement

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1. INTRODUCTION

Organisations all over the world have been actively working over the past several decades to cope with the quickly changing business landscape in which management must attempt to develop a long-term solution to maintain or acquire a competitive edge [1]. To meet new global problems, most organisations have implemented new philosophies such as Lean Production, Just-In-Time [JIT] methods, Total Quality Management [TQM], Business Process Re-engineering [BPR], amongst others [2]. The primary motivation for these ideologies is to improve the organisation's performance both internally and externally within its market goals.

Total Quality Management [TQM] is a management tool, philosophy, and set of principles that can be implemented across all operations and functions of an organisation to continuously improve the quality of products and services [3], exceed customer satisfaction, and continuously reduce production costs. The TQM technique is not just limited to quality enhancements in manufacturing.

Singh, et al., [1] notes that the absence of one feature in one banking institution may cause clients to choose a competing bank. As a necessity to the success of the banking system, it is important for a bank to deliver the best service quality [4]. The Financial Services sector is a highly competitive market and thus this study focuses on the impact of TQM on organisational performance in the context of the banking sector, within South Africa. This research study will focus on the context of the research challenge, the justification of the study, research objectives, discussion of key concepts of the study as well as a framework of the research methodology.

1.1 The research problem

According to a series of complaints in day-to-day interactions with bank clients, comments on social media platforms, and opinions on print media, despite the attention paid by banks to TQM, clients are nevertheless unsatisfied in most situations. Given the highly competitive nature of the financial sector, as well as high operating expenses, high research, and development (R&D) expenditures, and high client expectations, many organizations are always looking for methods to increase quality while remaining cost efficient (Nazar et al. 2018). Because of the ever-changing technological environment, all economic units are being forced to undertake digital transformation as part of comprehensive quality management (Khwela, N.C., 2019). The banking sector has increased its IT investments to continually modify its business model to improve how the bank interacts with its clients, manage internal processes, and remain competitive and be future ready. The challenge is whether clients are willing to adapt to new ways of doing business and whether general staff can provide the required customer satisfaction and service quality that has been promised. The reality is that banks clients often complain about service concerns such as delayed ATM cards, card retraction, illegal withdrawals, long queues in banking halls, and the bad service of bank personnel in attending to customers and addressing such complaints, among other things. Below are the stats for the complaints reported to the Ombudsman for Banking Services (OBS) South Africa. In terms of Section 8 of the conduct of standards for banks, banks must establish, maintain, and operate an effective an adequate complaints management framework to ensure the fair treatment of consumers. Table 1 shows some of the categories of complaints captured by OBS.

Table 1: Banking Complaints opened by Ombudsman for Banking Services by year.

	2020	2021	2022
Current Account	12%	19%	16%
Internet Banking	18%	13%	19%
Credit Cards	15%	11%	9%
Mortgage Finance	8%	8%	8%
Personal Loans	11%	11%	11%
ATM	13%	9%	7%

Source: OBS (2021)

Table 2: Cased opened by OBS South Africa by banks Category.

	2019	2020	2021
Standard Bank	1 127	1 572	2 070
Capitec Bank	763	1 259	1 651
FNB	1 707	2 197	1 452
Nedbank	1 094	1 220	1 273
ABSA	1 483	943	1 068
African Bank	151	255	285

Source: (OBS)

Internet banking complaints increased by 6% year on year, 45% of these complaints were brough against the Capitec and 20% against Standard Bank. Mobile banking made up 25% of this category. Current accounts complaints were the 2nd highest category of complaints opened by the OBS. Table 2 reveals ATM complaints decreased in 2020 and 2021 as most people were isolating due to the COVID-19 pandemic (OBS).

Table 3: Banking Complaints opened by Ombudsman for Banking Services by year Banking Complaints opened by Ombudsman for Banking Services by category

	Complaints about advice to financial customer	Complaints about service, support and staff conduct	Complaints about design of financial products and fees	Complaints about disclosures to and information provided	Complaints about performance of financial products and services	Complaints about customer services
ATM			180	1	442	
Internet Banking			75	79	1216	
Business Finance				38	21	1
Car Finance		80	165	136	207	20
Credit Cards	1	25	334	257	204	36
Credit Information Disputes			14	10	282	

	Complaints about advice to financial customer	Complaints about service, support and staff conduct	Complaints about design of financial products and fees	Complaints about disclosures to and information provided	Complaints about performance of financial products and services	Complaints about customer services
Covid -19				78	27	
Savings Account			19	146	304	9
Current Account			149	555	496	
Investments	5	20	5	34	89	1

Source [OBS]

Table 3 indicates the problems experienced by banks and is huge concern should banks want to remain competitive. Moreover, the South African Consumer Satisfaction Index, which is operated by the consultation group Consulta, surveyed almost 15 000 customers from across the 6 major retail banks in South Africa. The results of the survey showed that the South African banking standards are rated like world class for customer satisfaction, and thus expectations are extremely high and likely to keep rising. Therefore, banks need to understand the nature of these expectations which includes striking a balance between digital convenience, value delivery and human intuition and client engagement.

1.2 Aim of the study

The aim of this study is to assist financial services industry understand the impact of Total Quality Management (TQM) on organisational performance.

1.3 Research questions

The following research questions were defined for the study:

- What are the TQM factors that influence organisational performance at the South African banking organisation?
- What is the impact of the TQM factors on organisational performance at the banking organisation?
- What recommendations can be made to the banking management, as input to their organisational strategy on how TQM can be practiced to improving organisational performance?

2. OVERVIEW OF TOTAL QUALITY MANAGEMENT

Quality is a criterion that determines whether a product or service is superior or inferior. Quality is a feature that distinguishes a product or service from its rivals [5].

In the 1960s Feigenbaum conceptualised Total Quality Control. He believed that all departments in a company have some responsibility for the achievement of quality. The challenge with TQC concept was that it did not embrace other management principles such as teamwork, supplier development relationship and people development and leadership [6, 7]. Converting organisational goals into results is accomplished through three managerial processes called the Juran Trilogy [Quality Planning, Quality Control, and Quality Improvement] [8]. According to Ross [9], TQM is more than simply a management tool; when implemented well it may provide significant competitive advantage. The TQM strategy incorporates in an organised manner the core techniques and ideas of quality function deployment, statistical control, and current management tools.

TQM focuses on organisational frequent process improvement to produce greater client value and attain their requirements [10,11]. TQM, as a common organisational management guideline, is used to produce organisation information that is important for creating strategic information maps [12].

3. LITERATURE REVIEW OF TOTAL QUALITY MANAGEMENT PRINCIPLES

There are various approaches for businesses to take to achieve this, with the road to successful continuous improvement based on the use of strategy, data, and effective communication to embed a quality discipline into the organisation’s culture and procedures [13]. Bajaj, Garg and Sethi [14] point out that to successfully implement TQM procedures, the entire organisation must work as a unified unit in a quest for excellence.

TQM focuses on the processes that businesses use to generate their goods, and it requires organisations to identify those processes, continually evaluate and assess their performance, and utilise that performance data to drive changes [1]. Moreover, it encourages all workers and organisational divisions to participate in this process.

TQM procedures are also dependent on a common set of values and beliefs across all organisational members [11]. Quality has evolved from being viewed as a non-price component on which imperfect competition in markets is based to being viewed as a strategic resource of enterprises. In other words, quality is no longer one-dimensional property of a product but a multidimensional construct that must be controlled and whose application leads to a dynamic capability of enterprises [12].

TQM may have a significant and positive impact on personnel and organisational development [11]. Companies may build and preserve cultural norms that ensure long-term success for both clients and the firm by having all workers focus on quality management and continual improvement [6]. TQM's emphasis on quality aids in the identification of skills gaps in personnel, as well as the required training, education, or mentorship to remedy such weaknesses.

3.1 TQM in context of the study

The higher the degree of satisfaction and original anticipation attained by clients, the higher the service quality obtained [15]. The scientific foundation of quality management is built on the genesis of quality objectives, which are based on the demands of the customer [9]. According to Nazar et al. [16], the term service quality means that the organisation should assure customer satisfaction as well as the lack of faults or delays. An effective quality management system must fulfil and exceed the expectations of the customer. [17] identifies critical TQM factors which are, customer focus; continuous improvement; teamwork and participation; top management commitment; training and development; quality systems and policies; supervisory leadership; supplier management; people and culture change. According to Al-Qahtani, et al., [18] organisations have realised that to remain internationally competitive, they must conduct self-evaluations to continually improve organisational performance.

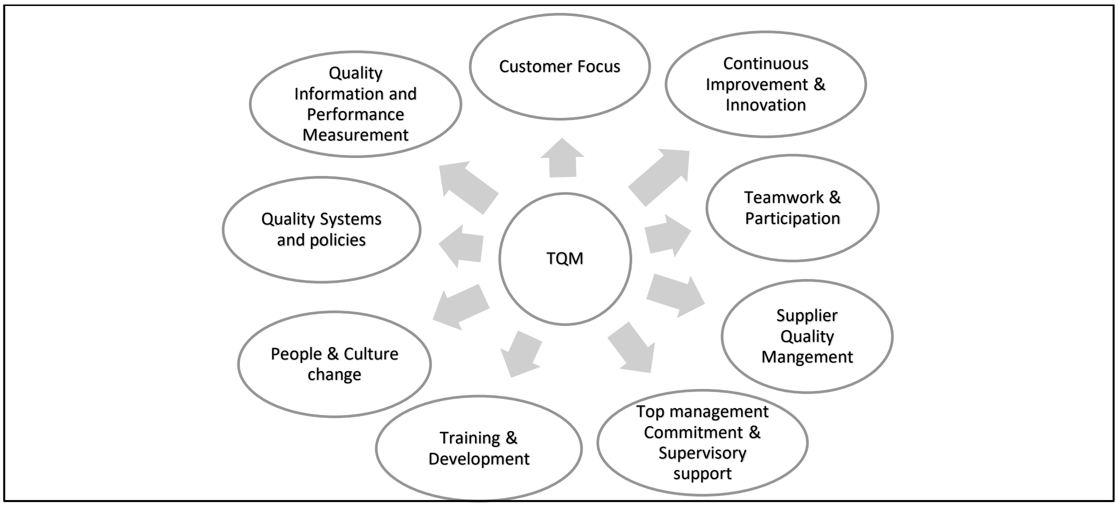

Figure 1: TQM Critical Success Factors *[17]*

Implementing a TQM system must be part of pleasing customers and exceeding their expectations. Such a system must be dynamic, adaptive to the needs, requests, and expectations of the clients. Singh, et al., [1] claim that all organisations want to expand their operations; but, to reach these goals, products and services must be carefully designed and of high quality. The TQM strategy is crucial for ensuring that the goods or service meets or exceeds the customer's expectations. The critical factors required to measure organisational performance are listed on Figure 2 shows which are productivity, Lower lead times, less rework, customer loyalty and relations, improved market share customer satisfaction, lower costs, long term relations and affinity [19, 20].

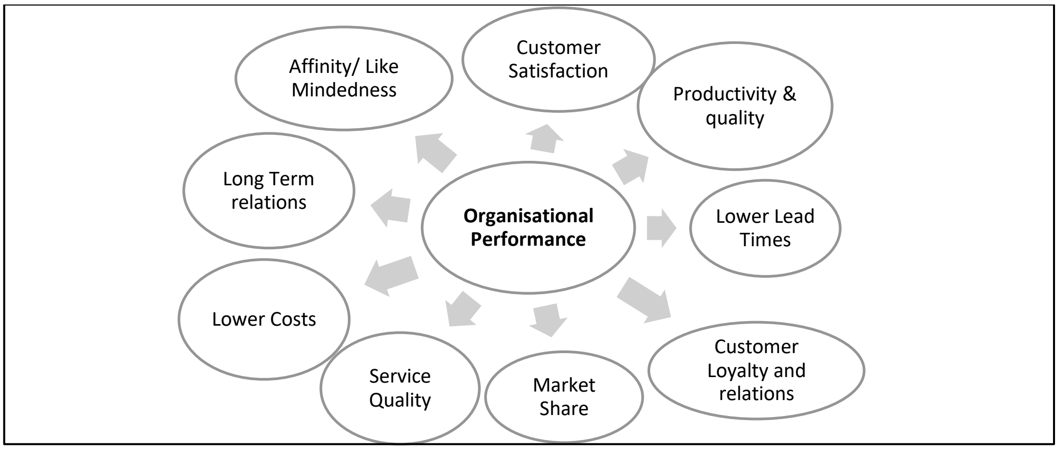

Figure 1: Organisational performance factors [20]

Total Quality Management is thus a technique that seeks to confirm that the final service or product offered to the consumer meets the required standards. The effective implementation of TQM could then lead to the fundamental solutions required for organisations to have competitive advantage in the ever-changing global market conditions.

3.2 Total Quality Management Key Factors

3.2.1 Customer focus

Customer focus becomes an important aspect for an organisation's success since it is the beginning point for every quality project [10]. It is encouraged to conduct research in the case of service sector and to clarify the long-term influence of customer focus on other organisational performance.

3.2.2 Continuous improvement

Continuous improvement focuses on collection of processes that enable an organisation to improve efficiencies and effectiveness. It drives the organisation to be both analytical and creative in finding ways to become more competitive and effective at meeting stakeholders and client expectations. The organization determines and selects opportunities for improvement and implements necessary actions to achieve the intended outcomes. Considering the results from analysis, evaluation and management review, the organization continually improves suitability, adequacy and effectiveness [11].

3.2.3 Strategically based TQM

The strategic strategy of a complete quality firm is meant to offer it a lasting competitive edge in the marketplace, writes Goetsch and Davis [21]. The key motivator for TQM application in organisations is the competitive edge that it provides to the organisations as they provide world class quality products and services. It also includers various aspects such as mission, broad aims, and actions carried out with the aim of achieving the objectives of the business in which senior management is responsible for quality leadership [17]. The TQM strategy considers customer satisfaction, cost of quality and partnerships [21].

3.2.3.1 Customer Satisfaction

According to Lau et al. [11], customer satisfaction, staff participation, executive leadership, and process improvement and control are four components usually recognised as vital to a successful TQM approach.

3.2.3.2 Cost of Quality

Özmen et al. [15] believe that the cost of quality to be the fundamental method for gauging quality. It is utilised in their strategy to track the efficacy of the TQM process, choose quality improvement projects, and justify costs to sceptics.

3.2.3.3 Partnership

Long-term, cooperative partnerships with some of the suppliers will help to achieve excellent resources and/or services encourage supplier quality management that is effective [12]. By endorsing improved supplier commitment to product design and quality, keeping a small number of suppliers promotes product quality and buyer productivity.

3.3 Total employee participation

Through opportunities to obtain and exercise new skills, total employee participation and collaboration may inspire employee motivation and success. The improvement of the employee information, skills, and determination will result in the organisational growth [7]. Employee involvement and empowerment, as well as the utilisation of self-managed teams, are employed as indicators of complete employee involvement in this study.

3.4 Organisational Performance

Considerable effort has been devoted in organisational research to examine the organisational performance factors [13]. This is due to the subject's relevance in reflecting the course of growth for any company, as well as the consequences of these studies on organisational performance and competitiveness [9].

3.5 Conceptual framework

The conceptual framework in figure 3 depicts the factors investigated for this study.

Figure 3: Conceptual framework

From the literature review, it was evident that customer focus, continuous improvement, TQM strategic planning, and total employee participation are the essential characteristics of TQM [16].

4. RESEARCH METHODOLOGY

This chapter discusses the key methodological process that will be followed in this study. the thrust is to assess the impact of total quality management on organisational performance at the banking institution.

4.1 Research design

The research design articulates the exact logical steps that researchers choose to take when solving a research question [22]. This means that the study design is used to determine the type of data needed to conduct the study, the methods for starting the sample, collecting the data, and its subsequent analysis

4.1.1 Descriptive Research Design

The study used a descriptive research design, in which researchers attempted to observe subjects without intervention. The study used a survey approach to solicit valuable information for the research,

4.1.2 Quantitative research approach

This study used quantitative research methods. The goal of quantitative research is to better understand the social environment [22]. This study used a causal research design to establish causal relationships between quantitative variables.

4.1.3 Research Strategy

Research strategies are thought to be influenced by the nature of the hypothetical relationship that exists between research and theory [23]. The study used a questionnaire with standardised questions to allow easy comparison of responses.

4.1.4 Population and sample framework

A population is the total group about whom one wishes to draw conclusions [23]. The target population for this study is business support employees of financial service organisations in South Africa. The identified organisation assisted in providing access to data collection across all South Africa.

4.1.5 Sampling strategy

The study employed probability sampling as it mitigates and avoids bias by using statistics rather than judgement or bias [22]. The same strategy allows researchers to estimate the reliability of the data by testing the validity and reliability of the data.[23] further demonstrated that probabilistic sampling makes the study of the entire population feasible by allowing the study to study a portion and generalise the results.

4.1.6 Sample Size

A sample is the exact group from whom statistics are collected. According to Kumar's (2018) suggestion, a sample size of at least 100 observations is sufficient for quantitative studies. The research will select a sample of 100 employees in the financial services organisation. Convenience sampling was used, whereby respondents who were easily available were selected.

4.1.7 Data collection method

This study involved the use of primary data. The questionnaire was uploaded to Quest Survey, and the link was shared via online platforms like WhatsApp and emails.

4.1.8 Rationale for Using Survey Questionnaires

In general, it is relatively quick to collect large amounts of data using questionnaires. The questionnaire was structured on a 5-point Likert scale, in which responses were listed from a list of agree, strongly agree, neutral, disagree, and strongly disagree. The questionnaire was sent by mail [22].

4.1.9 Pilot Study

Pilot studies are also known as feasibility studies, in which research tools are tested on a small group of participants who will not be included in the actual study.

4.1.10 Validity

The notion of validity characterises the degree to which the test indicates the universe of substances from which it is generated [25] . This infers a degree to which the assessment determines the proposed outcomes.

4.1.11 Reliability

The concept of reliability assesses whether a research instrument will produce similar results if stressed in similar conditions [23]. The reliability of the scales will be assessed using Cronbach's alpha. For a scale to be considered reliable, the alpha coefficient should be greater than 0.7 [25].

5. DATA ANALYSIS

The quantitative data collected with the online research questionnaire were analysed with descriptive and inferential statistics.

Convenience sampling was used to select 150 employees, and an email invitation was sent to them to participate in the online survey. A total of 99 usable data sets were received, giving a participation rate of 66%.

5.1 Department Profile of Respondents

Respondent's department profile and department composition statistics are presented in Figure 4.

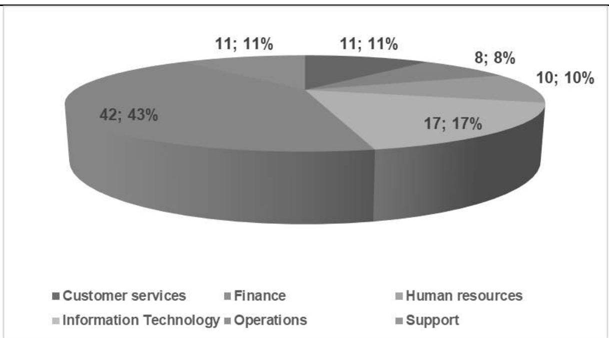

Figure 4: Department Profile of Respondents (n = 99)

Figure 4 shows that the bulk of the respondents—43%—work in operations, with 17% in IT. Customer Services and Support each at 11%, and the remaining 8% at Finance and 10% at Human Resources. It is accepted that most of the respondents are operational.

5.2 Descriptive Statistical Analysis of Quantitative Data

In this section, the descriptive statistics of the qualitative data collected with the research questionnaire are presented. The respondents were presented with an online questionnaire and asked to indicate how much they agreed with a set of statements.

5.2.1 Organisational Performance Scale

The descriptive statistics of the organisational performance questions are presented in Table 4.

Table 4: Descriptive statistics of Organisational Performance Scale (*n* = 99)

	Median	*SD*	*1*	*2*	*3*	*4*	*5*	*N*
9.6: There is need to improve on the quality of services rendered by the bank to the customer.	4	0.74	0	3	25	53	18	99
			0%	3%	25%	54%	18%	100%
9.7: There is an increase in production percentage.	4	0.82	0	8	17	55	19	99
			0%	8%	17%	56%	19%	100%
9.8: There is an increase in sales compared to the previous periods.	4	0.74	0	4	19	57	19	99
			0%	4%	19%	58%	19%	100%
9.9: There is an increase in profits compared to the previous periods.	4	0.84	0	6	23	46	24	99
			0%	6%	23%	46%	24%	100%
9.10: The bank provides a measurable indicator for operations performance.	4	0.75	0	4	20	55	20	99
			0%	4%	20%	56%	20%	100%

The majority of the respondents agree there is a need for the quality of the services rendered by the bank to customers to be improved (M = 4, SD = .74).

5.2.2 Organisational Strategy Scale

The descriptive statistics of the organisational strategy questions are presented in Table 5.

Table 5: Descriptive statistics of Organisational Strategy Scale (n = 99)

	Median	*SD*	*1*	*2*	*3*	*4*	*5*	*N*
8.1: The bank applies and support the culture of collective leadership to manage the bank operations.	4	0.82	0	12	37	41	9	99
			0%	12%	37%	41%	9%	100%
8.2: The bank encourages employees to participate in quality improvement initiatives.	4	0.77	0	10	39	43	7	99
			0%	10%	39%	43%	7%	100%
8.3: The bank management has transparent policies to manage employee experience.	4	0.82	0	9	38	40	12	99
			0%	9%	38%	40%	12%	100%
8.15: The bank circulates the strategy to all employees.	4	0.91	1	14	27	46	11	99
			1%	14%	27%	46%	11%	100%
9.16: The bank follows appropriate actions that aimed to increase customer satisfaction.	4	0.80	0	3	36	40	20	99
			0%	3%	36%	40%	20%	100%
9.18: The bank manages customer relationships according to a clear and structured approach.	4	0.77	0	5	33	47	14	99
			0%	5%	33%	47%	14%	100%

Most of the respondents agree that the bank encourages employees to participate in improvements and that the bank manages customer relationships according to a clear and structured approach (*M* = 4, *SD* = .77).

5.2.3 Leadership Scale

The descriptive statistics of the leadership questions are presented in Table 6.

Table 6: Descriptive statistics of Leadership Scale (*n* = 99)

Leadership	*Median*	*SD*	*1*	*2*	*3*	*4*	*5*	*N*
8.4: Bank management has the flexibility and ability to make the right decisions based on the available information, experience, and knowledge.	4	0.80	0	9	37	43	10	99
			0%	9%	37%	43%	10%	100%
8.12: The senior bank management has a long-term plan for the service quality.	4	0.81	0	7	41	38	13	99
			0%	7%	41%	38%	13%	100%
8.13: The bank management revises the statistics used to measure the performance quality to make sure it's valid for the future operations.	3	0.76	0	8	42	41	8	99
			0%	8%	42%	41%	8%	100%
8.14: The banks strategy based is on the understanding of the internal performance of the bank and the available possibilities.	3	0.79	0	10	43	38	8	99
			0%	10%	43%	38%	8%	100%
8.20: Employees are actively involved in planning in our organisation.	3	0.91	1	16	40	32	10	99
			1%	16%	40%	32%	10%	100%
8.21: Reporting work problems is encouraged in our bank.	3	0.86	2	12	41	37	7	99
			2%	12%	41%	37%	7%	100%
8.22: Job satisfaction surveys are conducted regularly to measure employee's satisfaction in our bank.	4	0.91	1	11	35	38	14	99
			1%	11%	35%	38%	14%	100%
8.23: The bank relies on suitable policies to ensure equality and equal opportunities in recruitment, promotion process and employee's rewards.	4	0.88	0	11	38	35	15	99
			0%	11%	38%	35%	15%	100%
8.24: The bank determines the skills and competencies of employees and the required performance level to achieve the vision, objectives and strategy.	4	0.82	0	8	38	40	13	99
			0%	8%	38%	40%	13%	100%
	4	0.89	0	13	29	43	14	99

Leadership	*Median*	*SD*	*1*	*2*	*3*	*4*	*5*	*N*
8.25: The bank evaluates the performance of employees regularly.			0%	13%	29%	43%	14%	100%

The mode values in the above Table 6 show neutral, thus neither agree nor disagree with the statements that the bank management revises the statistics used to measure the performance quality to make sure it is valid for the future operations (*M* = 3, *SD* = .76); the banks strategy based is on the understanding of the internal performance of the bank and the available possibilities (*M* = 3, *SD* = .79); and reporting work problems is encouraged in the bank (*M* = 3, *SD* = .86).

5.2.4 Employee Involvement Scale

The descriptive statistics of the employee involvement questions are presented in Table 7.

Table 7: Descriptive statistics of Employee Involvement Scale (*n* = 99)

Employee Involvement	*Median*	*SD*	*1*	*2*	*3*	*4*	*5*	*N*
8.5: Bank management encourage all employees to submit ideas and suggestions to innovate.	3	0.83	0	12	43	34	10	99
			0%	12%	43%	34%	10%	100%
8.6: Bank management recognises quality improvement suggestions from employees extensively and implement them after evaluation.	3	0.80	0	9	43	37	10	99
			0%	9%	43%	37%	10%	100%
8.7: Bank management seeks to engage all employees in the bank and get their support and contributions.	3	0.88	1	13	37	38	10	99
			1%	13%	37%	38%	10%	100%
8.16: The bank regularly reviews the current strategy in order to improve it.	4	0.88	0	17	26	47	9	99
			0%	17%	26%	47%	9%	100%
8.17: The bank allows employees to participate in its decision making.	4	0.84	1	12	34	45	7	99
			1%	12%	34%	45%	7%	100%
8.18: Bank employees are actively involved in quality-related activities.	3	0.82	0	12	41	37	9	99
			0%	12%	41%	37%	9%	100%
8.19: The bank recognises quality improvement suggestions from employees and extensively implement them after evaluation.	3	0.83	0	13	40	37	9	99
			0%	13%	40%	37%	9%	100%

The respondents indicated that the bank recognise and implement valuable suggestions and input from employees (*M* = 4, *SD* = .81).

5.2.5 Total Quality Management Scale

The descriptive statistics of the Quality Management questions are presented in Table 8.

Table 8: Descriptive statistics of Quality Management Scale (*n* = 99)

	Median	*SD*	*1*	*2*	*3*	*4*	*5*	*N*
8.8: The bank management has general strategic goals for quality dependent on the wants and needs of customers.	4	0.95	1	14	33	36	15	99
			1%	14%	33%	36%	15%	100%
8.9: The bank management uses data of the other competitors to improve the service.	3	0.91	1	13	38	35	12	99
			1%	13%	38%	35%	12%	100%
8.10: The bank has a system to study the market and the economic changes.	4	0.85	1	11	35	43	9	99
			1%	11%	35%	43%	9%	100%
8.11: The bank management has methods to follow up changes in customer needs.	4	0.83	0	9	36	41	13	99
			0%	9%	36%	41%	13%	100%
9.19: The bank management and its employees are making preventive and immediate corrective actions for the errors reported.	4	0.85	1	7	30	47	14	99
			1%	7%	30%	47%	14%	100%

Table 8 depicts the agreement of the respondents that the bank has methods to follow up on changes in customer needs (M = 4, SD = .83) and that bank management and its employees are taking preventive and immediate corrective actions for the errors reported (M = 4, SD = .85).

5.2.6 People Management Scale

People management is the act of hiring, leading, and developing team members to fulfil the overall purpose of the business (Burns, 2012). People managers are in charge of all people-related functions such as discovering new talent, engaging employees, and advancing their careers (Burns, 2012). They are often in charge of new employee onboarding and training. The descriptive statistics of the People Management questions are presented in Table 9.

Table 9: Descriptive statistics of People Management Scale (*n* = 99)

	Median	*SD*	*1*	*2*	*3*	*4*	*5*	*N*
9.1: The bank provides the necessary training to improve employee's performance.	4	0.76	0	4	24	53	18	99
			0%	4%	24%	54%	18%	100%
9.2: Bank employees are satisfied with the working conditions.	4	0.75	0	2	39	42	16	99
			0%	2%	39%	42%	16%	100%

9.3: The bank has greatly improved in the overall quality of services rendered to their customer.	4	0.75	0	3	34	47	15	99
			0%	3%	34%	47%	15%	100%
9.4: Every member of the bank staff is committed to maintaining high standard of work in every aspect of the banks' operation.	4	0.87	0	10	24	48	17	99
			0%	10%	24%	48%	17%	100%
9.5: There is increase in the quality of services provided by the bank to customers.	4	0.74	0	3	29	51	16	99
			0%	3%	29%	52%	16%	100%
9.25: The bank set an indicative target for improvement and continuous development process.	4	0.84	0	9	32	44	14	99
			0%	9%	32%	44%	14%	100%

Table 9 shows that the respondents agree with the statements on people management, especially that there has been an increase in the quality of services provided by the bank to customers (M = 4, SD = .74) and that the employees are satisfied with the working conditions (M = 4, SD = .75).

5.2.7 Customer Focus Scale

The descriptive statistics of the Customer Focus questions are presented in Table 10.

Table 10: Descriptive statistics of Customer Focus Scale (*n* = 99)

	Median	*SD*	*1*	*2*	*3*	*4*	*5*	*N*
9.11: The employees know their roles and responsibilities in implementation, maintenance, and development of the bank's operations.	4	0.67	0	1	36	51	11	99
			0%	1%	36%	52%	11%	100%
9.12: The bank management listens to the customer complaints and provide an immediate solution.	4	0.75	0	4	37	45	13	99
			0%	4%	37%	45%	13%	100%
9.13: The bank measures the customer satisfactions on the quality of services and operational efficiencies.	4	0.74	0	3	36	46	14	99
			0%	3%	36%	46%	14%	100%
9.14: The bank gives attention to clients' needs.	4	0.80	0	4	36	41	18	99
			0%	4%	36%	41%	18%	100%

From Table 10, employees agree with the statement that they know their roles and responsibilities in the implementation, maintenance, and development of the bank's operations (M = 4, SD = .75) and the bank measures customer satisfaction on the quality of services and operational efficiencies (M = 4, SD = .75).

5.2.8 Continuous improvement Scale

The descriptive statistics of the Continuous Improvement questions are presented in Table 11, and show that many of the respondents agree that the bank has a programme in place to eliminate processes and activities that have become redundant (M = 4, SD = .75) and that the bank provides feedback to customers once a query has been resolved (M = 4, SD = .80).

Table 11: Descriptive statistics of Continuous improvement Scale (*n* = 99)

	Median	*SD*	*1*	*2*	*3*	*4*	*5*	*N*
9.15: The bank gives feedback to clients after resolution of their enquiries.	4	0.80	0	4	36	41	18	99
			0%	4%	36%	41%	18%	100%
9.20: The management has a goal to minimise the cost of different operational processes.	4	0.83	0	6	32	43	18	99
			0%	6%	32%	43%	18%	100%
9.21: The bank has a documentation system that is introduced and applicable for employees in all levels.	4	0.83	0	9	31	46	13	99
			0%	9%	31%	46%	13%	100%
9.22: The bank has processes in place to analysis the activities required to provide excellent service.	4	0.82	0	5	30	44	20	99
			0%	5%	30%	44%	20%	100%
9.23: The bank has a program to simplify the steps required to provide the service to customers.	4	0.82	0	5	43	35	16	99
			0%	5%	43%	35%	16%	100%
9.24: The bank has a program to eliminate the redundant processes and activities.	4	0.75	0	5	33	49	12	99
			0%	5%	33%	49%	12%	100%

Table 11 shows that many of the respondents agree that the bank has a program in place to eliminate processes and activities that has become redundant (*M* = 4, *SD* = .75) and that the bank provides feedback to customers once a query has been resolved (*M* = 4, *SD* = .80). T

5.3 Section C: Factor Analysis

Eight factors were extracted that explained about 68% of the variance in the factor space.

5.3.1 Reliability Analysis of the Questionnaire Dimensions

Table 12 is a summary of the reliability findings.

Table 12: Cronbach's Alpha Findings by Scale

Variable	Factor	Cronbach's Alpha	Number of Items
Leadership (LS)	1	0.91	10
Organisational Performance (OP)	2	0.83	5
Continuous Improvement (CI)	3	0.89	6

Employee Involvement (EI)	4	0.89	7
Customer Focus (CF)	5	0.84	4
TQM	6	0.87	5
People Management (PM)	7	0.86	6
Strategy (STY)	8	0.86	6

Al the scales of the questionnaire yielded Cronbach Alphas of .84 or higher, indicating acceptable internal consistency reliability (Pallant, 2020). This means all the scales can be used in the inferential statistical analysis.

6. ANALYSIS OF REASEARCH QUESTIONS

This study focused on reviewing literature on organisational performance and its relationship with TQM.

6.1 Research question 1

What are the TQM factors that influence organisational performance at the banking organisation?

Based on the findings of the primary research it is concluded that:

Customer Satisfaction: Organisational Strategy: Job Satisfaction Employee recognition, work culture, Leadership [LS], Continuous Improvement [CI], Employee Involvement [EI], Customer Focus [CF], TQM, People Management [PM] and Strategy [STY] influence Organisational Performance. This conclusion is supported by empirical evidence that TQM increases the possibility for organisations to improve organisational performance [14; 6].

6.2 Research question 2

What is the impact of the TQM factors on organisational performance at the South African banking organisation?

Based on the findings of the primary research, it is concluded that if there is any improvement or deterioration of any of the related TQM factors Leadership [LS], Continuous Improvement [CI], Employee Involvement [EI], Customer Focus [CF], TQM, People Management [PM] and Strategy [STY] it will have an influence on organisational performance. This conclusion is consistent with the literature.

7. RECOMMENDATIONS

Based on research findings, the following recommendations are made to banking management as input to their organisational strategy on how TQM can be practised to improve organisational performance.

7.1 Recommendation 1: Customer satisfaction

It was found that although there is a strong focus on customer satisfaction, many of the respondents feel there is room for improvement. Based on this finding, it is recommended that the current processes to improve customer satisfaction be revisited to determine weak points and new processes put in place with the view of improving these customer enhancement processes.

7.2 Recommendation 2: Employee performance interventions

It was found that the characteristics of employees play a role in how they respond to the work environment. Based on this finding, it is recommended that, during the development of an intervention to improve performance, an investigation be conducted of how categories of different demographical characteristics of employees will respond to that specific intervention.

8. MANAGERIAL IMPLICATIONS

Further, according to the research of Adusa-Poku and Anokye [2], efficient use of employee participation has a beneficial influence on perceived organisational performance. People management is one of four TQM aspects that contribute significantly to both operational and financial performance [2]. In a study by Ahmed and Idris [2020] on the relationship between total quality management and long-term organisational success in manufacturing companies in Malaysia, total quality management was found to be a crucial factor as it contributes to the long-term success of the company.

9. CONCLUSION

In the globalised economy, the survival of organisations depends on delivering quality products and services with a focus on exceeding customer expectations. Organisations are going through a shift from a production-oriented focus to a customer-oriented approach. Organisations with a high service quality approach will present a challenge to their competitors, and they will become the benchmark for achieving competitive advantage. However, despite the attention paid by financial services organisations to total quality management [TQM], customers have shown dissatisfaction with the services they receive in most situations. customer focus, people management, and strategy. This implies that if there is any improvement or deterioration in any of these factors, it will have an influence on organisational performance. It is therefore recommended that management of the financial services organisation focus on improving the identified TOM factors to improve the organisation's performance.

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EXAMINING THE DIFFICULTIES IN BUDGET DEVELOPMENT FOR HERITAGE BUILDING PROJECTS

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ABSTRACT

Project cost is an important performance consideration for new and maintenance building projects. However, due to the high uncertainty associated with heritage building projects, they tend to encounter a higher variability in cost. Thus, budgeting methods that include appropriate risk analysis may improve the likelihood of meeting project cost expectations. The Monte Carlo Method can be used for this purpose since it can provide a confidence level associated with a budget for a specific project. This study investigated the factors influencing project cost overruns, the methods used for preparing budgets and how professionals involved with heritage building restoration perceive the application of the Monte Carlo Method. The study was limited to a single organisation. Still, the findings illustrate that professionals perceive organisational factors to be influential in budget overruns and that even though the Monte Carlo Method is not widely utilised, it could possibly improve budget forecasting.

Keywords: maintenance, heritage buildings, cost, estimate, Monte Carlo Method

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1 INTRODUCTION

Heritage building projects differ from other construction projects in terms of concepts, techniques, and procedures when compared to modern construction projects. The uncertainties in heritage buildings are likewise distinct and higher than in modern buildings [1]. Most of the time, the precise work can only be determined after the structure has been opened and dismantled. Due to the challenges in safeguarding the character of such work in terms of its ultimate content, scope, and specification, Nawi *et al*. [1] found that preparing estimates for conservation work is complex and challenging. Poor cost in developing a maintenance budget for heritage buildings might be the key factor in ineffective repair solutions. Therefore, cost is considered one of the most essential attributes and a critical driver of project success [2].

Lazarus and Hauptfleisch [3] suggest that estimating maintenance costs should start with a complete understanding of all expenditures incurred. Thus, costing should include all processes, procedures, materials, skilled specialised labour, and methodologies, including the possible risks. Accurate costing aids in the production of an accurate budget. Therefore, costing methods that promote reliable expectations should be adopted. The Monte Carlo Method may be used to minimise uncertainties associated with maintenance project budgeting methods [4].

Industrial and Systems Engineers aim to utilise engineering tools to among other develop predictions of complex socio-technical systems to achieve the optimal potential [5]. For this reason, this article explores the challenges encountered in the population of budget for heritage building projects and the perception of project managers in using the Monte Carlo Method as a budgeting tool for heritage building projects.

2 LITERATURE REVIEW

2.1 Maintenance of Heritage Buildings

Maintenance is critical for conserving heritage buildings and extending their useful lives [6]. Poor designs may increase building deterioration, faulty construction, maintenance, defective materials, and faulty usage [7]. Au-Yong et al. [8] add that cost creep may also be caused by a lack of maintenance workers, ineptitude, inadequate maintenance equipment and technologies, insufficient maintenance budget allocation, and incorrect maintenance practices. As the number of heritage buildings increases worldwide, their maintenance has become vital to a building’s life cycle [9].

Heritage buildings/structures, unique landmarks worldwide, have particular cultural importance, and the lack of professional maintenance management has proven disastrous [10]. As a result, as Francis et al. [11] say, heritage building upkeep management is vital and must be handled efficiently.

2.2 Principles of Maintenance of Heritage Buildings

Historic structures require different care than modern buildings. Heritage building maintenance, restoration, and preservation must follow specified rules. Building components, for example, must be fixed and conserved in their original state rather than removed and replaced. This is restoration, which is defined as returning a structure to its original state as precisely as possible without adding new pieces to the fabric [12].

This complicates matters since, as Azizi et al. [13] ascertain, heritage building conservation and upkeep are concerned with keeping as much original fabric as possible while differentiating later additions and renovations from the original structure. As a result, conservation permits broad alteration as long as the improvements are aesthetically and historically significant and improve and retain the original structure's character. The instrument or strategy for preserving cultural structures is known as "minimal intervention" and must be followed. This indicates that preserving heritage architectural elements contributes to the preservation of cultural significance by achieving and carrying out maintenance with the least degree of interference. Forster and Kayan [14] ascertain that the main purpose of minimal intervention is to keep deterioration at bay while keeping the building's character and minimising unnecessary disruption. Brereton [15] defines minimal intervention as "as much as necessary", but [16] advises "as little as practical".

There are also specific criteria and processes to follow when maintaining heritage buildings from different nations or areas. English Heritage includes, for example, the goal of repair, the necessity for repair, avoiding unnecessary harm, analysing historical development, implementing established processes, truth to materials, removal of previously damaged alterations, restoration of lost features, and safeguarding the future. Baharuddin et al. [17] suggest that these principles should be seen as needed rules and methods to preserve the building's originality and quality.

It is apparent from the preceding that the supervision and administration of competent and skilled craftsmen or experts are required to maintain and preserve historic structures.

2.3 Challenges in Executing Heritage Building Projects

Heritage projects' difficulties have been witnessed worldwide, including in India, Canada, Finland, Taiwan, the United States, the Middle East, Slovenia, Italy, Israel, Denmark, Austria and England, among other countries. Perovic et al. [18] found in their research in Australia that project managers frequently fail to execute heritage building projects on time, within budget and scope. Both data management and risk assessment are challenging undertakings [19], [20].

Scope Determination

Heritage building projects may also have difficulties since scope determination might be ambiguous [21]. According to Whiteman and Irvvig [22], the problem with the building's user utilisation throughout the maintenance process also presents problems. Albino et al. [23] discovered that most participants in heritage projects in Italy are small firms or small contractors. Mckim et al. [24] recognised unexpected site circumstances, owner-driven scope revisions, design adjustments, procurement challenges, design coordination issues, and regulatory needs in Canada.

Juan et al. [21] discovered that inadequate design information, poor building data, insufficient condition data, and a lack of communication between customers and contractors were all major difficulties in Taiwan. In England, Lee et al. [25] identified the most challenging impediments to be subtle changes and mistakes that are not obvious. Naaranoja and Uden [26] found that the major concerns in Finland were the lack of a decision-making process, scheduling time, clarity of the user's expectations, and risk.

Mitropoulos and Howell [27] found that discovering pre-existing difficulties late in the design process was more prevalent in the United States, tenant-landlord dilemma [28] in Denmark, and failure to record and analyse assumptions in the United States [29].

Resource Constraints

According to Shohet and Perelstein [30], financial constraints influence historical endeavours in Israel. This is obvious in several countries, not just Israel. In their research in Malaysia, Akasah et al. [31] identified a lack of funding for historic project preservation as one of the problems, followed by insufficient management systems, competent individuals, continuous care, shared values, training, and recruiting.

In Lithuania, Dvorak et al. [32] discovered several challenges, including a lack of funds, human resources, time, planned renovation measures, timely documentation, collaboration and communication, different perceptions of the project's goal, changes in politics and policies, a lack of competency, ignorance of benchmarking, and poor management supervision.

Political Influence and Competence

According to Roy and Kalidindi [33], heritage project underperformance may be due to a variety of political, socio-cultural, economic, and technical factors such as urban growth, tourism pressure, a lack of cultural funds, authoritarian governments, improper project selection, corruption, inaccurate conservation policy, and so on. Roy and Kalidindi [33] observed challenges related to agency competency, cost estimating issues, inadequate and unviable documentation, resource constraints, client capabilities, lack of expertise, project stakeholders, and issues in restoring structures to their original state during their research in India.

Inadequate skills among craftspeople have also been identified as a significant issue [34]. Su and Li [35] and Munoth [36] identified that the inability to extract local knowledge could be a significant issue.

As can be seen from the above, heritage projects are riddled with uncertainty, making project management extremely complex. Heritage projects worldwide confront challenges such as time, cost, and poor quality. Furthermore, in their research in Malaysia, Azizi et al. [13] uncovered around 46 problems from previous studies and grouped them into five focal themes to reflect the type of concern: environmental, human, technical, financial, and organisational challenges.

The table below summarises the challenges identified in the literature that impede a Heritage Project's performance.

Table 1: Challenges affecting heritage building projects

No.	Author	Year	Country	Challenges
1	Lee [37] Whiteman and Irvvig [22]	1998	USA	1. The user's usage of the structure during the maintenance process
2	Daoud [21]	1997	Middle East	1. Scope Determination Uncertainty 2. During the execution, the scope may change
3	Albino *et al.* [23]	1998	Italy	1. The majority of the participants are small businesses
4	Mckim *et al.* [24]	2000	Canada	1. Unexpected site circumstances, 2. Owner-driven scope modifications 3. Design adjustments, 4. Procurement issues, 5. Design coordination issues, and 6. Regulatory requirements
5	Shohet and Perelstein [30]	2004	Israel	1. Financial constraints
6	Lee *et al.* [25]	2006	England	1. Errors that are not readily apparent 2. Subtle adjustments
7	Naaranoja and Uden [26]	2007	Finland	1. The absence of a decision-making process 2. Scheduling time 3. Clarity of the user's requirements 4. Risk Evaluation 5. Managing Change

No.	Author	Year	Country	Challenges
8	Juan *et al.* [38]	2009	Taiwan	1. Insufficient design information 2. Totally inadequate building data 3. Insufficient condition data 4. There is a lack of communication between the customer and the contractors
9	Akasah *et al.* [31]	2011	Malaysia	1. Insufficient funds 2. A good management system 3. Skilled personnel 4. Consistent attention 5. Values that are shared 6. Recruitment and training
10	Mitropoulos and Howell [27]	2011	USA	1. Identifying pre-existing problems late in the design process
11	Rahman *et al.* [39]	2012	Malaysia	1. Technical Problems 2. Management and administration problems 3. Financial problems 4. Human behaviour and attitudes 5. Spare parts problems 6. Lack of institutional and training facilities
12	Astmarsson *et al.* [28]	2013	Denmark	1. Tenant-landlord issues
13	Perhavec *et al.* [34]	2014	Slovenia	1. Insufficient skills among craftsmen
14	Gao *et al.* [29]	2014	USA	1. An inability to document and evaluate assumptions
15	Baharuddin *et al.* [17]	2014	Malaysia	1. A lack of maintenance personnel with the necessary knowledge and experience 2. Attack on the Spot or Unplanned 3. The lack of heritage building maintenance guidelines 4. Insufficient financial resources
16	Azizi *et al.* [13]	2016	Malaysia	1. Environmental issues - economic pressure, building conditions, location, business opportunity and third-party interference 2. Human issues - human errors, poor communication between professionals, craftsmen and general labourers 3. Technical issues - limited availability of resources, financial support 4. Financial issues 5. Organisational issues
17	Perovic *et al.* [18]	2016	Australia	1. Project management struggles to fulfil schedule, financial, quality, and scope delivery targets on a regular basis.

No.	Author	Year	Country	Challenges
18	Roy and Kalidindi [33]	2017	India	1. Issues relating to agency competency 2. Estimation issues 3. Inadequate and unviable documentation 4. Restrictions on resources 5. Issues with the client's capabilities 6. A lack of expertise 7. Issues with stakeholders 8. Issues in restoring structures to their original state

From **Table 1**, it can be seen that there are common challenges in different countries. And they can be classified into different categories as follows and demonstrated in **Table 2** using themes [13].

Human Challenges

The human element is crucial and one of the most difficult aspects of heritage project implementation. Inadequate trained staff or artisans, lack of maintenance personnel, bad recruiting, poor communication, lack of competence, human mistakes, and other factors have all been mentioned as barriers to heritage project completion.

Financial Challenges

These problems, which are frequent in many nations, include a lack of cash, inadequate funds, financial challenges and financial limits. This demonstrates that allocating adequate financing for heritage/conservation initiatives remains an issue in many nations. Another crucial component, which is a result of the technical issues discussed previously, is project management to keep costs within budget.

Technical Challenges

Table 2 illustrates that technical concerns make up a higher portion of the obstacles than the other classes/groups indicated above. Insufficient design information, scope determination uncertainty, inability to document and evaluate assumptions, inadequate building data, change management, errors that are not readily apparent, design coordination issues, identifying problems later in the design, issues in restoring structures to their original state, spare parts problems, scheduling time, lack of communication between client and contractors, and lack of maintenance guidelines are all included in this category. These difficulties are a significant factor in the realisation of heritage building projects.

Environmental Challenges

Economic pressures, building conditions, location, and regulatory requirements contribute to these challenges. The majority of participants were small businesses and substantially influenced by third-party interference.

Organisational Challenges

Heritage projects face obstacles from organisations working on them. Opposing conservation ideologies, perplexing rules and guidelines, no standard conservation technique, recruiting and training, concerns linked to agency competency, organisational issues, stakeholder issues, and client capacities are some of the obstacles they face.

The above have been tabulated in **Table 2**, categorising the challenges into themes [13].

Table 2: Categorising Issues in Heritage Projects

Categories/Themes	Challenges
Human	Skilled Personnel Insufficient skills among craftsmen Lack of institutional training Lack of maintenance personnel Recruitment training Poor communication Human behaviour and attitude Weak management and supervision Values that are shared Lack of expertise
	Human errors
Financial	Financial constraints Financial problems Insufficient financial resources Financial issues Estimating issues
Technical	Insufficient design information Scope determination uncertainty Inability to document and evaluate assumptions The user's usage of the structure during the maintenance process Inadequate building data Managing change Technical problems Project management struggles to fulfil project objectives Errors that are not readily apparent Design Coordination issues Risk evaluation Identifying pre-existing problems late in the design process The absence of the decision-making process Issues in restoring structures to their original state Spare parts problems Management and administration problems Scheduling time There is a lack of communication between clients and contractors Lack of maintenance guidelines Inadequate and unviable documentation
Environmental	Economic pressures Building conditions Location Regulatory requirements The majority of participants are small businesses /contractors Business opportunity and third-party interference

Categories/Themes	Challenges
Organisational	Opposing conservation philosophies Confusing laws and guidelines
	No standard method of conservation Recruitment and training Issues relating to agency competency Organisational issues Issues with stakeholders Issues with client capabilities

2.4 Costing in Heritage Building Projects

Cost is regarded as one of the most important factors influencing project success. Among other things, poor cost performance has been a key cause of concern for all stakeholders in new construction and maintenance projects. Devi and Ananthnarayanan [2] argued that projects frequently face cost overruns or escalation that raise the project budget. According to Odeck [40], potential cost overruns should preferably be determined during the planning stage when the design, scope, specification, and ultimate cost are all created.

As previously mentioned, historic projects differ in concepts, techniques, and procedures compared to new building projects. The typical hazards associated with heritage building projects also differ from modern buildings. Costing should incorporate all processes, methods, materials, specialised labour, methodology, and potential risks to meet expectations.

Nawi et al. [1] argued that preparing estimates for conservation work is complex and difficult due to the difficulties in preserving the nature of such work in terms of its eventual content, scope, and specification. The precise task is usually only established after the structure has been opened and destroyed. Because the fabric of the heritage building is culturally significant and should be conserved to the greatest extent feasible, the present building's structure is one of the most crucial criteria in deciding the project's ultimate cost. Mahmoud et al. [41] define heritage building maintenance as "restoring the building fabric as nearly as feasible to the original using traditional techniques and matching materials while being mindful of the original structure". Mechanical and electrical services, on the other hand, are typically expensive due to the complexity of the existing systems. The lack of a clear and precise way of evaluating heritage building maintenance expenses, according to Mahmoud et al. [41], makes it difficult for historical building custodians and owners to design maintenance budgets and financial plans for managing heritage building restoration.

3 METHODOLOGY

The research used a convenience and judgemental sample [42] that was based on one organisation that manages over 704 building properties, of which 351 buildings are listed as heritage buildings. Before data was collected, the authors applied and received ethical clearance from the research institution, and all respondents provided informed consent. Secondary data collected was based on the conservation projects carried out in recent years. About 14 conservation projects were executed and completed between 2011 and 2022. The projects are listed in

Table 3, named A to N. The fourteen projects were executed on buildings which were 60 years old. Three conservation projects were further selected for case studies, whereby the team members who worked on each project were interviewed using semi-structured interview questions. The targeted team members in these case studies were those who were involved in budget preparations and managing project costs until completion.

Projects C, G, and H were chosen for case studies. These heritage-building projects were chosen based on the availability of team members from the organisation who had previously worked on similar projects. Budget overruns also happened on these projects.

Table 3: Criteria for projects selected for the case study

No.	Criteria for selection	Projects		
		C	G	H
1	Heritage building project	√	√	√
2	Budget overruns	√	√	√
3	Completed project	√	√	√
4	Availability of project team members	√	√	√
	Suitability for this study	Yes	Yes	Yes

4 RESULTS

Table 4 shows the secondary data for the heritage building projects. The data set includes 14 heritage building projects completed between 2011 and 2022. The most notable aspect is that the projects had cost or budget overruns ranging from 5% to 180%. This illustrates the high amount of budget uncertainty associated with heritiage restoration projects.

Some of the oldest buildings experienced the biggest budget overruns (see **Table 4**). For example, Project A involved a building that was 107 years old at the time of the study and experienced a cost overrun of 180%. Project K, a building that was 91 years old, had a cost overrun of 87%. A 137-year-old building from Project M had a cost overrun of 60%, and an 82-year-old building in Project C had a cost overrun of 43%.

Table 4: Heritage buildings executed

Project Name	Construction Date (Year)	Building Age (Years)	Original Maintenance Budget (ZAR)	Final Amount (ZAR)	Cost-Overrun (ZAR)	Cost-Overrun (%)
A	1915	107	3 850 000.00	10 789 373.22	6 939 373.22	180%
B	1930	92	13 600 000.00	16 430 409.27	2 830 409.27	21%
C	1940	82	6 500 000.00	9 317 117.83	2 817 117.83	43%
D	1957	65	15 100 000.00	16 756 196.53	1656 196.53	11%
E	1957	65	28 399 000.00	38 648 368.16	10 249 368.16	36%
F	1960	62	32 000 000.00	35 382 984.28	3 382 984.28	11%
G	1926	96	25 000 000.00	33 035 020.15	8 035 020.15	32%
H	1925	97	51 000 000.00	53 556 409.22	2 556 409.22	5%
I	1956	66	102 570 162.68	113 267 986.07	10 697 823.39	10%
J	1946	76	12 500 000.00	16 235 830.77	3 735 830.77	30%

Project Name	Construction Date (Year)	Building Age (Years)	Original Maintenance Budget (ZAR)	Final Amount (ZAR)	Cost-Overrun (ZAR)	Cost-Overrun (%)
K	1931	91	3 500 000.00	6 553 457.00	3 053 457.00	87%
L	1940	82	16 000 000.00	17 052 489.98	1 052 489.98	7%
M	1885	137	800 000.00	1 283 398.18	483 398.18	60%
N	1921	101	16 607 975.00	18 359 612.04	1 751 637.04	11%

Professional Careers, experience and time, worked in the institution

Table 5 illustrates the personal background of the three experts that were interviewed. Each of them worked on populating the budget for these projects and was part of the professional team that worked on them until their completion. Their experience is mostly 10 to 15 years, while the other three have more than 20 years of working experience. Most have worked in this organisation for between 5 and 10 years except for two project managers who worked below five years. The interviewed professionals were Project Managers, Quantity surveyors, and Architects.

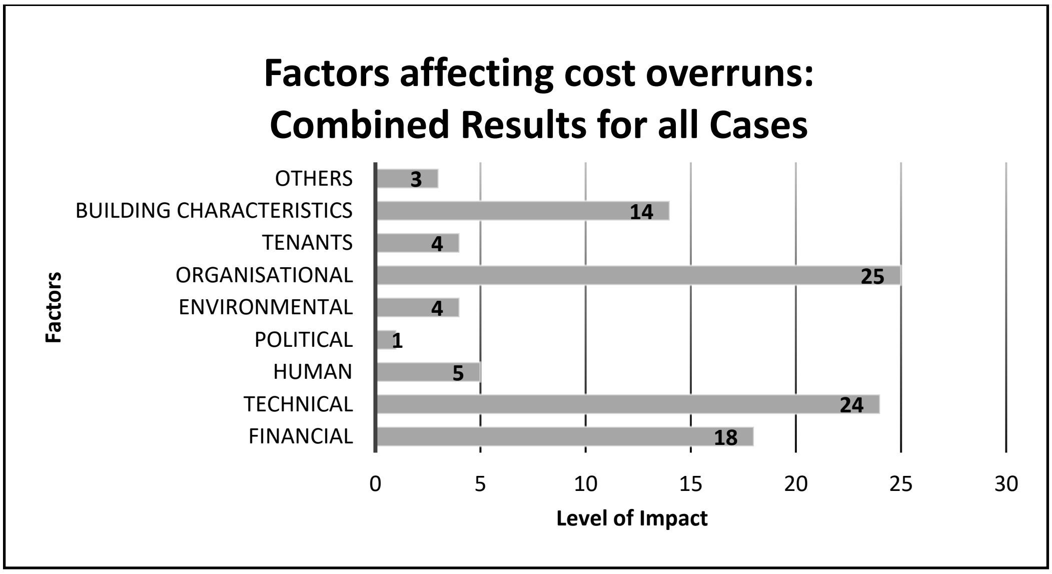
Table 5: Interviewed professionals with experience and years working at the entity

Professional Careers	No. of Professionals	Experience (Years)	Years Worked in the Organisation
Project Manager[1]	3	> 20	5 - 10
Project manager[2]	2	10 - 15	< 5
Quantity Surveyor	2	10 - 15	5 - 10
Other (Architect)	2	10 - 15	5 - 10
Total	**9**		

Factors affecting cost overruns

The interviewees were requested to rate the influence of nine factors affecting cost overruns. A six-point Lickert Scale from 0 to 5 was used. The results indicate that organisational factors were believed to have the most influential impact on project performance (see Figure 1, which illustrates the sum of all the ratings gathered) and, after that, technical factors. Financial factors followed this and then building characteristics. Political factors were considered to have the lowest influence, and human, environmental, tenants, and other factors were considered to have a low influence.

Figure 1: Factors affecting cost overruns (combined results)



Methods used to populate budgets for heritage building projects

The response from the three case studies shows that the professionals used two methods, namely, the elemental estimate method, which also goes with assessing the condition of heritage buildings and the parametric method, using the area method (rate/m^2). They used these estimating methods because they are familiar, quicker and easier to use.

Monte Carlo as a tool for budgeting for heritage building projects

Most of the respondents indicated that they were unfamiliar with Monte Calo Method and were provided with an Open Source Excel Monte Carlo Simulation model [43] to evaluate its capabilities. They indicated that it caters to uncertainty and can therefore be more appropriate for budgeting on heritage building projects.

Monte Carlo Simulation compared with the used estimating techniques

Under this question, the respondents were asked to rate any method they used with the Monte Carlo Method with a rating from 0 to 5, as shown in Figure 2.

Figure 2: Discrpitor rating

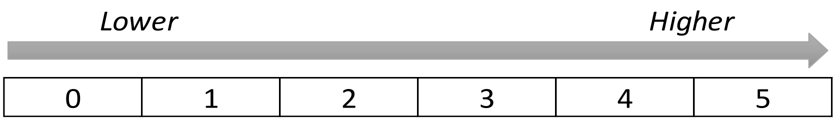
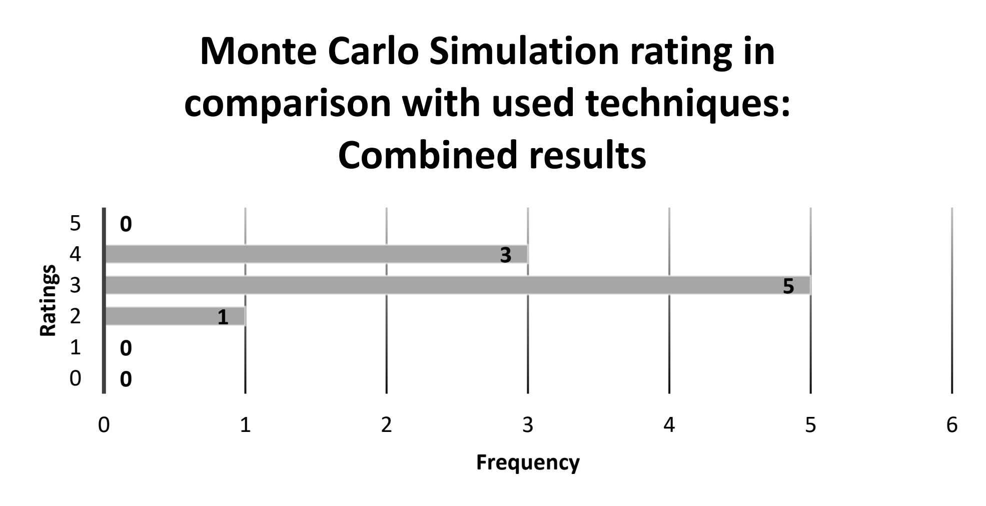


Figure **3** illustrates that the majority of the respondents rated the Monte Carlo Method either three or four out of five, which is higher than the median and thus demonstrates that the respondents, in general, believed that the Monte Carlo Method would be better at preparing budgets than the tools they have historically utilised.

Figure 3: Rating Monte Carlo Method in comparison with used methods



5 FINDINGS

Heritage building projects encounter budget overruns. The 14 heritage building projects considered for this study experienced budget overruns between 5% and 180%. Uncertainty contributed to an increase in project budget overruns. This confirms that heritage building projects are faced with a high amount of uncertainty. Even though not statistically significant, it appears that the older the building, the higher the probability of considerable budget over expenditure.

The respondents indicated that Organisational challenges had the most influence on project performance. After that, Technical aspects were considered to have a substantial impact.

To generate the budgets for heritage building projects, project managers are most comfortable utilising an elemental estimate and parametric approaches (rate/m^2). They found the procedure to be simple and quick to implement. Most project managers in this organisation were unfamiliar with the Monte Carlo Method.

6 CONCLUSION

Scope determination uncertainty, change in scope, inadequate building data, insufficient design information and spare parts problems cause difficulties in preparing a budget for conservation projects. The budget can also be influenced by a lack of heritage building guidelines, issues in restoring structures to their original state, tenant-landlord issues, and identifying pre-existing problems late in the design process. The three case studies demonstrated that organisational issues and technical issues are prevalent.

Project managers preferred the elemental and parametric methods (rate/m^2) when preparing budgets. However, project managers indicated that they expect that using the Monte Carlo Method could assist them with preparing budgets that will provide a better representation of the uncertainty associated with heritage projects. By adding this piece to their toolkit, industrial, systems and engineering managers can provide optimised solutions to complex socio-technical puzzles.

7 RECOMMENDATIONS

The study only considered projects that had already been completed without using the Monte Carlo Method when the project budget was prepared. However, it indicated that the Monte Carlo Method could possibly assist with illustrating uncertainty associated with projects and that this could assist with creating more realistic expectations of projects' financial performance. For this reason, it is recommended that more project managers are trained to use the Monte Carlo Method and that more research is performed to evaluate how it influences project budgeting and performance.

The study was performed within one department of a single organisation. The external validity of the research may be improved by adding additional case studies.

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EXPLORING GRAPHENE PRODUCTION IN SOUTH AFRICA: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Graphene is a recently discovered super material that will most certainly play a big part in the future of manufactured products and nanotechnology. The main limitation to its total takeover of the market, however, is scalability and efficient production. Due to this, not many countries have started producing their own graphene, including South Africa. In this paper, a sustainable graphene production methodology for South Africa is designed for the mass production of graphene through plasma-enhanced methods, due to promising scalability. Waste management becomes a core issue in South Africa with regards to plant design. A systematic literature review explores the core design considerations and capabilities of graphene production in South Africa by means of plasma-enhanced methods. The applicable Sustainable Development Goals are also considered during the analysis. This study exposes the core competencies for graphene production in South Africa and similar developing countries.

Keywords: Graphene, Sustainable Development Goals, Plasma, Waste Management

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1 INTRODUCTION

1.1 Background

Graphene is known as a wonder-material and is undergoing an immense amount of research in a variety of fields today. It was discovered in 2004 and has since been a buzzword throughout many of the different science and engineering disciplines, with many research papers on the topic being released each year.

Graphene is a one-atom-thick sheet of carbon atoms arranged in a honeycomb-like pattern, often referred to as a two-dimensional material. It is the strongest, thinnest, lightest, and most conductive material of both electricity and heat known to man [1]. The capabilities of the material are seemingly endless, and it can be used to shape the future of mankind. South Africa has much to gain from producing its own graphene, since the material is soon to be widely used across many industries and the market is still in its early development.

Graphene is produced in a few countries today, including the United States, the UK, Spain, and China. Most other countries are not producing graphene since they are either still in the early stages of utilising this new technology or have not acquired such technology due to the immense challenge of mass-production. This includes South Africa, which currently has no large-scale graphene production facilities.

Graphene has the potential to further development in a wide range of industries due to its valuable characteristics, especially in terms of nanotechnology, where graphene powder is often used to strengthen polymers. Other uses include biomedical applications, energy storage devices, conductive inks for printed electronics, graphene-based separation membranes and more [2].

The current methods of producing graphene are extremely costly and still developing in terms of efficiency, with most methods generally yielding small amounts of graphene or simply having too high operating costs [3]. According to Dasari et al. [4], the most popular methods that have been developed for graphene production are: Chemical exfoliation of graphite and chemical vapor deposition methods (CVD). These production methods have both been scaled up to a certain degree to produce graphene in larger quantities.

Plasma-enhanced chemical vapour deposition (PECVD) is a type of CVD that enables graphene to be produced more efficiently and at a lower cost than with normal CVD. Inductively Coupled Plasma (ICP) is one popular form of conducting PECVD. PECVD also shows promise of being much more scalable than other known methods [3]. In addition to this, PECVD and other plasma-related graphene production methods allow for the use of low-cost, carbon-containing solids as precursor material, which means that waste material or biomass can be used in production, making the process sustainable to the environment as shown by Ye et al. [5]. This addresses yet another problem South Africa, as well as the rest of the world, is currently facing, namely the efficient use of waste and combatting waste build-up. PECVD is, however, still not an optimal graphene production method since it still requires a high amount of energy and takes time. Thus, further research towards a more efficient graphene production method is still required.

Another issue that needs to be considered is whether South Africa in its current state will be able to maintain or fund the production of graphene, despite the undoubtable benefits of graphene production.

The 17 sustainable development goals will be taken into consideration when conducting this research.

In summary, the following problems currently exist in the graphene industry: Graphene production often incurs high costs and energy usage, whilst also not guaranteeing quality graphene based on the production method used. Graphene is extremely costly even though it has become more affordable in recent time. An optimal graphene production method has yet to be discovered. Successful implementation of a graphene production can thus be a great source of income for the development of the South African economy. For this to realise, it is pertinent that the essential factors are well understood. For example, graphene production scalability still needs to be improved. South Africa has many flaws that might stand in the way of successful graphene production. A deep analysis of the current state of the country is needed. This is important, as South Africa is still a developing country, currently struggling due to the power crisis at hand.

1.2 Research problem

Graphene is a resource not yet tapped into by the South African economy, and the scalability of graphene production in a sustainable manner is one of the greatest challenges in the graphene industry.

1.3 Research aim and objectives

The aim of this study is to establish the conditions for sustainable graphene production in South Africa.

To achieve this, the following objectives are set out:

1. Research graphene production methods, specifically PECVD, as well as how it can be upscaled for mass production
2. Conduct a systematic literature review (SLR) to explore the current state of graphene production
3. Categorise the conditions for sustainable graphene production in South Africa
4. Align the results from this study with those relevant to the Sustainable Development Goals (SGDs)

2 RESEARCH METHODOLOGY

A systematic literature review (SLR) is conducted to answer specific research questions regarding graphene production in South Africa. The general structure of this SLR was formulated by using the SLR conducted by Maisiri et al. [6] and Mangaroo-Pillay [7].

The main aim of this systematic literature review is to evaluate whether the PECVD graphene production method is the best, most scalable, option for the synthesis of graphene. The information obtained will also give insight regarding the extent to which graphene production can be conducted in a sustainable manner. This is to ultimately determine the conditions for graphene production in South Africa. Information is also gathered on the applications of graphene, as well as how often the different types of graphene production are used or mentioned.

2.1 Inclusion and exclusion criteria

The following inclusion and exclusion criteria were formulated and used to identify which of the obtained research papers were to be deemed important for further research.

Table 1: Inclusion and Exclusion criteria

Criteria type	Criteria	Description
Exclusion	Duplicate papers	Paper appears more than once throughout the search
	Full text not available	Not able to retrieve the full text version of the paper

Criteria type	Criteria	Description
	Paper not relevant	Not related to search criteria, or ICP found, but not as an acronym
Inclusion	Partially related	One of the search terms mentioned, whilst discussing potentially useful information
	Closely related	Both search terms mentioned, whilst discussing useful information

2.2 Search strategy

The following search string was applied: "Graphene production" AND ("PECVD" OR "ICP"). utilised to prevent any plasma-related graphene production method from being left out of the search results. These terms were used in a Boolean search string to increase the probability of the search returning relevant research papers, which was demonstrated by Aliyu [6].

In order to effectively gather as much relevant information as possible, the search was conducted on three different scientific journal databases, namely Sciencedirect, Scopus, and Web of Science. Note that no specific time frame was applied since graphene is still a relatively new subject of research with many well-established production methods.

2.3 Study selection

The papers selected for this systematic literature review were obtained and filtered by using the inclusion and exclusion criteria shown in table 1. Figure 2 shows the exact steps followed to obtain the results in the form of a flow diagram. This diagram also shows the exact number of papers used in the final SLR.

Firstly, the search string mentioned in 2.3 was applied to ScienceDirect, Scopus, and Web of Science. After obtaining all the results, a scan was conducted to check if any of the papers might have appeared more than once across the different databases.

Next, each result was analysed to check whether the full text versions were available. If so, the papers were reviewed to check if the search terms were correctly featured, and whether they contain useful information.

In many cases where "ICP" was identified by the search algorithm it would not be due to the use of the acronym, but rather at parts of a sentence containing "atmospheric pressure", highlighting the end of the first word, and the beginning of the latter. This was a frequent occurrence, and papers containing this search result usually did not have any relation to plasma-enhanced graphene production and were thus discarded.

The papers that were not discarded due to the exclusion criteria to this point were thus classified as relevant to the study. These papers were analysed further to group them into different categories, with only few being discarded at a later stage upon further inspection.

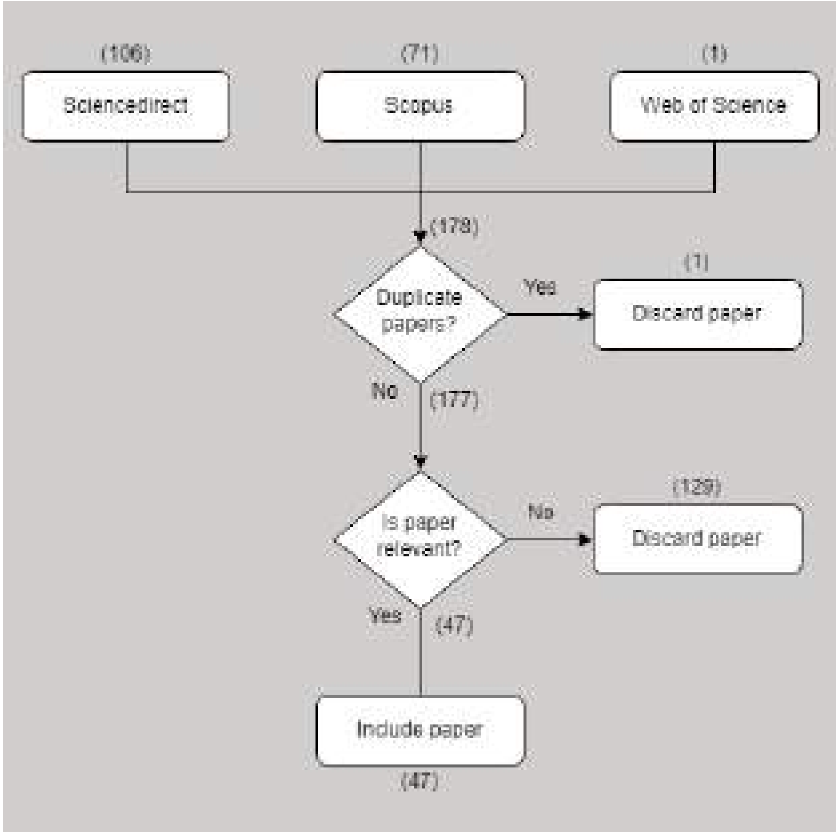

Figure 1: Systematic literature review flow diagram

2.4 Data collection and analysis

Any paper that discussed or mentioned graphene production was analysed to see in what manner they can provide more information. Papers used thus ranged from different categories such as: Scientific experiments where graphene was produced and its quality analysed, research projects where the sustainable use or production of graphene was investigated, reviews on the applications of different types of graphene, synthesis studies where graphene was synthesised on different substrates, and studies where different graphene production methods were compared.

The papers deemed important were each analysed qualitatively and categorised based on the information they contain in Appendix A. These categories are discussed further in section 2.7.

These papers are used to justify the use of PECVD graphene production and to decide whether graphene can be used and produced reliably in a sustainable manner. It also explores whether PECVD graphene production can be carried out on a large scale. Much insight was also gained regarding other plasma-related graphene production methods that have emerged in recent time.

3 FINDINGS

Different results have been formulated from this research. The first set of data pertains to the SLR full paper qualifiers. These appear in Appendix A. These papers are further analysed by presenting several discussion themes in Section 3.2.

3.1 SLR publications

A total of 178 papers were obtained from the three academic databases. From this dataset, one paper was a repetition and 129 were excluded after falling outside the inclusion criteria.

Ultimately, 47 papers were selected for full text reading. The prevalent themes were CVD, PECVD, other plasma-related graphene production methods, waste material usage, scalability of graphene production, graphene applications, comparing graphene production methods, and sustainability.

From these papers, Figure 2 showcases the number of papers per year that were produced. It shows a steady increase in publications as time progresses, indicating that Graphene is becoming more and more relevant.

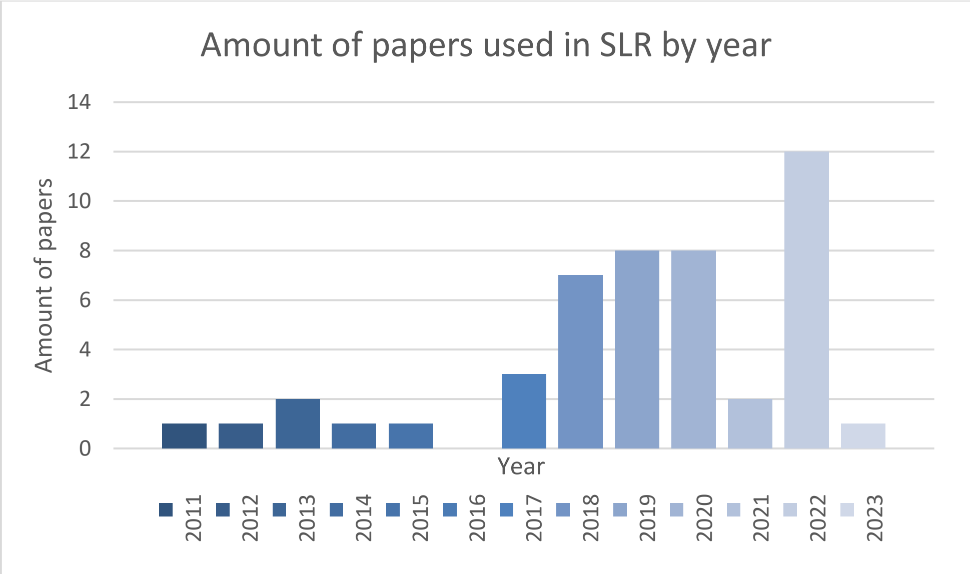

Figure 2: Bar chart of number of papers per year

3.2 Discussion of prevalent themes used to classify papers

3.2.1 PECVD

The paper in question focuses on the PECVD method for the production of graphene or researched the method and communicated findings.

PECVD is an established method of graphene production, and the goal is to include it as the method used in the methodology to be designed, since it is also seen as the most cost effective and scalable method for mass production.

PECVD is used to produce thin films of graphene, and it is preferred to normal, or thermal, CVD due to its lower operating temperatures. A plasma consisting of ions, electrons and some neutral species in both ground and excited states is used in this process. These plasmas are then ignited by means of a high frequency voltage applied to a low-pressure gas. Inelastic collisions then take place within the plasma between electrons and gas molecules, forming excited neutrals and free radicals, as well as ions and electrons. PECVD deposits thin films at lower temperatures by taking advantage of these reactive species [54].

3.2.2 CVD

The papers [13-14, 20-21, 26, 38] place a primary focus on CVD for graphene production.

CVD is often seen as the best graphene production method of graphene, since it has undergone the most research and produces good quality large-area graphene films. CVD is the precursor to PECVD, meaning that both methods produce the same product. CVD is often used as an umbrella term to cover all the different types of CVD that have been developed from the base method, with PECVD only being one of them.

CVD is popular because of its excellent quality products, as well as its enormous potential for scalability. It is, however, in its normal form not a very cost-effective method and is thus not considered for the methodology, but rather its popular derivative in PECVD.

3.2.3 *Various graphene production methods*

Several papers [4, 7, 9-12, 15-18] discussed multiple methods of graphene production. These papers place focus not only on one graphene production method but research many different methods to compare the types of graphene they can be used to produce, or to compare their effectiveness.

These methods can range from chemical exfoliation, CVD, PECVD, Plasma-related graphene production methods, and epitaxial growth. These methods are each useful for the synthesis of different types of graphene products or structures and are thus all researched for their possible improvement or usage.

3.2.4 *Applications of graphene listed*

Certain studies [1-2, 4, 11, 15-18] listed how graphene can be used, whether it be focussed on one specific application, or multiple based on different types of graphene products. Graphene is known to have many different applications, form electronic engineering applications to the biomedical industry, and many papers focus on identifying more new possible applications or refining existing applications.

The various applications of graphene include high frequency transistors, touch screens, solar cells, high-power LEDs, graphene-polymer nanocomposites, clean energy devices, sensors, and field effect transistors.

These are only a few of the currently known applications, and many more will be identified as research continues and graphene becomes more common worldwide.

3.2.5 *Plasma-related graphene production methods*

Many papers [3, 20, 29, 32] had a focus on other plasma-related graphene production methods, showcasing the value of plasma when it comes to the production of graphene. In these papers, plasma torches are usually used in different ways to produce graphene without CVD or other basic production methods.

Plasma-based graphene production is also undergoing immense research and has shown that it can be applied to larger scales to produce graphene of an acceptable quality. Papers containing these results were analysed to compare whether these processes may be more viable than PECVD.

While these methods of graphene production show great merit for producing the material, they are not yet developed to the point of being considered as a scalable method for the mass production of graphene in the same way as CVD methods. For example, the high operating and energy costs incurred make graphene costly and ineffective. They are, however, useful for producing certain types of graphene other that the films produced through CVD methods, like graphene powder, graphene flakes, carbon nanotubes, and vertically oriented graphene.

3.2.6 *Mass production*

Many research papers [14, 16, 18, 21-22] were listed under the category of mass production due to them paying great attention to the possibilities of scalability in the graphene production industry. PECVD or other types of CVD were most commonly mentioned as methods for graphene production at a large or industrial scale.

Mass production is currently one of the main research problems in the graphene industry, and scientists are working hard to find more efficient ways of producing graphene at a large scale.

There was significant evidence in the papers that this is being improved for certain graphene production processes.

The mass production of graphene will undoubtedly spark a great shift in the global economy, as many countries and large corporations are patiently awaiting the arrival of more sustainable, cost-effective methods of graphene production. Graphene will be adopted in many industries, from electronics to aeronautics and biomedicine. It will truly be the material the future is built upon, and it might even be the material to take mankind to Mars.

3.2.7 Sustainable Development Goal alignment

A significant portion of the papers [3, 4, 7, 9] mentioned that graphene has many possible sustainable applications, especially in wastewater treatment, where graphene was used to filter impurities from contaminated water.

Other sustainable uses of graphene include graphene production by using waste materials, which can be of great use for waste management applications.

During this study, it was found that the categories can be linked with some of the SGDS. More specifically, goal numbers eight (Decent work and economic growth), nine (Industry, motivation, and infrastructure), and twelve (Responsible consumption and production) are very important with regards to the application of graphene in South Africa.

In terms of decent work and economic growth, the commercialisation of graphene will most certainly create more job opportunities upon being more commercialised, which is of great importance to South Africa considering the high level of joblessness in the country. Graphene is also in high demand, and this demand is sure to only increase with time, meaning that any country within the industry has the opportunity to grow their economy by producing and exporting the material. The graphene industry can set an example to other production companies of what sustainable production should look like by means of incorporating sustainable production methods and power sources into their daily operation.

With regards to Industry, motivation and infrastructure, graphene will lead to great changes in how many products or structures for infrastructural needs are developed. Graphene's light weight and strength will be used in many different applications, which could include housing and the design of other structural materials. Graphene production facilities will also be able to function sustainably by means of using waste material for the synthesis of graphene, whilst using minimal energy sources. Renewable energy can also be used as a primary source of energy for such facilities, further emphasising sustainability. Graphene is currently also developing and promoting research in a number of different fields, which is another target of this goal. (Mention biomedical application again)

As for responsible consumption and production, measures can be put in place and prioritised to effectively manage all waste from graphene production. Waste management strategies will incorporate the use of graphene production to process certain types of wastes that can be used to produce graphene, reducing the burden of waste on mankind. Graphene production methods can be optimised to minimise waste produced during production. Finally, the limited resources on earth must be carefully considered when designing facility infrastructure, all the way to the operating processes taking place within the production facilities. Any prospective graphene producer must take into account the immense potential uses of graphene production facilities to improve sustainability worldwide.

3.2.8 Reflection on the results

Appendix A shows that many papers tend to discuss more than one graphene production method in somewhat detail. The papers listing many different production methods usually also listed many applications of graphene and discussed how the different production methods can be used in unique ways. 40% of the papers used for this SLR focus primarily on PECVD, with many of the others giving mention to it. The other bulk of the results, however, clearly indicate that many studies have been conducted to produce graphene by means of PECVD. A small portion of the results were focussed on normal CVD or a variety of different CVD methods in one paper.

Other plasma-related graphene production methods also appeared frequently throughout the results, giving insight regarding in what other modes plasma can be used to produce graphene. The plasma-related graphene production methods are often very sustainable, with most of them utilising waste material or other forms of sustainable materials to produce graphene at a low temperature, confirming that these methods can also be used successfully for graphene production. These methods are, however, not recognised to the degree that an established method like PECVD or normal CVD is recognised.

Furthermore, the research conducted confirms that graphene can in fact be used or produced sustainably, especially with regards to waste management, which is one of the core goals set out for sustainable graphene production in South Africa. A popular sustainable use of graphene that appeared multiple times was the use of graphene in wastewater treatment. This can be especially useful in many developing countries like South Africa for more reliable sources of water for rural communities.

Other uses of graphene that were identified include the design of different types of highly effective sensing devices and equipment, the use of graphene films as screens for devices with digital displays, the strengthening of materials through graphene oxide powder, energy storage devices, and even water desalinisation.

It is important to note that most papers, whether they cover the production of graphene through various methods or one specific method, mention that CVD or PECVD is widely considered as the most effective way of producing high quality graphene at a large, or industrial scale. The only downside is that the process is costly, but the advantages of the different PECVD methods over normal CVD and other graphene production methods are too significant. PECVD is also undergoing constant research and improvement, making it the most viable option for graphene production regardless of cost.

The improvement if PECVD is mostly centred around reducing the required energy by decreasing operating temperatures and using the most efficient source material to produce graphene sheets.

4 DISCUSSIONS AND CONCLUSION

This study highlights the fact that graphene is an emerging material of great value and will surely be one of the main building blocks for the future of humankind. A systematic literature review yielded results showing that Plasma-Enhanced Chemical Vapour Deposition is currently seen as the most effective graphene production method, and that graphene can also be used or produced sustainably, further emphasising its usefulness in modern society. Graphene is an untapped market, and countries will soon start producing their own graphene. This knowledge validates the need for graphene in South Africa since the economic benefits of graphene production could be immense.

Future research could explore the detailed costs of implementing a graphene production facility making use primarily of PECVD for graphene production. This could then be used to gauge how accessible graphene currently is worldwide, which can be done by conducting a Monte Carlo simulation taking into account the various contributing factors. Further research with regards to the sustainability of graphene could constitute researching the specific types of waste material that could be used to produce graphene, or how graphene production could be used for waste management. Finally, scalability the scalability of graphene production, specifically through PECVD, could be researched further to draw better conclusions regarding its imminent adoption.

South Africa is a diamond in the rough, a country of great value with challenges in the form of social problems and technological issues. These challenges block the path to imminent greatness and are slowly being broken. Similar to South Africa, graphene is a material of immense value to humanity on the brink of a breakthrough. Just as the visionaries who have brought South Africa to where it is now dug deep to bring change, scientists had to isolate graphene from graphite to reveal its true potential. If we consider scalability and efficiency as puzzle pieces, the key to breaking the boundaries of graphene is placing together these puzzle pieces correctly in order to reveal sustainable Graphene production in South Africa.

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6 APPENDIX A

Systematic literature review publications

#	Author(s)	Year	Research title	Prevalent themes
1	Bayram, O	2019	A study on 3D graphene synthesized directly on Glass/FTO substrates: Its Raman mapping and optical properties.	• PECVD • Applications of graphene listed
2	Bayram, O. & Simsek, O	2019	Vertically oriented graphene nano-sheets grown by plasma enhanced chemical vapor deposition technique at low temperature.	• PECVD • Applications of graphene listed
3	Casanova, A., Rincón, R., Muñoz, J., Ania, C.O. & Calzada, M.D	2021	Optimizing high-quality graphene nanoflakes production through organic (bio)-precursor plasma decomposition.	• Other plasma-related graphene production method used • Waste materials used
4	Mishra, S., Jindal, T. & Choudhary, R	2023	Going green and sustainable with graphene: A wider prospect.	• Various graphene production methods covered • Applications of graphene listed • Mention of green applications for graphene
5	Tyurnina, A.V., Tsukagoshi, K., Hiura, H. & Obraztsov, A.N.	2013	Structural and charge transport characteristics of graphene layers obtained from CVD thin film and bulk graphite materials.	• PECVD • Mass production mentioned • PECVD considered as best graphene production method
6	Mouralova, K., Zahradnicek, R. & Bednar, J	2019	Study of vertical graphene growth on silver substrate based on design of experiment.	• PECVD
7	Ikram, R., Jan, B.M. & Ahmad, W	2020	Advances in synthesis of graphene derivatives using industrial wastes precursors; prospects and challenges.	• Various graphene production methods covered • Waste materials used
8	Naghdi, S., Rhee, K.Y. & Park, S.J.	2018	A catalytic, catalyst-free, and roll-to-roll production of graphene via chemical vapor deposition: Low temperature growth.	• PECVD used, but mentioning that it needs refinement
9	Kumari, P. & Samadder, S.R.	2022	Valorization of carbonaceous waste into graphene materials and their potential application	• Various graphene production methods covered

#	Author(s)	Year	Research title	Prevalent themes
			in water & wastewater treatment: a review.	• Waste materials used • Graphene used for wastewater treatment
10	Lim, J.Y., Mubarak, N.M., Abdullah, E.C., Nizamuddin, S., Khalid, M. & Inamuddin.	2018	Recent trends in the synthesis of graphene and graphene oxide based nanomaterials for removal of heavy metals — A review.	• Various graphene production methods covered • Graphene used for wastewater treatment
11	Ghany, N.A.A., Elsherif, S.A. & Handal, H.T.	2017	Revolution of Graphene for different applications: State-of-the-art.	• Various graphene production methods covered • Applications of graphene listed
12	Lee, X.J., Hiew, B.Y.Z., Lai, K.C., Lee, L.Y., Gan, S., Thangalazhy-Gopakumar, S. & Rigby, S.	2019	Review on graphene and its derivatives: Synthesis methods and potential industrial implementation.	• Various graphene production methods covered • CVD and few other production methods labelled as suitable for mass production
13	Wang, J., Ren, Z., Hou, Y., Yan, X., Liu, P., Zhang, H., Zhang, H. & Guo, J.	2020	A review of graphene synthesis at low temperatures by CVD methods.	• CVD seen as best graphene production method • Many types of CVD discussed
14	Bonaccorso, F., Lombardo, A., Hasan, T., Sun, Z., Colombo, L. & Ferrari, A.C.	2012	Production and processing of graphene and 2d crystals.	• CVD seen as best graphene production methods • Mass production through CVD
15	Ikram, M., Bari, M.A., Bilal, M., Jamal, F., Nabgan, W., Haider, J., Haider, A., Nazir, G., Khan, A.D., Khan, K., Tareen, A.K., Khan, Q., Ali, G., Imran, M., Caffrey, E. & Maqbool, M.	2023	Innovations in the synthesis of graphene nanostructures for bio and gas sensors.	• Various graphene production methods covered • Applications of graphene listed
16	Reddy, Y.V.M., Shin, J.H., Palakollu, V.N., Sravani, B., Choi, C.-H., Park, K., Kim, S.-K., Madhavi, G., Park, J.P. & Shetti, N.P.	2022	Strategies, advances, and challenges associated with the use of graphene-based nanocomposites for	• Various graphene production methods covered • Applications of graphene listed

#	Author(s)	Year	Research title	Prevalent themes
			electrochemical biosensors.	• Mass production through CVD
17	Nag, A., Simorangkir, R.B.V.B., Gawade, D.R., Nuthalapati, S., Buckley, J.L., O'Flynn, B., Altinsoy, M.E. & Mukhopadhyay, S.C.	2022	Graphene-based wearable temperature sensors: A review.	• Various graphene production methods covered • Applications of graphene listed
18	Dasari, B.L., Nouri, J.M., Brabazon, D. & Naher, S.	2017	Graphene and derivatives – Synthesis techniques, properties, and their energy applications.	• Various graphene production methods covered • Applications of graphene listed • Mass production through CVD
19	Kumar, R., Joanni, E., Singh, R.K., Singh, D.P. & Moshkalev, S.A.	2018	Recent advances in the synthesis and modification of carbon-based 2D materials for application in energy conversion and storage.	• CVD main method of graphene production • PECVD
20	Seo, D.H., Rider, A.E., Kumar, S., Randeniya, L.K. & Ostrikov, K.	2013	Vertical graphene gas- and bio-sensors via catalyst-free, reactive plasma reforming of natural honey.	• ICP-CVD (PECVD) used to convert honey to graphene
21	Seah, C.-M., Chai, S.-P. & Mohamed, A.R.	2014	Mechanisms of graphene growth by chemical vapour deposition on transition metals.	• Mass production through CVD
22	Mittal, G., Dhand, V., Rhee, K.Y., Park, S.-J. & Lee, W.R.	2015	A review on carbon nanotubes and graphene as fillers in reinforced polymer nanocomposites.	• Various graphene production methods covered • Applications of graphene listed • Mass production through CVD
23	Singh, V., Joung, D., Zhai, L., Das, S., Khondaker, S.I. & Seal, S.	2011	Graphene based materials: Past, present, and future.	• Various graphene production methods covered • Applications of graphene listed
24	Bahri, M., Gebre, S.H., Elaguech, M.A., Dajan, F.T., Sendeku, M.G., Tlili, C. & Wang, D.	2023	Recent advances in chemical vapour deposition techniques for graphene-based nanoarchitectures: From synthesis to contemporary applications.	• PECVD and more CVD graphene production methods listed • Applications of graphene listed • Environmental applications of graphene listed

#	Author(s)	Year	Research title	Prevalent themes
25	Levchenko, I., Mandhakini, M., Prasad, K., Bazaka, O., Ivanova, E.P., Jacob, M.V., Baranov, O., Riccardi, C., Roman, H.E., Xu, S. & Bazaka, K.	2022	Functional Nanomaterials from Waste and Low-Value Natural Products: A Technological Approach Level.	• Covers variety of plasma-based graphene production methods, PECVD included • Utilisation of waste materials
26	Alrefae, M.A., Shivkumar, G., Alexeenko, A.A., Macheret, S.O. & Fisher, T.S.	2022	Roll-to-Roll Deposition of Thin Graphitic Films and Dependence on Discharge. Modes in Radio Frequency Capacitively Coupled Plasma.	• PECVD • Mass production through PECVD
27	Wang, H., Han, Y., Luo, P., Zhou, Y., Chen, Q., Zhu, H., Yang, Y., Zhang, B. & Huang, K.	2022	Advances in Microwave-Enhanced Chemical Vapor Deposition for Graphene Synthesis.	• PECVD
28	Josline, M.J., Kim, E.-T. & Lee, J.-H.	2022	Recent Advances in the Low-Temperature Chemical Vapor Deposition Growth of Graphene.	• PECVD • Applications of graphene listed • Mass production through PECVD
29	Aissou, T., Braidy, N. & Veilleux, J.	2022	A new one-step deposition approach of graphene nanoflakes coating using a radio frequency plasma: Synthesis, characterization and tribological behaviour.	• Plasma-related graphene production method
30	Sakai, Y., Takeda, K. & Hiramatsu, M.	2021	Graphene growth in microwave-excited atmospheric pressure remote plasma enhanced chemical vapor deposition.	• PECVD
31	Cho, J.H., Cayll, D., Behera, D. & Cullinan, M.	2021	Towards Repeatable, Scalable Graphene Integrated Micro-Nano Electromechanical Systems (MEMS/NEMS).	• CVD chosen over other methods • Applications of graphene listed • Mass production through CVD
32	Snirer, M., Kudrle, V., Toman, J., Jašek, O. & Jurmanová, J.	2021	Structure of microwave plasma-torch discharge during graphene synthesis from ethanol.	• Plasma-related graphene production method
33	Vinoth Kumar, S.H.B., Muydinov, R. & Szyszka, B.	2021	Plasma Assisted Reduction of Graphene Oxide Films.	• Various graphene production methods covered • PECVD • Mass production through PECVD

#	Author(s)	Year	Research title	Prevalent themes
34	Agudosi, E.S., Abdullah, E.C., Numan, A., Mubarak, N.M., Khalid, M. & Omar, N.	2019	A Review of the Graphene Synthesis Routes and its Applications in Electrochemical Energy Storage.	• Various graphene production methods covered • Applications of graphene listed • CVD seen as cost effective and scalable for mass production • Waste materials used
35	Santhosh, N.M., Vasudevan, A., Jurov, A., Filipič, G., Zavašnik, J. & Cvelbar, U.	2020	Oriented Carbon Nanostructures from Plasma Reformed Resorcinol-Formaldehyde Polymer Gels for Gas Sensor Applications.	• PECVD • Mass production through PECVD
36	Mustonen, P., Mackenzie, D.M.A. & Lipsanen, H.	2020	Review of fabrication methods of large-area transparent graphene electrodes for industry.	• PECVD • Mass production through PECVD
37	Jašek, O., Toman, J., Jurmanová, J., Šnírer, M., Kudrle, V. & Buršíková, V.	2020	Study of graphene layer growth on dielectric substrate in microwave plasma torch at atmospheric pressure.	• Various graphene production methods covered • PECVD
38	Alancherry, S., Jacob, M.V., Prasad, K., Joseph, J., Bazaka, O., Neupane, R., Varghese, O.K., Baranov, O., Xu, S., Levchenko, I. & Bazaka, K.	2020	Tuning and fine morphology control of natural resource-derived vertical graphene.	• PECVD • Natural resources used for graphene
39	Mohanta, A., Lanfant, B. & Leparoux, M.	2019	Induction Plasma Synthesis of Graphene Nano-flakes with In Situ Investigation of Ar-H2-CH4 Plasma by Optical Emission Spectroscopy.	• Plasma-related graphene production method
40	Tewari, A., Ghosh, S. & Srivastava, P.	2019	Graphene-CNT hybrids by thermal and plasma-enhanced chemical vapor deposition process: Numerical modeling of growth and energy kinetics.	• PECVD chosen over normal CVD
41	Kim, J., Sakakita, H. & Itagaki, H.	2019	Low-Temperature Graphene Growth by Forced Convection of Plasma-Excited Radicals.	• Mass production through PECVD
42	Rozel, P., Radziuk, D., Mikhnavets, L., Khokhlov, E., Shiripov, V., Matolínová, I., Matolín, V., Basaev, A., Kargin, N. & Labunov, V.	2019	Properties of Nitrogen/Silicon Doped Vertically Oriented Graphene Produced by ICP CVD Roll-to-Roll Technology.	• PECVD

#	Author(s)	Year	Research title	Prevalent themes
43	Dato, A.	2019	Graphene synthesized in atmospheric plasmas—A review.	• Plasma-related graphene production method chosen over PECVD
44	Ye, X., Zhou, H., Levchenko, I., Bazaka, K., Xu, S. & Xiao, S.	2018	Low-Temperature Synthesis of Graphene by ICP-Assisted Amorphous Carbon Sputtering.	• Plasma-related graphene production method • Mass production through CVD mentioned
45	Shavelkina, M.B., Filimonova, E.A., Amirov, R.K. & Isakaev, E.K.	2018	Methane/nitrogen plasma-assisted synthesis of graphene and carbon nanotubes.	• Plasma-related graphene production method
46	Melero, C., Rincón, R., Muñoz, J., Zhang, G., Sun, S., Perez, A., Royuela, O., González-Gago, C. & Calzada, M.D.	2017	Scalable graphene production from ethanol decomposition by microwave argon plasma torch.	• Plasma-related graphene production method
47	Ghosh, S., Polaki, S.R., Kumar, N., Amirthapandian, S., Kamruddin, M. & Ostrikov, K.	2017	Process-specific mechanisms of vertically oriented graphene growth in plasmas.	• PECVD

THE DEVELOPMENT OF A MAINTENANCE STRATEGY PERFORMANCE MEASUREMENT FRAMEWORK

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ABSTRACT

Maintenance personnel and asset care managers need to understand how maintenance contributes to the organisation's business objectives. The effectiveness of a maintenance strategy can only be determined if it can be identified and evaluated as a given maintenance strategy. Organisations measure maintenance performance to remain competitive, identify existing gaps, indicate improvements, and run cost-effective businesses. In situations where operational costs remain high and maintenance costs persist, implementing the maintenance strategy is ineffective. However, using financial data alone is inefficient and does not reflect maintenance performance. This paves the way for the introduction of additional measurement methods. This study followed a systematic literature review to collect data and create new concepts. A maintenance strategy measuring framework is developed to help rail maintenance practitioners measure the effectiveness of their maintenance regimes. The developed framework enables practitioners to identify gaps for improvement.

Keywords: maintenance, key performance indicators,

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1 INTRODUCTION

Maintenance personnel and asset care managers have a crucial role in contributing to an organisation's business objectives [1], [2]. Extensive research has been conducted on maintenance performance measurements, aiming to examine the impact of maintenance strategies within organisations. Breakdowns and downtimes significantly affect plant performance [3], [4]. As stated by Raouf et al. (2006), it is essential to identify and evaluate a given maintenance strategy to determine its effectiveness. In today's competitive landscape, organisations measure maintenance performance to remain competitive, identify gaps, drive improvements and ensure cost-effective operations. [1], [6]–[8]. Traditionally, financial data has been used to measure performance, aiming to reduce operating costs while optimising maintenance expenses [9]. However, relying solely on financial data proves inefficient and fails to provide a comprehensive assessment of maintenance performance. This paves the way for alternative measurement methods, such as balanced scorecards and intelligent systems [10]. A comprehensive performance measurement system encompasses both financial and non-financial metrics, as well as soft and hard metrics [10], [11]. Soft metrics include factors like employee attitude, which are important to consider in assessing maintenance performance. The study of maintenance performance measurement holds significant importance as it challenges the notion that maintenance is simply wasteful, as some managers claim [1], [12]. Nevertheless, Lundgren et al. [13] stated that quantifying maintenance strategy effectiveness is challenging, leading researchers to develop various models and frameworks for quantification.

2 LITERATURE REVIEW

Researchers have proposed several performance maintenance measurements. Some of the proposed measurement methods are generic, whereas others are specific to the manufacturing, energy, and aviation industries. For example, according to Peach et al. [14], maintenance performance can focus on various aspects such as equipment performance, cost performance, process performance, and maintenance function. However, the method proposed by Kang et al. [9] states three categories that need to be established to measure maintenance performance are key performance indicators (KPI), measurement system and metrics.

According to Parida et al. [1], some researchers consider a metric to be a unit of measure. In this case, the measure refers to specific observations characterising performance, whereas the performance indicator is a defined variable. However, despite extensive research, the industry's application of these measurement models, frameworks, concepts, and strategies is limited. Consequently, it remains challenging to quantify the effectiveness of maintenance strategies, signifying a gap between research and practice [13].

2.1 Measurement system

A measurement system can be defined as a set of metrics used to quantify the effectiveness and efficiency of an action [1], [15]. This includes a balanced scoreboard. According to Kumar et al. [6], measurement systems help to identify and integrate four aspects: financial, customer, internal business, and innovation. Before the advent of balanced scoreboards, maintenance performance was mainly based on financial measurements. Maintenance measurement systems are mainly divided into models and frameworks. A framework helps identify boundaries and set up dimensions and relationships among dimensions [16]. In the nonfinancial performance measure, the focus when considering relationships is generally on quality, profitability, effectiveness, efficiency, and survival for growth [16].

Peach et al. [9] proposed a maintenance performance measurement framework that included human aspects . These included knowledge, skills, abilities, and personal characteristics, which are known as competence elements. Maintenance work quality, efficiency, and effectiveness rely on the maintenance workers performing maintenance activities. Phogat and Gupta [17] further emphasised the importance of the level of skill of personnel and the availability of resources. Therefore, human factors should not be ignored in maintenance performance measurements, as they ensure safe, effective, and efficient system performance.

2.2 Key Performance Indicators

According to Kumar et al. [6], maintenance performance first requires the identification of indicators. Performance indicators highlight an organization's deficiencies and help determine the root cause [1]. In the manufacturing industry, KPIs are variables used to reflect on the operational performance. KPIs are used to evaluate the effectiveness of a carried-out activity, and the best method is to consider KPIs that are specific to the organization [16], [18]. When properly utilised, KPIs should highlight company improvement opportunities [19]. Examples of KPIs include efficiency, throughput, availability, productivity, and product quality. Therefore, KPIs are a set of quantifiable variables within a maintenance measurement system that reflects an organization’s performance [6], [9]. However, it is difficult to measure everything that is associated with maintenance. Therefore, it is essential to select what is considered critical for meeting an organization’s objectives.

An example is the manufacturing industry, in which meeting production goals is deemed critical. Therefore, measuring the availability is ideal in such cases [6]. In addition, the European standard BS EN:15341 (2007) [20] for maintenance performance KPI, provides three indicators: economic, technical, and organisational [6].

Researchers have used performance indicators to measure maintenance effectiveness and compare actual conditions to specific preference conditions [6]. Researchers have also argued for the importance of analysing the relationships between different KPIs. This is because KPIs affect one another; therefore, knowing which influences the other is critical. Several KPIs have been identified, some of the KPIs identified by Kumar et al. [6] and Ku and Kim [16] are customer satisfaction, cost, equipment, maintenance safety and environment, employee satisfaction, downtime, change over time, planned maintenance tasks, unplanned tasks, number of new ideas generated, skill, number of training, failure rate, equipment availability, improvement training, quality returned, and employee complaints, respectively. Metrics for maintenance performance are essential in an industry, as they help develop corrective actions and guide steps to meet organizational objectives. According to Wijesinghe and Mallawarachchi [7], the availability of spare parts and the frequency of purchases can be used to measure maintenance performance and calculate the amount spent on maintenance. According to Parida et al. [1], performance indicators can be divided into categories: economic, technical, equipment performance (availability, reliability), cost performance (maintenance, labour, and material cost), and progress performance (ratio of planned and unplanned work, schedule compliance). In analyzing key performance indicators (KPIs), Kumar et al. [6] devised a list of maintenance goals, maintenance functions, and associated key performance indicators.

Researchers have developed frameworks and models for industrial applications. Their utilization is organizational based. The following section focuses on the frameworks and models that were developed. A thin line exists between the framework and model as researchers interchange the two [1]. However, we have adopted the terminology used to present them. We followed the term developer of the tool used’.

2.3 Frameworks

Parida et al.[1] identified 27 frameworks based on a literature review. However, some of the identified frameworks measure the overall company performance and lack focus on evaluating the maintenance strategy. For example, Sink and Tuttle’s [32] framework does not include any specific measures related to maintenance such as maintenance costs or downtime. However, maintenance is a critical aspect of many organisations, and it may be challenging to evaluate maintenance performance without including maintenance-specific indicators [21].

Some previously proposed frameworks are based on financial ratios and may not be the best fit for measuring maintenance strategy performance. The Du Pont Pyramid is an example of such a framework [22]. However, this is a setback in the framework because maintenance strategy performance is not solely determined by financial performance, but involves various factors, including operational efficiency, asset reliability, safety, and compliance.

Some frameworks focus solely on evaluating maintenance strategies. This includes the Preventative Maintenance (PM) matrix framework. Although the framework is commonly used for maintenance strategy performance, it focuses on cost factors and does not fully capture broader aspects of performance, such as reliability, safety, and compliance. While cost is an essential factor in maintenance management, it should not be the only metric used to measure the performance. In addition, the PM matrix does not consider the long-term effects of the maintenance strategies. For example, a maintenance strategy that reduces costs in the short term but leads to equipment failures and costly repairs in the long term may not be considered an effective strategy using the PM matrix. It is commonly used for maintenance strategy performance but has some limitations that should be considered when using it as a performance measurement tool. The PM matrix primarily focuses on the cost factors.

The PM matrix does not account for external factors that impact maintenance strategy performance, such as regulation changes, market conditions, or technological advancements. Finally, the PM matrix may oversimplify the complexity of maintenance management because it treats maintenance as a series of discrete tasks rather than a continuous process. However, this may not fully capture the interconnectedness nature of maintenance management.

The PM Questionnaire is widely used to measure the performance of maintenance strategies. However, the framework focuses on preventive maintenance and does not consider other maintenance strategies such as corrective or predictive maintenance. This narrow focus can lead to an incomplete understanding of the overall maintenance performance and may not provide a comprehensive picture of maintenance strategy effectiveness. The complete list of identified frameworks and measures/indicators/criteria is shown in Appendix A.

2.4 Models

Several models have been proposed to measure the maintenance strategy framework performance. The results are summarised in Table 1.

Table 1: Models for measuring maintenance strategy performance

	Categories	Models	Description
Maintenance measurement methods	Economic value	❖ Value-driven maintenance ❖ Life cycle cost analysis (LCC) ❖ Life cycle profit (LCP) ❖ Sustainability statement	The models that fall under this category are of the economical type. The focus is on costs, net present value or profitability
	Categorisation of maintenance losses	❖ Cost of poor maintenance (CoPM) ❖ Cost deployment ❖ Waste reduction (related to maintenance)	The models that fall under this category describe different approaches to map the losses related to maintenance activities. In addition, these models identify maintenance losses in the system.
	Cost and cost-effectiveness	❖ Total quality maintenance (TQMain)	In this category, the focus is on cost-effectiveness on

	associated with maintenance	❖ Model to describe and quantify the impact of vibration-based maintenance. ❖ A computerized model to enhance the cost-effectiveness of production and maintenance dynamic decisions. ❖ Maintenance function deployment (MFD) ❖ CA-Failure ❖ Fuzzy multiple criteria decision-making model ❖ Activity-based costing (ABC) for cost estimation ❖ Cost-effective degradation-based maintenance ❖ Probability distribution of maintenance costs ❖ Cost model for maintenance services	maintenance issues. The models aim to assess the changes suggested in a system.
	Overall management	❖ Total productive maintenance ❖ The Eindhoven University of technology model	The models in this category provide guidelines on how to work with maintenance management. The main objective of these models is to plan and control maintenance activities.
	Function oriented planning	❖ Reliability-centred maintenance (RCM) ❖ Terotechnology model ❖ Kelly's Philosophy ❖ Risk-based maintenance	Models included in this category are related to the function and reliability of the maintenance system. The focus is on evaluating the different types of failures, among other things.
	Maintenance and simulation	❖ Simulation and maintenance	The model focuses on preventive and corrective maintenance and their impact on resource allocation, performance, and costs.

Table 1 highlights the diverse range of models available for measuring maintenance strategy framework performance. The lessons from these models can help organisations optimize their maintenance strategies and improve the efficiency and effectiveness of their maintenance activities. These models can also assist organisations in optimising resource allocation and making informed decisions to achieve better maintenance strategy outcomes.

3 METHODOLOGY

Three electronic databases were used for this study. These are Scopus, Web of Science, and Emerald. In this process, different maintenance performance measurements and management articles were retrieved and analysed. In addition, this study focused on the methods used in maintenance strategy performance measurement. This has resulted in the identification of various maintenance performance measurement issues and challenges.

The search was restricted to peer-reviewed academic journals, conference articles, book sections and which are in Engineering and written in English. Screening of the initial search results was done through the review of the title and abstract. Articles that were not about maintenance performance measurement were discarded. The final review was on reading the full article text, those that did not address the maintenance performance measurement were discarded.

The remainder of this paper is organised as follows. After a brief introduction, a literature review methodology is provided in Section 2. The section discusses the maintenance performance measurement methods. These are the proposed models and frameworks, including the KPIs. Section 3 discusses the methodology while section 4 discusses the gaps in this study. The development of the proposed conceptual framework is discussed in section 5, and section 6 concludes the paper. Section 7 provides future research.

4 GAP

We identified several gaps in the proposed methods for measuring the performance of the maintenance strategies. These include frameworks with a financial focus, approaches for short-term measures, and failure to measure and integrate all the factors critical to the success of the maintenance strategy.

Traditional financial performance measures provide little indication of future performance and encourage short-termism [1], [23]. The proposed methods are internal rather than externally focused, with little regard for competitors or customers [15], [24]; they lack strategic focus and often inhibit innovation. There is little evidence that organizations ensure complete reflection of organizational maintenance strategies, thus implementing new measures to add new priorities.

5 DEVELOPING THE FRAMEWORK

The developed framework is guided by the integration of maintenance results derived from the overall organisational maintenance strategy [25], [26]. This can be realised through an improved understanding of the operation and maintenance process by identifying, developing, and implementing appropriate quantitative and qualitative performance indicators (PIs) for the maintenance strategy performance measurement system [1]. Furthermore, we assume that the maintenance objectives pursued at a given plant influence performance indicators [27].

The developed maintenance strategy performance measurement framework is used to measure different aspects such as maintenance financial reports; customer satisfaction; monitoring the performance of employees; the health, safety, and environmental (HSE) rating; and overall equipment effectiveness, competitor ranking, productivity, and improvement of the organisation [10]. In addition, it also measures the maintenance budget, plant or system availability targets, and between failures and repair (MTBF and MTTR), maintenance reliability, and downtime are examples of KPIs.

Therefore, asset managers need to measure and determine the relationship between the outputs of the maintenance process and their total contribution to the business objectives. In addition, the efficiency and quality of maintenance need to be measured through key performance indicators (KPIs) to justify investment in maintenance [18]. Key performance indicators must be developed and implemented with the total involvement of the entire organisation.

Maintenance strategy performance indicators are linked to reducing downtime, costs, and waste and enhancing capacity utilisation, productivity, quality, health, and safety. The maintenance strategy performance indicators differ for different industries [28]. Maintenance performance indicators can be classified into several categories. One common method is to classify them into two categories: economic and technical indicators [29]. We use several maintenance strategy performance indicators to enable different practitioners to use our framework. However, the maintenance strategy performance indicators in our developed framework are not exhaustive. However, when organisations develop maintenance strategy performance indicators, the number should be kept as low as possible because monitoring and controlling several indicators is impossible[30].

The framework highlights both lagging and leading indicators. Establishing a link between the lagging and leading indicators helps monitor and control the performance of the process, and the indicators to be linked are selected according to the chosen maintenance strategy [1]. The leading indicator is the maintenance process. Maintenance leading indicators monitor whether tasks are performed well to attain the desired production results [27]. The maintenance strategy process is addressed through identifying work, planning, scheduling, executing, completing work and the continuous improvement phase [31]

The lagging factors are the results of the maintenance process [27]. Our framework is based on maintenance financial reports, reduction of downtime and waste, equipment performance, customer satisfaction, breakdown frequency, health, safety, environmental rating, and competitor rating. In addition, we included benchmarking under lagging performance indicators because it is critical for achieving world-class maintenance performance levels [32], [33]. Therefore, benchmarking is a critical element in the continuous improvement process.

The developed maintenance strategy performance framework aligns business and maintenance objectives, operation and maintenance requirements, and provides a link between the maintenance objectives, maintenance process/efforts, and maintenance results [27].

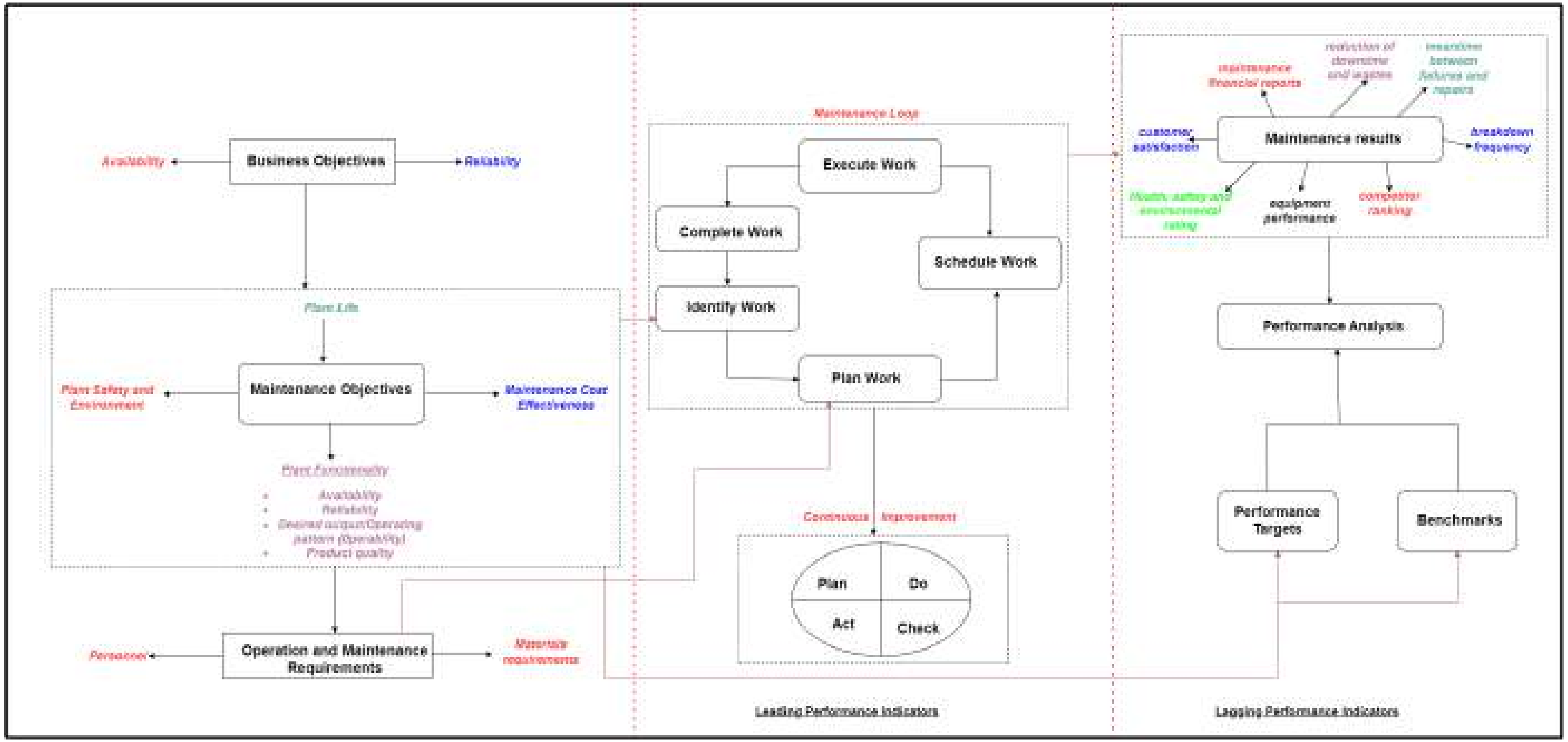

Figure 1 Maintenance strategy performance measurement framework

6 CONCLUSION

An approach (framework) for maintenance strategy performance measurement was developed based on an extensive literature review of different environments. It was developed to make the measurement of maintenance strategy performance feasible. The literature review identified business objectives, maintenance objectives, operation and maintenance requirements, maintenance processes, and maintenance results to formulate a maintenance strategy performance measurement framework. The framework establishes a link between maintenance and business objectives. From the developed framework, business objectives influence the type of maintenance objectives to be implemented. Maintenance objectives enable the organization, in this instance, to meet its business objectives. This study developed a conceptual framework that provides guidelines for choosing maintenance performance indicators by aligning manufacturing and maintenance objectives. The conceptual framework provides a generic approach for developing maintenance performance measures with room for customization to individual company needs. The aim is to ensure that key maintenance processes that may lead to the desired results are carried out and evaluated. This research demonstrates that performance indicators are not defined in isolation but should be the result of a careful analysis of the interaction of the maintenance function with other organizational functions. It seems evident that in the overall interest of the organization, maintenance performance criteria should be balanced with the requirements of the manufacturing objectives.

7 FUTURE RESEARCH

The next step of this research is to validate the framework. This will be conducted through interviews with subject matter experts in the field, such as academics and maintenance practitioners. Second, further research is recommended on the methodological approach of choosing the appropriate maintenance performance indicators among the indicators listed in the literature. Third, research is required to investigate how performance measures can effectively improve performance in practice.

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9 APPENDIX A

Table 2: Adopted from Parida et al [1]

Framework	Measures/Indicators/Criteria	Reference
Sink and Tuttle (1989)	Efficiency, effectiveness, quality, productivity, quality of life and innovation, profitability/budget ability, excellence, survival and growth	[32]
Du Pont Pyramid	Financial ratios	[33], [34]
PM matrix	Cost factors, non-cost factors, external factors and internal factors	[35]
Results and determinants matrix	Financial performance, competitiveness, quality, flexibility, resource utilisation, innovation	[36]
PM Questionnaire	Strategies, actions and measures are assessed, the extent to which they support? Data analysis as per management position or function, range of response and level of disagreement	[37]
Brown's framework	Input measures, process measures, output measures, outcome measures	[38]
SMART pyramid (Performance pyramid)	Quality, delivery, process time, cost, customer satisfaction, flexibility, productivity, marketing measures, financial measures	[39]
Balanced Scoreboard (BSC)	Financial, customer, internal processes, learning and growth	[23]
Consistent PM system	Derived from strategy, continuous improvement, fast and accurate feedback, explicit purpose, relevancy	[40]
PM frameworks for small businesses	Flexibility, timeliness, quality, finance, customer satisfaction, human factors	[41]
Cambridge PM process	Quality, flexibility, timeliness, finance, customer satisfaction, human factors	[42]
Integrated dynamic PM system	Timeliness, finance, customer satisfaction, human factors, quality, flexibility	[43]
Integrated PM framework	Quality, flexibility, timeliness, finance, customer satisfaction	[44]
Dynamic PM systems	External and internal monitoring system, review system, internal deployment system, IT platform needs	[45]
Integrated measurement model	Customer satisfaction, human factors, quality, flexibility, timeliness, finance	
Comparative business scoreboard	Stakeholder value, delighting the stakeholder, organisational learning, process excellence	[46]
Skandia navigator	Financial focus, customer focus, human focus, process focus, renewal and development focus	[47]
Balanced IT Scorecards (BITS)	Financial perspective, customer satisfaction, internal process, infrastructure and innovation, people's perspective	[48]
BSC of advanced information. Services Inc (AISBSC)	Financial perspective, customer perspective, people, infrastructure and innovation	[48]
Intangible Asset Monitor (IAM)	Internal structure: growth, renewal, efficiency, stability, risks (concept models, computers, administrative system). External structure: customer, supplier, brand names, trademark and image Individual competence: skills, education, experience, values, social skill	[47]
QUEST	Quality, economic, social and technical factors	[48]
European Foundation for Quality Management (EFQM)	Leadership, enablers: people management, policy and strategy, resources, processes Results: people and customer satisfaction, impact on society, and business results	[49]
EN 15341	Maintenance key performance indicators	[50]
Multicriteria hierarchical framework for MPM	Balanced and considering the strategic, tactical and operational perspective	[2]
Link and effect model	Technical indicators like availability, capacity utilisation, etc. at the operational level are linked to a strategic level through the tactical level and vice versa	[51]
Venezuela Norma Covenin	Manual for evaluation of maintenance systems through questionnaire and scoresheets	[52]

THE EFFECTS OF SCOPE DEFINITION ON INFRASTRUCTURE PROJECTS: A LITERATURE REVIEW

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ABSTRACT

It has been revealed that good project management in the early stages of a project provides significant chances for reducing many of the challenges that limit project success. In project management, a clearly defined project scope increases the likelihood that the project will be successfully completed within the given timeframe, budget, and desired quality. The goal of this research is to conduct a systematic literature review relating to the effects of scope definition on infrastructure projects. This paper used the literature review method and reviewed published literature ranging from 2013 to 2023. The literature reveals that, despite the fact that project scope determination is viewed as a critical component in successful project management, research on the subject is scarce. The results of the literature review further point out that defining scope in the planning phase maximizes the probability of project success.

Keywords: infrastructure, project management, project success, scope definition

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1 INTRODUCTION

Projects can be thought of as the accomplishment of a particular goal and require the use of resources on numerous tasks or activities [1].The effective execution of a project within the baseline time, approved budget, and quality parameters depends on a clearly defined project scope [2]. When crucial and legally binding decisions are made about the project's early phases, this is commonly referred to as the front-end of the project. Front-end planning (FEP) is a critical stage before the project is carried out since it determines the project's scope [3].

The goal of FEP is to define a project in sufficient detail to clarify what needs to be done to satisfy the needs of the recipients of project deliverables [4]. Pre-planned projects with a clear scope are thought to be less prone to experience unforeseen events like scope creep, timetable slippages, cost overruns, and poor deliverables [5]. According to research [6], pre-project planning is key for capital projects and has a positive impact on project success. Higher levels of pre-project planning effort can result in significant cost and schedule savings, according to the results of a recent study. The study specifically characterized 53 capital facility projects into three distinct pre-project planning effort intensities and examined the overall possible cost and schedule performance variations as stipulated below:

- 20% cost reduction achieved through extensive pre-project planning
- schedule savings of 39% with intensive pre-project planning

The study came to the conclusion that a thorough scope definition prior to project execution is essential to project success because of the significant savings linked to better project predictability [7]. One of the important pre-project planning phase sub processes is the creation of the scope definition package[8]. The amount of effort spent during the scope definition phase will have a substantial impact on the project's success during the detailed design, construction, and start-up phases [9].

It has been proven that this endeavour is an efficient strategy for improving the likelihood of project success while significantly decreasing project implementation risks[10]. The project's risks are examined at this crucial stage, where the project's specific execution strategy is also established [11]. Failure of a clearly defined scope causes execution-related scope variations that increase costs and cause schedule delays [12].

Padalkar and Gopinath [13] looking at the development of the various themes in project management research, they found that the scope management theme had the least amount of influence on articles. Kagogo and Steyn [6] who cited that 87 project experts have recognized inadequate scope definition as a key cause of project failure, emphasizes the need of scope definition. Additionally, scope management was noted as one of the key factors contributing to project success in the Pulse of the Profession survey results [14], and scope control begins with scope definition and scope preparedness.

The following is the paper's structure: section 2 covers the objectives; section 2 the research methodology; and the literature review is presented in section 4. The results of the review study are discussed in section 5; section 6 covers the conclusion of the study; and lastly, future research is discussed in section 7.

2 RESEARCH OBJECTIVES

The proposed study's objective was to conduct a review on the existing literature related to the effects of scope definition on infrastructure projects. The goal was to focus on the impact of how defining scope can influence the performance in the literature on infrastructure projects and shortcomings in order to maximize the probability of project success.

3 RESEARCH METHODOLOGY

The systematic review method was used in the study methodology. A detailed analysis of the literature on the topic at hand is the basis of a systematic literature review. A literature review is an important part of any research studies. In order to identify potential research gaps, the pertinent literature is evaluated and examined through literature reviews. The research gaps ought to be of the kind that, if filled, would advance the field of study. As highlighted by [15], [16]a structured review of the literature is conducted by iteratively selecting appropriate search terms, looking for the pertinent material, and performing the analysis at the conclusion. In this paper, the authors adopted a similar review procedure.

To enhance the analysis of the reviewed literature, the process began with the identification of the key ideas that related to the research question. The criteria included a generic review of the area under research, as well as limiting reviewed papers to those in English, and ensuring the relevance of the reviewed articles to the area under study. To obtain relevant information consent with the purpose and direction of the research, a keyword search of online databases was conducted on the following topics: effects of scope definition of infrastructure projects, impact of scope definition of construction projects, effect of scope readiness on construction projects.

Filters based on the PRISMA technique were constructed according to[16] in order to determine the degree of relevance of the articles to the topic under investigation. According to the PRISMA technique divides the article extraction procedure into four stages: (1) identification; (2) selection; (3) eligibility; and (4) inclusion. Keywords and complementary terms were employed in all the database searches during the identification step, and all articles identified were extracted for the second stage (selection). In the second stage, the following filters were used: The article type, peer-reviewed status, and English language. Titles and abstracts were read in the third step (eligibility), and papers with content directly linked to the topic were selected, with all others being discarded.

An initial search using the search string was conducted which yielded 80 articles. The researchers conducted a preliminary assessment based on reading the abstracts of all selected papers in order to concentrate on the most pertinent literature.

Searches were conducted from Google Scholar. The inclusion criteria were papers published from 2013 to 2023. From the pre-selected papers, we decided to focus on contributions that responded to three characteristics: peer-review published papers; articles in international journals; and papers written in English. Furthermore, papers were filtered according to abstract and full paper relevance. In the end, only selected articles that are relevant to the subject of discussion were reviewed. A structured review methodology adopted a four-step process as presented in Figure 1 below.

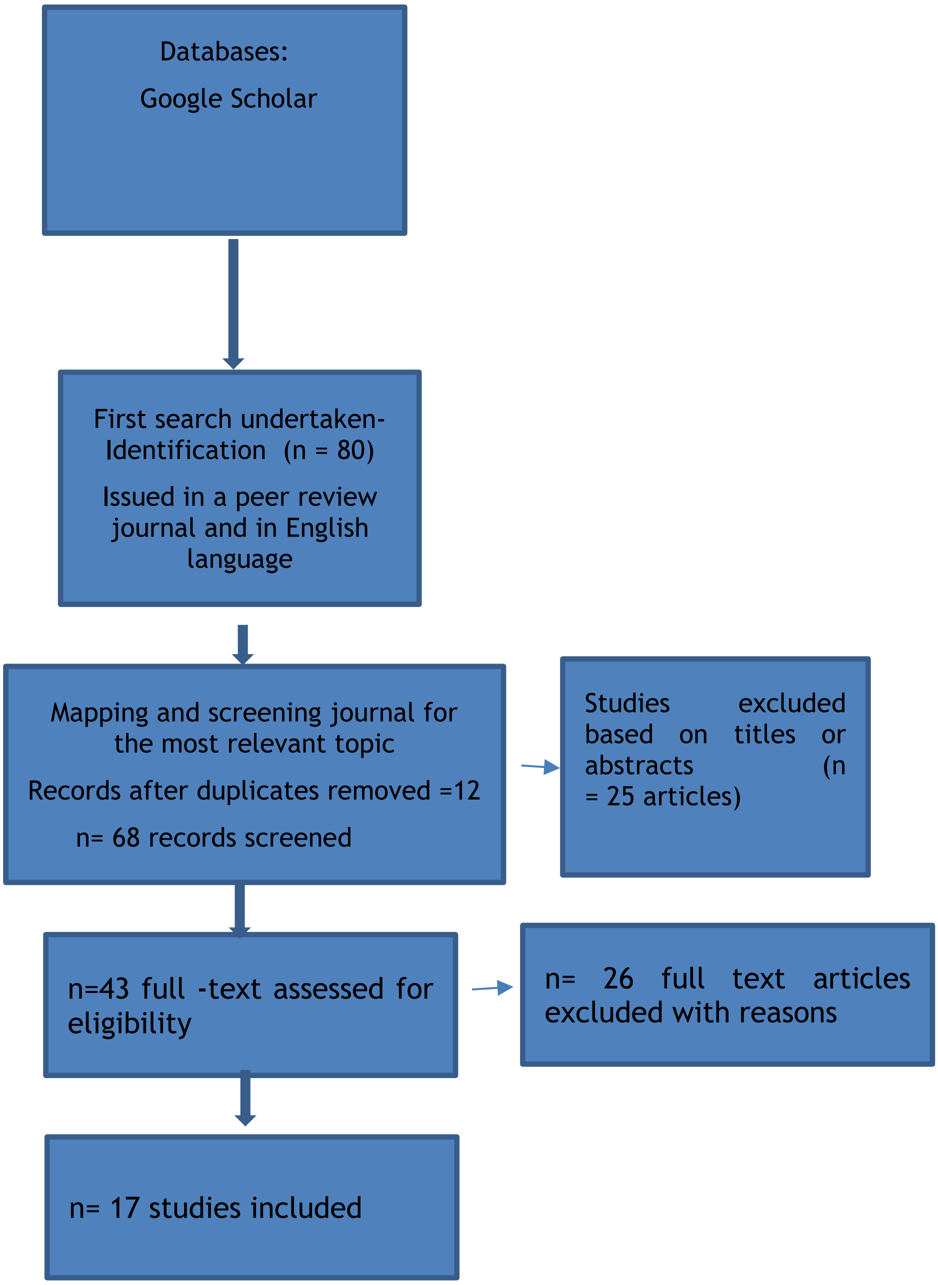

Figure 1: Systematic review flow diagram. Source: Adapted from [15]

3.1 Selection and criteria inclusion of the analysed studies

The research methodology is represented in Figure 1. We used the systematic review principles proposed by [15], [16]. The literature was searched via the search engine of Google Scholar. An iterative process, was used to derive information from the abstracts of published papers. After the first search, a total of 80 studies were identified for our systematic review. To select the final studies to be included in this review, a practical screening was conducted that consisted of the following two steps: 1) the setting of inclusion criteria and 2) the strategy for selecting the potential studies.

3.1.1 Inclusion criteria

To be included in our systematic review, first, a practical screening of the titles and abstracts was conducted following the next inclusion criteria. A study had to meet the following criteria to be included:

- The study must be an article published in a peer review journal in the English language within the last twenty years (2013-2023). Thus, other publication forms (conference proceedings, books, newspaper articles, unpublished works) were not included

3.2 Studies selection

In the second stage, the identified articles were subjected to a double screening. A first sorting of the articles' titles and abstracts allowed us to include 80 potentially relevant studies. Each of these 80 articles were reviewed and assessed according to the inclusion criteria. The second screening went beyond the title and abstract into the full text of the papers. Therefore, after the two-step practical screening, the literature review on finally involves 17 potentially relevant studies that met all the inclusion criteria. All the papers that fulfilled the practical and methodological inclusion criteria were analysed.

4 LITERATURE REVIEW

One of the most important and least understood aspects of management is project management [9]. Construction, defence, power generation, aerospace, product development, software, and other industries are plagued with delays and cost overruns. Projects often appear to be on schedule until near the finish, when faults made earlier are revealed, causing costly rework, expediting, overtime, hiring, schedule slippage, or project scope or quality reductions [17].

4.1 Infrastructure project lifecycle

Implementing phases of the project lifecycle are better for managing infrastructure projects. As illustrated in Figure 2, these projects are normally selected and executed in accordance with four main phases: (1) initiation phase; (2) planning phase; (3) execution phase; and (4) project closure [3].

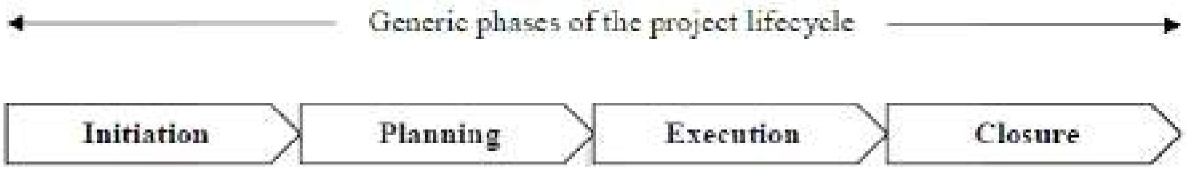

Figure 2: Project lifecycle phases. Source: Adapted from [18]

In the planning stage, a project's requirements and limitations are determined. In the planning stage, a comprehensive project scope is developed, including resource estimation, budgeting, and risk planning [19].

4.2 The project definition rating index (PDRI)

A more recent Construction Industry Institute (CII) study focused on developing an effective technique for measuring the amount of project definition when the project is approved for final funding. The PDRI for Industrial Projects is a new project management tool that helps determine a total score that indicates the degree of scope definition. It is a useful tool that enables a planning team to assess the likelihood of accomplishing project goals during pre-project preparation [17]. The PDRI tool was originally developed for industrial enterprises, including heavy manufacturing, chemical and power plants, and oil refineries [20]. The PDRI for Industrial Projects is a weighted worksheet of 70 scope definition components. The 70 components are broken down into 15 categories and three major divisions. The components were assigned a pre-defined weighting score; the overall score represented the extent of project definition; with a lower score showing better project definition and forecasting the chance of project success [21]. The project team assesses each of the 70 elements' level of definition, and a score is calculated; the lower the score, the more well-defined the project is and the better the chances of predicting the success of the project.

PDRI can be used as:

- a worksheet that the project team can use to decide what procedures to follow in order to define the project scope
- a list of common terms used in scope definitions across the building construction industry
- an industry standard for evaluating the project scope definition package's completeness that would help with risk assessment and forecasting potential for conflict, escalation, etc
- a way to keep track of development at different points during the front-end planning process
- a way to point out areas in a scope definition package that need more clarification, as well as an instrument that promotes communication and alignment between owners and design contractors
- a benchmarking tool for businesses to utilize in comparing the performance of previous projects, both internally and externally, to the completion of scope definition in order to forecast the likelihood of success on future projects

The project's scope management process can be made more effective with the support of the PDRI. When the project scope is established and verified, it is simple to integrate the PDRI into the preliminary planning stage[22]. In particular, the five main pre-project planning sub processes (scope management) can be improved with the PDRI: initiation, scope planning, scope definition, scope verification, and scope change control [6].

- **Initiation:** The PDRI can assist in defining the project's overall requirements for creating and putting together the project team. It can help in comprehending the scope definition's needs and goals by all project stakeholders. The PDRI can also be utilized to establish a baseline for comprehending the building's current state of project definition.
- **Scope planning:** The project team can determine which components of the scope package for the building project are most important using the PDRI. A scope management plan and a scope statement are the end products of scope planning.
- **Scope definition:** In order to measure progress, evaluate risk, and focus future work, the project scope package's completeness can be scored using the PDRI during the planning process.
- **Scope verification:** From the perspective of the project participant, PDRI scores represent the quality and completeness of the project scope package.
- **Scope change control:** The PDRI forces a good, written scope description when utilized correctly.

4.3 Project scope versus product scope

Mirza, Pourzolfaghar and Shahnazari [1] said within the project or program system, the product is a separate system. There are various needs, goals, objectives, stakeholders, drivers, and interfaces for both the project and product scopes. The project scope will have an effect on the product, but other factors will also play a role. The work necessary for creating the project deliverables will be covered by the project scope. The project's scope is defined by the work necessary to accomplish its objectives. On the other hand, a product scope refers to the attributes and characteristics of the outputs of a project [23].

4.4 Project success factors

The guiding concepts that steer the project team's work are scope and objectives. They determine if a project will succeed or fail. One of the most crucial duties in new or development projects is the division of large projects into smaller projects or work packages [18], [24].

Figure 3: Combination of project and product scope influences project success Source: Adapted from [18]

5 RESULTS AND DISCUSSION

Table 1: Studies on effect of scope definition on infrastructure projects

Published	Authors	Title	Purpose	Conclusion
2013	[1]	Significance of scope in project success	Scope is a major contributor in project success.	It is concluded that a greater understanding of the distinction between project and product scope can increase the likelihood of project success.
2013	[9]	Building project scope definition using project definition	The key parts of project scope definition have been highlighted.	Poor scope definition is acknowledged as one of the primary causes of project failure by industry practitioners, influencing projects in terms of cost, schedule, and operational characteristics.
2013	[23]	Managing project scope definition to improve stakeholders' participation and enhance project outcome	The study's goal is to create a technique that will assist a project management team in determining the completeness of project scope specification.	Project definition is improved by managing scope definition and stakeholders.
2014	[25]	Significant Causes and Effects of Variation Orders (VO) in Construction Projects	Hence, the aim of this study is to determine the significant causes and effects of VO in construction projects	The results of the study showed that in Malaysia's projects often have Vo's; majority caused because of, poor workmanship, scope change and design complexity.
2016	[2]	The effect of scope definition on infrastructure projects: A case in	The purpose of this study was to investigate the impact of scope specification on public	According to the findings, there is a considerable direct association between scope

Published	Authors	Title	Purpose	Conclusion
		Malawi's public and private implementing agencies	building projects performed by project implementing agencies (PIAs) in Malawi.	specification and the performance of the sampled infrastructure projects. Projects that were well specified tended to have strong project performance indicators, whereas poorly defined projects tended to have poor project performance indicators.
2016	[26]	Causes and Effects of Scope Creep on Large-Scale Public Sector Construction Projects	The study identifies, explores and models the causes and effects of scope creep of large-scale public-sector construction projects in the Southeast Geopolitical Zone of Nigeria .	The result of the analysis indicates that lack of knowledge and poor understanding of products versatility, and complexity as the most significant cause of scope creep of construction projects with resultant adverse effects on both the projects and the managers
2017	[27]	Key activities in defining the scope for infrastructure projects	To investigate whether applying best practices to the project scoping process could have a positive impact and eventually improve the performance of the infrastructure project.	Defining a clear scope for infrastructure projects and increasing the overall success of infrastructure projects.
2017	[12]	Identifying and managing drift-changes	Project management of unexpected events by investigating a phenomenon known as drift-changes.	Drift-changes occur when external influences have an impact on a project, causing it to generate results that were not initially sought or anticipated by stakeholders.
2018	[28]	Scope creep in construction industry of Saudi Arabia	The impact of scope creep in construction industry of Saudi Arabia	Scope creep increases the duration of project
2019	[6]	Effect of scope readiness on capital projects in mining: a Namibian case study	The impact of scope readiness on mining capital projects.	Scope readiness definition improves project performance.
2019	[4]	The front-end of projects: a systematic literature review and structuring	A systematic literature review on front-end of projects.	Front-end planning is where scope must be defined to ensure project success.
2020	[29]	The impact of scope creep on project success: an empirical investigation	Identify scope creep factors and provide a conceptual framework for experimentally assessing the influence of scope creep on software project success.	The study's findings assist practitioners in understanding the dynamics of elements that inhibit scope creep in order to boost project success rates.
2021	[18]	Predefined project scope changes and its causes for project success	This paper aims to predefine the potential scope changes to keep the project scope on track and identify any weakness in scope definition at the early stages of a project.	Enhancing project scope quality has a massive impact on the success of a project and it adds more control over project scope.
2022	[24]	What is project success: a literature review guru	Factors that determine project success.	Neither practitioners nor academics appear to agree on the definition of project success. It appears to be a

Published	Authors	Title	Purpose	Conclusion
				difficult notion to grasp. This document seeks to present the perspectives of several researchers in this topic.
2022	[30]	Project scope management and successful implementation of infrastructural health program in Nairobi Country	The study was based on stakeholder's theory, the pure theory of public expenditure, theory of constraints, and theory of change which provided a theoretical framework upon which project scope management implementation can be understood.	The findings revealed that scope management has a positive and significant influence on the successful implementation of infrastructural health program. From the study findings, it was concluded that an increase in scope planning, scope scheduling and scope control would lead to an increase in the successful implementation of infrastructural health program
2022	[31]	Project Scope definition and performance of government construction projects in Kenya	The purpose of this study was to examine the relationship between scope definition and performance of government construction projects in Kenya.	The study found that scope definition had a positive and significant effect on project performance
2023	[32]	Project scope management and successful implementation of projects in non-government organizations in Nairobi	This study sought to establish the influence of project scope management on successful implementation of projects in non-governmental organization in Nairobi	The study concludes that scope definition has a positive and significant effect on successful implementation of projects in non-governmental organization in Nairobi

The researchers reported their findings related to effects of scope definition in infrastructure projects. The findings of the literature research indicate that there is a growing body of knowledge about scope definition. Below are the studies done. To some point, these studies make an attempt to understand the importance of scope definition, which happens during the front-end planning of the project and maximizes the probability of project success. Though even these efforts, little or no research has been done on understanding factors that influence insufficient scope definition and comprehensive project pre-planning regarding infrastructure projects, both external and internal factors, and the impact it has.

5.1 Distribution of articles based on year of publication

The number of scope definition-associated articles published from 2013 to 2023 is presented in Figure 4. In 2013 and 2022 a high number of articles related to this study was published compared to other years. This trend indicates the increasing amount of attention by researchers to improve project performance in infrastructure projects. Interestingly, a slow growth trend occurred in 2014,2018,2020,2021 and 2023, where an average of one article was published annually. In 2016,2017 and 2019, the interest in scope definition was increasing considering the number of articles published.

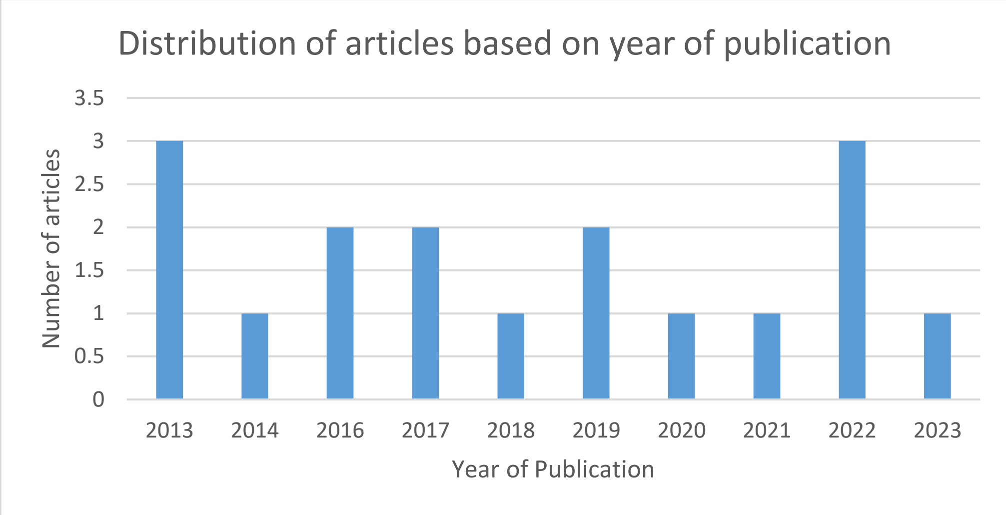

Figure 1: Articles based on year of publication

5.2 Distribution of articles based on journal name

The International Journal of Project Management has the highest number of publications as indicated in Figure 5, with four papers, followed by the South African Journal of Industrial Engineering with three articles, while Procedia Technology, Journal of Architectural Engineering, Institute of Electrical and Electronics, International Journal of Business Management and Procedia - social and behavioural sciences published one article each on the subject. This indicates that the topic of scope definition is covered across different journals with a widespread readership.

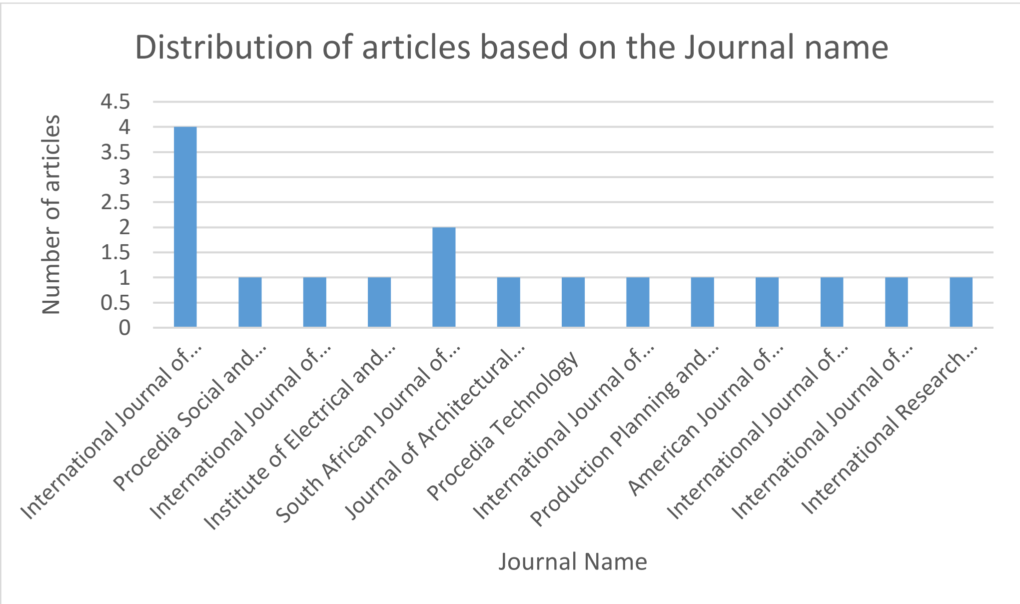

Figure 2: Distribution of articles based on journal name

6 CONCLUSION

The research undertaken identified literature related to scope definition and gaps in the literature. The literature reveals that although project scope definition is regarded as a vital element in successful project management, research on the subject is scarce if looking at the articles tabulated in table 1. The results of the literature review further point out that defining scope in the planning phase maximizes the probability of project success. More research must be done on this topic as it will assist infrastructure projects with better planning, and it will improve the performance of projects. The study's key problem was the scarcity of literature on project pre-planning and scope definition in infrastructure projects. As a result, this study provides a foundation for future research on infrastructure project pre-planning and scope definition.

7 FUTURE RESEARCH

This study suggests further research into the factors that influence insufficient scope definition and comprehensive project pre-planning in infrastructure projects. The implications of additional contingencies on potential poor planning in project life cycle phases should also be considered. There is a good chance that both internal and external forces will affect this occurrence.

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VALIDATING A BEHAVIOURAL SYSTEM DYNAMIC MODEL TO INVESTIGATE BIAS AND DECISION-MAKING INFLUENCES IN THE CIRCULAR ECONOMY

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ABSTRACT

The Circular Economy (CE) is an economic concept that seeks to promote sustainability and reduce waste by closing the loop of resource use; correspondingly, behavioural system dynamics combines systems thinking and behavioural sciences to analyse complex social systems such as the CE. This paper presents how a qualitative research approach such as grounded theory can validate a behavioural system dynamic model. In the context of evaluating causality between variables in a causal loop diagram, grounded theory is used to validate causes and effects. This involves the systematic analysis of existing literature to identify the relationships between variables in the causal loop diagram. This paper aims to identify the causal relationships between variables and to evaluate the strength of the causal effect. This approach can provide valuable insights into the relationships between CE variables and can inform decision-making in various fields.

Keywords: decision-making, circular economy, systems engineering, dynamic modelling

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1 INTRODUCTION:

1.1 Background of the study

The Circular Economy (CE) is a model that presents a framework to further sustainability and moderate waste by managing resource and material uses [1]. It is a complex social system that requires a comprehensive understanding of its dynamics to implement strategies and policies effectively. Behavioural system dynamics combines systems thinking and behavioural sciences to analyse and model such complex social systems [2]. This paper proposes using a qualitative research approach, specifically grounded theory, to validate a behavioural system dynamic model of the CE.

Grounded theory is a well-established research method that involves the systematic analysis of existing literature to identify and validate the relationships between variables also in a causal loop diagram (CLD) [3]. By using grounded theory, the authors can evaluate the causality between the variables and validate causes and effects in the context of the CLD. This approach is particularly useful in identifying the direction and strength of their causal effect within the CE.

This research aims to provide valuable insights into the relationships between behavioural variables in the CE by employing grounded theory to validate the behavioural system dynamic model. These insights can inform decision-making processes in various fields, including policy development, business strategies, and sustainability initiatives. By understanding the causal relationships and dynamics within the CE, stakeholders can identify leverage points for intervention and develop effective strategies to promote sustainability and reduce waste.

1.2 Purpose of the study

By examining existing literature and analysing the relationships between variables in a behavioural CE-CLD, this research aims to validate causes and effects and evaluate the strength of the causal effect. The findings of this study may provide valuable insights into the complex social dynamics of the CE.

This knowledge can guide the development and implementation of effective strategies and policies to promote sustainability and waste reduction [4]. Furthermore, the insights from this study can contribute to the existing body of knowledge on behavioural system dynamics and its application in analysing complex social systems such as the CE [5].

1.3 Significance of the study

The significance of conducting a study on the causal relationships within the CE using a qualitative research approach like grounded theory lies in its potential contributions and implications:

Firstly there is an improved understanding of complex dynamics. The CE is a complex social system with numerous interrelated variables. Investigating and identifying the causal relationships between these variables can lead to a deeper understanding of the dynamics at play.

Also, for more informed decision-making, by uncovering causal relationships and evaluating the direction and strength of the causal effects, this study can provide valuable insights into decision-making processes. Policymakers can utilise the findings to shape policies and regulations that support the transition to a CE. Sustainability practitioners can use the study's outcomes to inform their initiatives and interventions, ultimately driving positive environmental and social impacts. Decision-making in the Circular Economy is currently a focus point for some researchers such as Brenes-Peralta, et al. [6] and Bacher, et al. [7].

Lastly, the advancement of research and theory. This study contributes to the existing body of knowledge on behavioural system dynamics and its application in analysing complex social systems like the CE. It showcases the use of grounded theory as a qualitative research approach to validate behavioural system dynamic models. By expanding the understanding of the CE's causal relationships, this research can inspire further studies and theories in the field, promoting continuous learning and improvement in sustainable practices.

Overall, this study's significance for this paper lies in its potential to inform decision-making, improve understanding, and advance research in the pursuit of a more sustainable and practical CE.

2 LITERATURE REVIEW

2.1 Circular economy and its principles

The CE is an economic model that aims to decouple economic growth from resource consumption and environmental degradation [8]. Unlike the traditional linear economy, which follows a "take-make-dispose" approach, the CE seeks to create a closed-loop system where materials and resources are continuously reused, recycled, or regenerated [9]. This shift towards circularity can help address pressing environmental challenges, promote sustainable development, and unlock economic opportunities. Figure 1 shows the CE framework, with the biosphere on the left and the technosphere on the right.

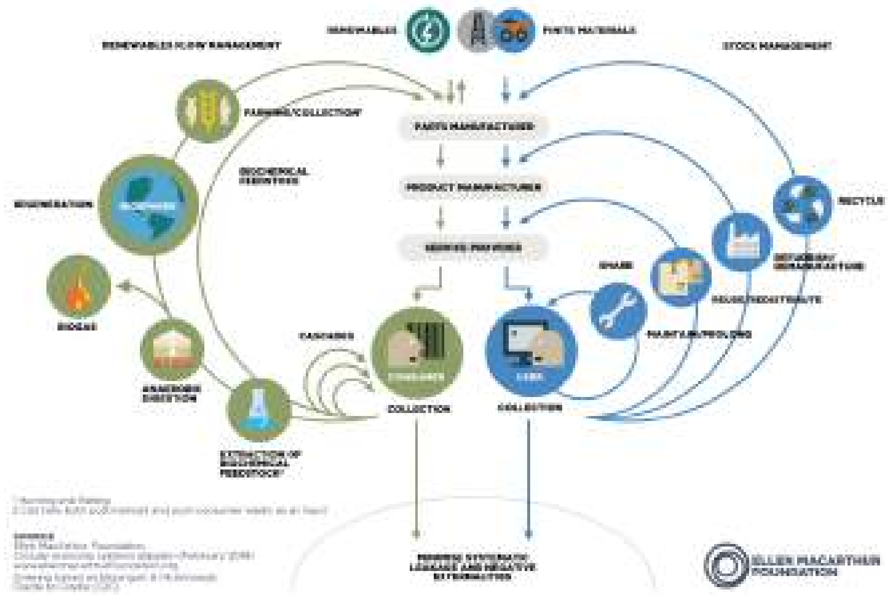

Figure 1: Circular economy butterfly diagram [10]

The principles of the CE can vary somewhat across different frameworks and publications, but they generally revolve around the following concepts:

- A design for circularity. The CE emphasises the importance of designing products and systems with circularity in mind. This principle encourages eco-design, focusing on durability, modularity, recyclability, and using renewable or bio-based materials. Designing for circularity can minimise waste generation, enable easier disassembly, and facilitate resource recovery [11].
- The regeneration of natural systems. This principle highlights the need to restore and regenerate natural systems and resources. It involves practices such as regenerative agriculture, reforestation, and sustainable land management to ensure the

preservation of ecosystems, biodiversity, and soil fertility. By safeguarding natural resources, the CE aims to maintain their availability for future generations [12].

- Preserve and extend the product lifespan. Extending the lifespan of products is crucial to the CE. This principle encourages repairing, maintaining, and upgrading goods to prolong their use. It also promotes sharing and access-based models, such as product leasing, rental services, and the sharing economy, to maximise the utilisation of products and minimise waste [13].
- Shift to renewable energy. The transition to renewable energy sources is a key principle of the CE. By replacing fossil fuels with renewable energy options like solar, wind, and hydropower, the CE aims to reduce greenhouse gas emissions and mitigate climate change. This principle emphasises the importance of energy efficiency and the adoption of clean energy technologies [14].
- Close material loops. Most importantly, closing material loops are central to the CE concept. It involves recycling and recovering materials at the end of their product life cycle. This principle promotes waste separation, sorting, and recycling infrastructure, as well as the use of innovative technologies to extract value from waste and reintegrate materials back into the production cycle [15].

These principles collectively contribute to the goals of resource efficiency, waste reduction, carbon neutrality, and sustainable economic growth within the CE.

2.2 Behavioural system dynamics and its application in the circular economy

Behavioural system dynamics offers a holistic approach to understanding the dynamics and interactions between human behaviour and the circular economy system.

A previous research article examines the suitability of system dynamics modelling in assessing the long-term behaviour and effects of circular business models through a specific case study. The study focuses on modelling and simulating the dynamics of a closed-sharing platform for healthcare institutions, specifically regarding the sharing of durables and consumables. The findings reveal significant potential impacts for durable products, which are influenced by product lifecycle time and the number of use cycles. By utilising system dynamics, this study enables experimentation with CE models by connecting sharing dynamics to resource utilisation and its consequences [16].

Another study focuses on the role of behavioural system dynamics in understanding and promoting circular business models. It demonstrates how the integration of behavioural insights into system dynamics models can facilitate the identification of barriers and drivers for circular business adoption. The research emphasises the need to account for human decision-making, organisational behaviour, and stakeholder interactions when designing circular strategies and interventions [17].

These studies as examples demonstrate the value of integrating behavioural system dynamics into the CE context. Researchers and practitioners can develop more comprehensive and effective strategies for promoting circular practices, influencing decision-making, and fostering sustainable behaviours within the CE by considering human behaviour and social dynamics. In section 3.2.1 a conceptual framework is shown to enable the aforementioned with integrating behavioural system dynamics into the CE context.

2.3 Grounded theory and its role in validating behavioural system dynamic models

Grounded theory is a qualitative research approach that plays a significant role in validating models. It provides a rigorous methodology for exploring and understanding the complex dynamics and relationships within a system, such as the CE.

Research exists that illustrates the application of grounded theory in validating behavioural system dynamic models. The study focuses on developing and validating a system dynamics model of sustainable tourism destinations. Grounded theory is used to analyse and synthesise existing literature, identify causal relationships, and validate the relationships within the model. The findings demonstrate how grounded theory can enhance the validity and reliability of behavioural system dynamic models by ensuring that the model accurately represents the empirical evidence [18].

Bastan *et al.* [19] emphasises the role of grounded theory in validating behavioural system dynamic models through the systematic analysis of literature. The research demonstrates how grounded theory can help identify and validate causal relationships and feedback loops within the model. The iterative process of theory development and testing ensures that the model represents the complex dynamics of the system accurately.

These studies highlight the significance of grounded theory in validating behavioural system dynamic models and can be used as background to develop models for the current research.

2.4 Previous studies on causal relationships between circular economy variables

Research by Geissdoerfer, et al. [1] investigates the causal relationships between various CE variables. The study utilises system dynamics modelling to analyse the interdependencies and feedback loops between variables such as resource efficiency, product design, and waste management. The findings highlight the causal relationships and leverage points within the CE system, shedding light on the factors that can drive or hinder the transition to a CE. These leverage have been included in the conceptual framework in Section 3.2.1.

Furthermore, a study by D'Amato, et al. [20] focuses on the causal relationships between circular business models and sustainability outcomes. The research employs a mixed-methods approach, combining quantitative analysis and interviews, to investigate the impact of circular business models on environmental and economic performance. The findings reveal causal relationships between circular strategies, such as product life extension and resource recovery, and positive sustainability outcomes. These findings show that the strategies followed to influence the succesful implemetation of the CE.

These studies provide insights into the causal relationships between various variables within the CE. By employing different research methodologies and focusing on specific aspects of the CE, they contribute to the understanding of how different variables influence the transition to a circular economy. The studies also show that a gap exists to include the human decision-making factors such as biases for example.

3 METHODOLOGY

3.1 Research design and approach

The research design for this paper follows a qualitative approach, specifically utilising grounded theory methodology. In this study, the research design systematically analyses existing literature to identify and validate causal relationships between variables in a behavioural system dynamic model of the CE. The iterative nature of grounded theory allows for the refinement and validation of the model based on empirical evidence, which will be addressed in future research [21].

The approach begins with an extensive literature review of relevant studies, reports, and scholarly articles related to CE and behavioural system dynamics. The review aims to identify key variables, theoretical frameworks, and empirical evidence on the causal relationships between these variables. A preliminary causal loop diagram serves as the foundation for identifying these variables.

Next, the grounded theory approach systematically analyses the literature to identify patterns, themes, and relationships between the variables [22]. This analysis includes coding and categorising the data, looking for commonalities and divergences, and identifying the direction and strength of the causal effects. The process of constant comparison and theoretical sampling is employed to refine the causal loop diagram and validate the relationships between variables based on empirical evidence.

The research design also incorporates the use of theoretical sampling, where additional literature is selected strategically to fill gaps and explore specific aspects of the causal relationships. The iterative process of data collection, analysis, and theory development continues until saturation is reached, meaning that no new information or relationships emerge from the data [23].

Overall, the research design and approach for this study combine a rigorous analysis of existing literature through grounded theory methodology to identify, validate, and refine the causal relationships between variables in the behavioural system dynamic model of the CE. This approach ensures the integration of empirical evidence, providing a solid foundation for understanding the complex dynamics of the CE and informing decision-making in various fields.

3.2 Data collection and analysis

3.2.1 Data Collection:

The data collection process aims to gather empirical evidence and theoretical frameworks related to the causal relationships between the variables in the CE. The inclusion criteria for the literature will be based on the relevance to the research topic and the quality of the source.The authors looked for scientific behavioural system dynamics and CE-related papers in the Scopus database. Although other databases such as Web of Science (WoS), IEEE Xplore, ScienceDirect and Google Scholar can be included, studies have confirmed Scopus as a good academic database for bibliometric analysis studies [24-26].

The main keywords for the literature search were selected from a previously constructed CLD, as shown in Figure 2. Literature papers between 2005 and 2023 were chosen for the analysis, due to the emergence of significant developments in the field of CE around that time and the availability of a substantial volume of relevant literature. Lastly, the authors centred our focus on journals with high-impact factors according to the CiteScore on Scopus.

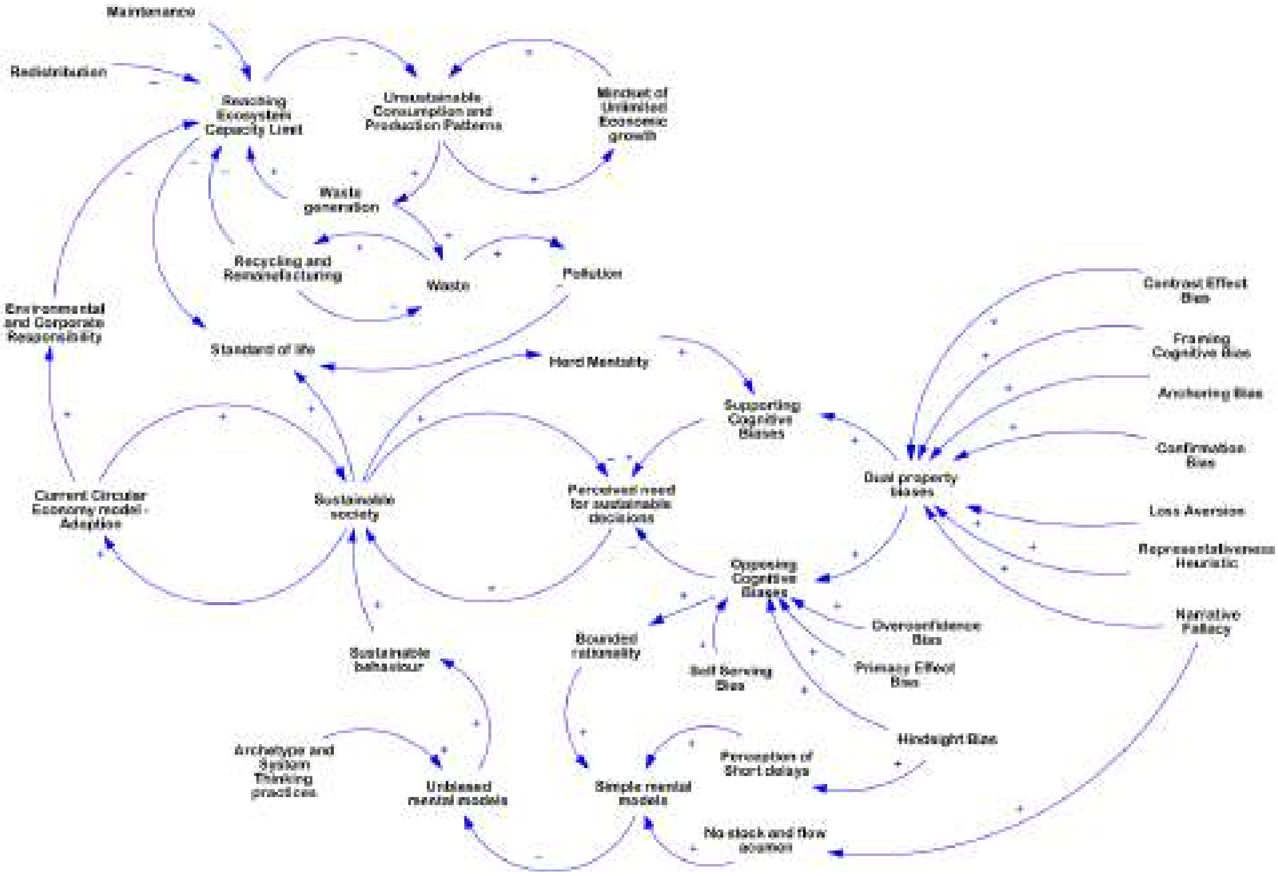

Figure 2: Conceptual integration of cognitive biases in the CE phases

The literature search resulted in a total of 186 papers. The most recent paper was published in March 2023, the same month when the literature retrieval stage was concluded. Figure 3 explains the literature search and retrieval process used. This systematic review methodology excluded any influential books because books are frequently categorised as grey literature possibly owing to the absence of a rigorous peer-review process, in certain instances [27].

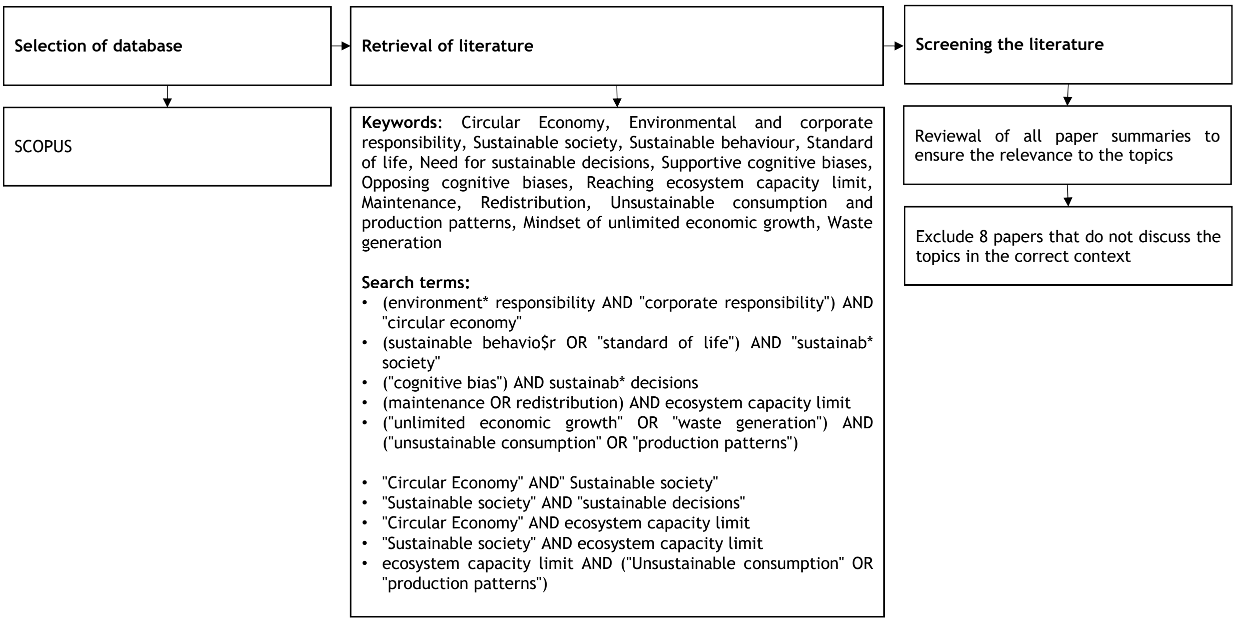

Figure 3: Literature retrieval and screening process

3.2.2 Data Analysis:

The data analysis begins with open coding, where the collected literature is thoroughly reviewed and coded to identify patterns, themes, and relationships between variables [21]. The coding process involves line-by-line coding, assigning codes to paragraphs representing specific concepts or relationships. Through constant comparison, codes are grouped into categories, allowing for the identification of recurring themes and concepts.

After the initial coding process, focused coding is conducted to refine further and consolidate the identified categories and subcategories. This involves selectively coding the most relevant data to the theoretical framework. This involves systematically analyzing the collected information to extract key insights and patterns that contribute to a deeper understanding of the framework. The focused coding process allows for identifying core categories and developing a conceptual framework that represents the causal relationships between variables in the CE.

The analysis process also involves constant comparison of the identified categories and relationships to refine and validate the emerging theory. The resulting codes and code groups for this research are shown in Figure 4 below.

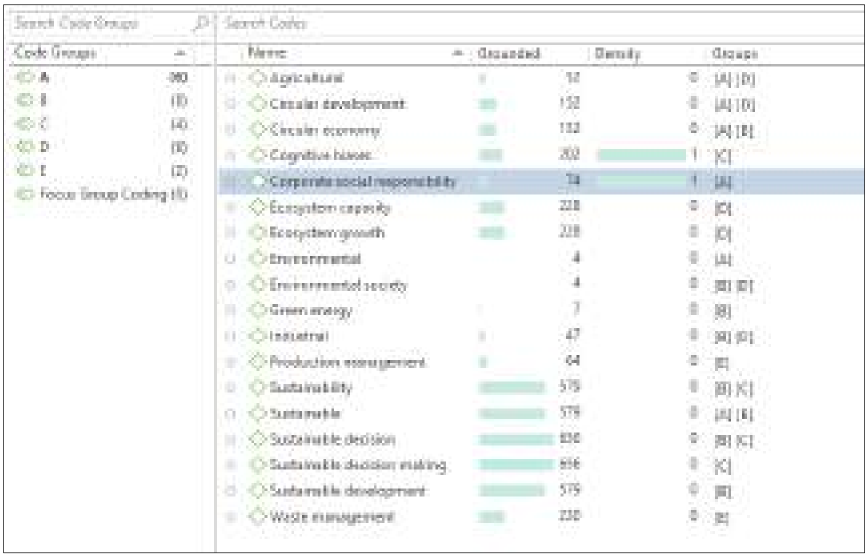

Figure 4: Code manager for the study

The data analysis is supported by qualitative data analysis software such as Atlas.ti to manage the coding process, organise the data, and facilitate the identification of patterns and relationships within the collected literature.

3.2.3 Saturation Test

The authors decided to do a saturation test that involved randomly reserving ten journal papers before coding the remaining papers and then recoding the reserved papers with the rest. After this step, all the existing codes and categories coincided identically. No new codes or themes related to the paper's topic appeared, meaning theoretical saturation had been achieved [28].

Overall, this study's data collection and analysis involved a rigorous and iterative literature review process, coding, and theoretical sampling, following grounded theory methodology. This approach ensures the systematic identification, refinement, and validation of the causal relationships between variables in the behavioural system dynamic model of the CE.

In summary, the saturation test involved a systematic process of coding both a subset of reserved papers and the rest of the dataset, followed by a comparison to ensure consistency.

3.3 Validating causal loop diagram through grounded theory

3.3.1 Grounded theory

The process steps followed to validate the CLD are shown in Figure 5. By following these steps, the researchers can validate the causal loop diagram and gain insights into the causal relationships between variables in the circular economy.

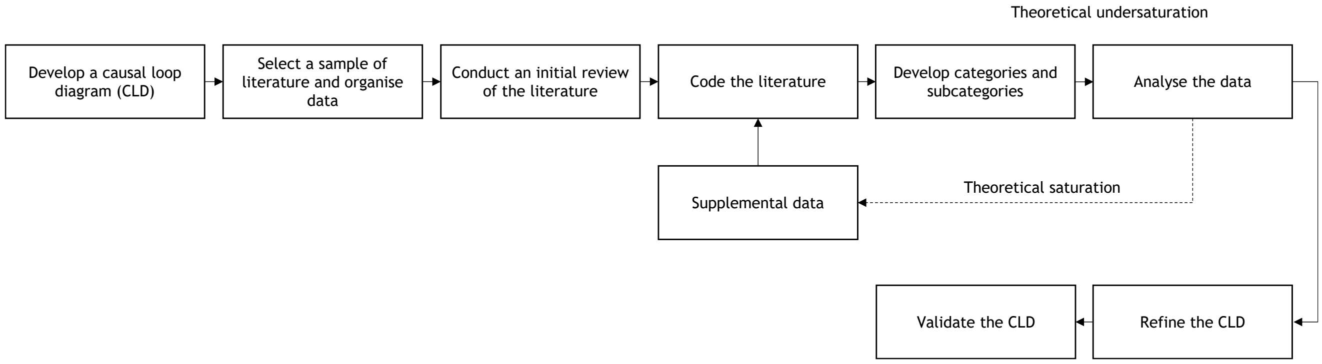

Figure 5: Grounded theory sequence as applied in this paper

The patterns and relationships are analysed to validate the CLD with the coded literature. The codes and CLD variables are reviewed and presented in a network in [6] to reveal any new relationships between variables or suggest changes to existing relationships in the CLD.

The CLD is refined based on the findings of the data analysis and validated by using the results of the grounded theory analysis. This involves assessing whether the causal relationships in the CLD are supported by the literature and the data analysis. In Figure 5 these steps are visualised in sequence. The following section presents the final version of the CLD after 2 iterations of coding and building the networks.

4 RESULTS AND DISCUSSION

4.1 Identification of causal relationships between circular economy variables

To highlight the interconnected nature of CE variables and demonstrate how changes in one aspect can influence and drive changes in others, fostering a more sustainable and circular economic system, the coded variables from the literature were applied to the CLD. For example in Figure 2 the sustainable society is influenced positively as the rate of adopting a CE increases and the negative is also true. The more sustainable the society gets, the perceived need for making sustainable decisions decreases.

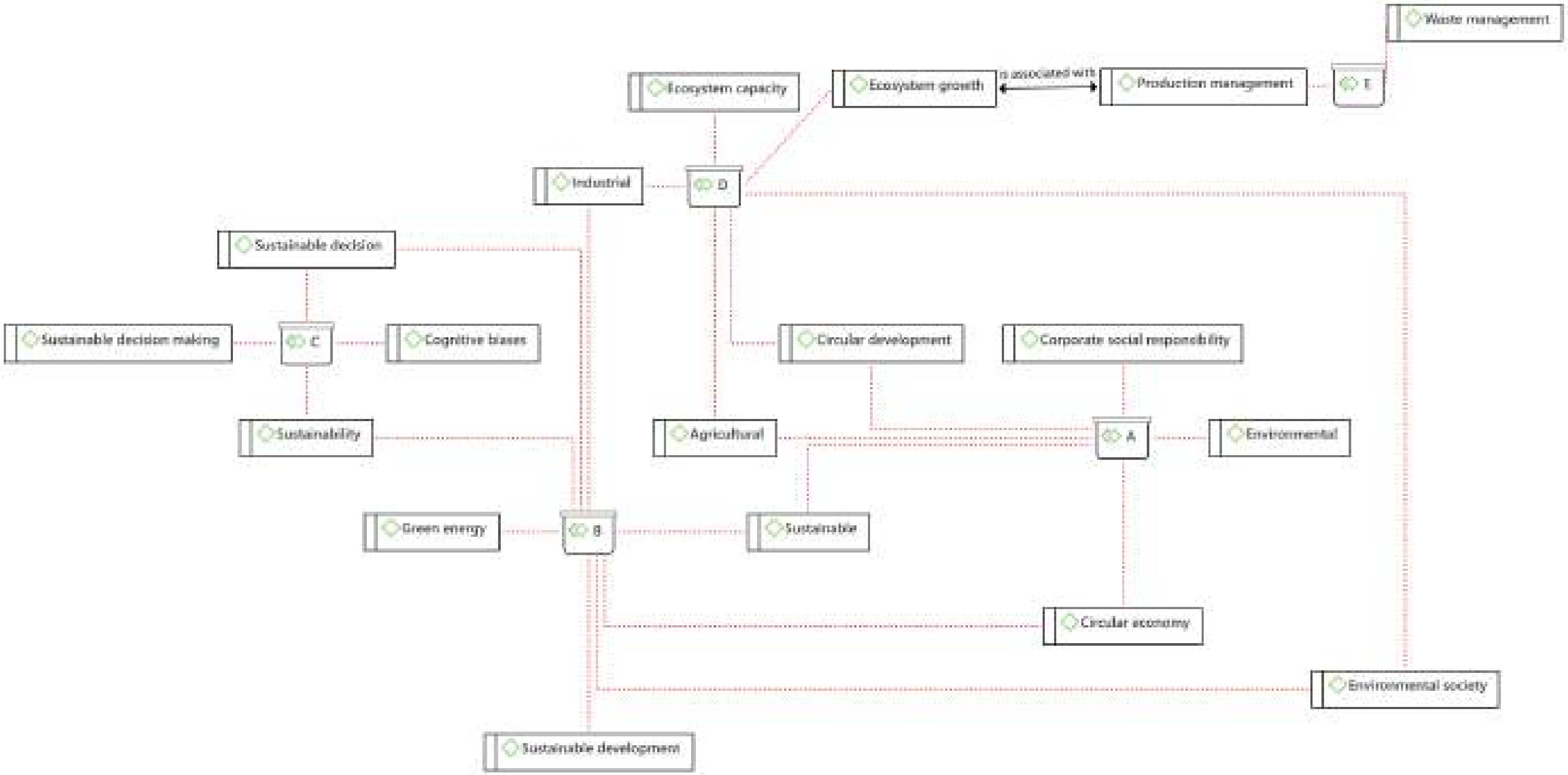

Figure 6: Code network with CLD

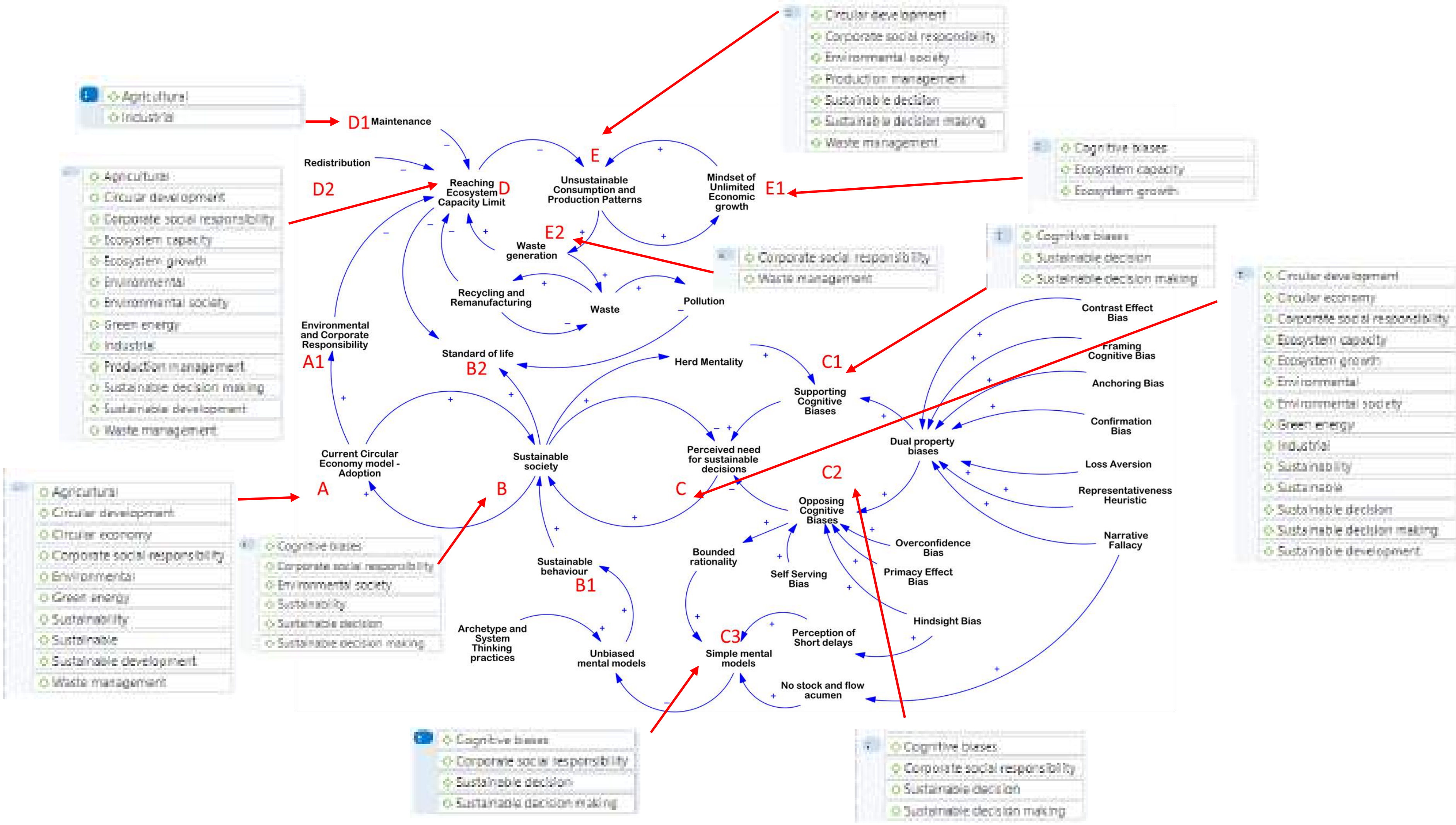

Figure 7: Variable coding added to the CLD

Figure 7 represents how sustainable decision-making can drive the adoption of CE practices, which in turn can enhance waste management and production management strategies. Additionally, the availability and utilisation of green energy sources can contribute to both environmental sustainability and sustainable development. Corporate social responsibility (CSR) influences sustainable decision-making within organisations. A strong commitment to CSR can lead to more environmentally conscious and socially responsible business practices, including adopting circular economy principles. Effective waste management practices positively impact production management. By implementing efficient waste reduction, recycling, and resource recovery strategies, businesses can optimise their production processes, reduce material waste, and enhance overall resource efficiency, which is the aim of the CE all together.

Cognitive biases can hinder the adoption of CE practices. Biases like status quo bias or risk aversion may discourage individuals and organisations from embracing innovative circular business models or making sustainable decisions that involve initial investments or changes to established routines. Consider a manufacturing company that has been using a traditional linear production model for years. Despite the potential benefits of transitioning to a circular economy approach, the management team might be influenced by the status quo bias. This bias could lead them to resist change and stick to familiar practices, even if circular models offer long-term advantages. Ecosystem growth and capacity impact agricultural practices. Sustainable agricultural techniques, such as agroecology or organic farming, can enhance ecosystem health, biodiversity, and soil fertility, leading to more resilient and sustainable food production systems.

Circular development approaches can contribute to the formation of environmental societies. By integrating CE principles into urban planning, waste management, and resource allocation, communities can create sustainable living environments that promote environmental awareness, resource conservation, and a culture of sustainability. Identifying causal relationships is crucial for developing comprehensive strategies and policies that promote a more circular and sustainable economic system.

4.2 Evaluation of the strength of the causal effect

The direction and strength of the causal effects between the mentioned CE variables can vary depending on the specific context and circumstances. In some cases, the causal relationships may exhibit strong positive effects, indicating a direct and significant influence from one variable to another. For example, strong corporate social responsibility practices within an organisation can lead to more sustainable decision-making and greater adoption of circular economy principles. Similarly, effective waste management strategies can directly improve production management efficiency. However, it is essential to note that external factors and complexities within the system can also influence causal effects. Some relationships may be more nuanced, exhibiting indirect or moderate effects. For instance, the influence of cognitive biases on sustainable decision-making may be less straightforward, as biases can impede the adoption of circular practices. However, their impact can be mitigated through awareness campaigns and educational interventions.

Additionally, the strength and direction of causal effects can vary across different sectors, industries, and regions. Factors like policy frameworks, technological advancements, market conditions, and cultural norms can influence the magnitude and direction of causal relationships between circular economy variables.

Table 1 indicates the strength of the causal links between the pre-defined coded groups, as specified in Figure 7, as well as the overall occurrence frequency of the respective codes. The strength of the link is considered by using the number of occurrences [29]. The CSR variable is the most substantial causal effect in the CLD, with sustainable decision-making a close second. The strongest causal links between the coded groups are between A, B and C, which are current CE adoption, a sustainable society and the perceived need for sustainable decisions. The lowest causality ratings are found in code groups D and E, ecosystem capacity limits and unsustainable consumption and production patterns, which correlates with the minimal literature found on the topics. The weakest causal effects in the respective codes with the CLD were found in production management. The sustainability, sustainable and circular economy code frequencies were grouped.

Table 1: Code co-occurrence in CLD by code and code group

Code	Occurrence in CLD
○ Corporate social responsibility Gr=82	8
○ Sustainable decision making Gr=663	7
○ Sustainable decision Gr=662	6
○ Cognitive biases Gr=207	5
○ Circular development Gr=156	4
○ Environmental society Gr=8	4
○ Waste management Gr=234	4
○ Agricultural Gr=55	3
○ Ecosystem capacity Gr=231	3
○ Ecosystem growth Gr=231	3
○ Environmental Gr=7	3
○ Green energy Gr=10	3
○ Industrial Gr=50	3
○ Sustainability Gr=582	3
○ Sustainable development Gr=582	3
○ Circular economy Gr=154	2
○ Production management Gr=66	2
○ Sustainable Gr=581	2

Coded groups	Occurrence in CLD
A Gr=870; GS=6	9
B Gr=875; GS=8	9
C Gr=867; GS=4	9
D Gr=490; GS=6	7
E Gr=298; GS=2	4

In Figure 8, an extract of Atlas.ti the software used, is shown. The grounded frequencies in this figure as well as in Table 1, are the number of occurrences across all the literature used in this study. The highest grounded code and code groups are sustainable decision-making and sustainable society.

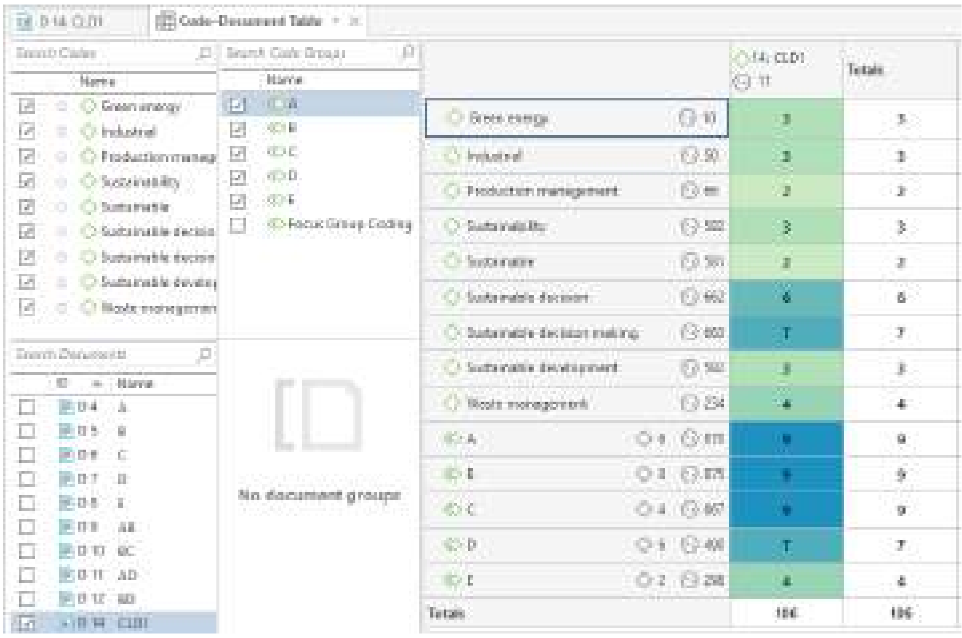

Figure 8: Grounded theory applied to codes and CLD

These insights can guide decision-making processes and support the development of effective strategies for promoting a more sustainable and circular economic system.

4.3 Implications of the results for decision-making in various fields

Developing effective strategies for promoting a more sustainable and circular economic system requires a thoughtful and informed decision-making process. Here are some key decision-making processes that can support the development of such strategies:

- Holistic analysis: Decision-makers should conduct a holistic analysis that considers economic, environmental, and social factors. This involves evaluating the potential impacts and trade-offs associated with different strategies and considering their long-term sustainability implications [30].
- Stakeholder engagement: Engaging relevant stakeholders, including businesses, policymakers, civil society organisations, and communities, is essential. Inclusive decision-making processes that incorporate diverse perspectives can lead to more comprehensive and socially acceptable strategies [31].
- Policy and regulatory frameworks: Establishing supportive policy and regulatory frameworks is essential for driving the transition to a sustainable and circular economy. Decision-makers should consider implementing measures such as incentives, regulations, and standards that encourage sustainable practices and reward circular business models [32].
- Collaboration and partnerships: Collaboration among various stakeholders, including government bodies, businesses, academia, and NGOs, is vital. Decision-makers should foster partnerships to share knowledge, resources, and best practices and collectively address systemic challenges [33].
- Innovation and research: Encouraging innovation and research is key to developing and implementing effective strategies. Decision-makers should support research and development initiatives that explore new technologies, business models, and practices that align with circular economy principles [34].
- Education and awareness: Promoting education and awareness among decision-makers, businesses, and the general public is crucial. Decision-makers should prioritise educational campaigns that raise awareness about the benefits of a circular economy, provide guidance on sustainable practices, and foster a culture of sustainability [35].

By integrating these decision-making processes, stakeholders can develop and implement effective strategies that promote a more sustainable and circular economic system. Continuous evaluation, monitoring, and adaptation of strategies based on feedback and new insights are also essential to ensure ongoing progress towards sustainability goals.

5 CONCLUSION

5.1 Summary of the paper

This paper explores using grounded theory to validate system dynamic models for CE sustainability transitions. The research highlights the iterative process of validating a system dynamics model based on a literature review. Grounded theory is employed to validate the relationships and feedback loops in the model, ensuring that it aligns with real-world dynamics and captures the complexities of CE sustainability transitions. The integration of the grounded theory and the CLD presents the value of identifying real-world links between the CE variables and the external environment. In Figure 6 the connections between the codes from the grounded theory and the CE is seen.

5.2 Limitations and future research directions

While efforts to promote a sustainable and circular economic system have gained momentum, there are certain limitations and areas for future research that warrant attention:

- Data availability and quality: Limited availability and quality of data on CE indicators pose challenges for decision-making. Future research can focus on improving data collection methods, standardising metrics, and developing comprehensive databases to enhance the accuracy and reliability of sustainability assessments.
- Complexity and interdependencies: The CE system has numerous interdependencies and feedback loops. Understanding and modelling these complexities present challenges. Future research can explore advanced modelling techniques, such as agent-based modelling or network analysis, to capture the intricacies of circular economy systems and improve decision-making processes.
- Policy integration and coherence: Coherence and integration across various policy domains are crucial for achieving a sustainable and circular economy. Future research can delve into approaches for integrating policies across sectors, addressing potential conflicts, and identifying synergies to foster a comprehensive and coordinated policy framework.
- Behaviour change and consumer engagement: Shifting consumer behaviours and promoting sustainable consumption patterns are pivotal for circular economy adoption. Future research can explore effective strategies to incentivise behaviour change, overcome cognitive biases, and enhance consumer engagement through targeted interventions, communication campaigns, and nudging techniques.
- Business models and market transformation: Transitioning towards circular business models requires overcoming barriers and incentivising transformative changes. Future research can explore innovative business models, financial mechanisms, and regulatory incentives to facilitate market transformation and encourage the widespread adoption of circular practices.
- Social and equity considerations: Ensuring social inclusiveness and equity within a circular economy is critical. Future research can investigate the social implications, distributional effects, and potential trade-offs of circular economy strategies. This includes exploring how circular practices can contribute to job creation, social well-being, and reducing inequalities.
- Global collaboration and policy transfer: The circular economy is a global challenge that requires international collaboration and knowledge sharing. Future research can explore mechanisms for facilitating cross-country collaboration, policy transfer, and learning from successful circular economy initiatives worldwide.

Addressing these limitations and pursuing these future research directions can provide valuable insights and tools to policymakers, businesses, and stakeholders in advancing sustainable and circular economic systems, ultimately leading to a more resilient and prosperous future.

5.3 Practical applications and recommendations

The validated causal relationships can provide valuable insights for decision-making processes in various fields. Stakeholders, including policymakers, businesses, and researchers, can use the validated model to inform their strategies, policies, and interventions related to the CE. The validated model can educate and raise stakeholders' awareness about the CE. It can serve as a basis for educational programs, training materials, and workshops aimed at fostering a better understanding of the interdependencies and impacts of CE variables. The study can pave the way for future research directions in behavioural system dynamics within the context of the CE. This includes exploring more complex system dynamics models, refining the causal relationships, and conducting empirical studies to validate the model's findings.

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DECISION SUPPORT FRAMEWORKS AND MODELS GUIDING MEDICAL DEVICE LOCALISATION IN LMICS: A STRUCTURED REVIEW

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ABSTRACT

Low- and middle-income countries (LMICs) need better access to cost-effective and value-adding medical devices to minimise their reliance on imported and donated equipment. Most of this equipment, which makes up 80% of the existing equipment base, is unsuitable for local needs and cannot be maintained due to a lack of local infrastructure. Rather than completely overhauling the system, innovation systems (IS) should refocus already-existing tasks, resources, and activities on the localisation of the medical device industry, putting into place prioritisation strategies. The author conducted a Structured Review (SR) to understand the current state of knowledge and establish a future research direction on localisation frameworks supporting the medical device IS in LMICs. The SR aimed to synthesise and investigate the evidence from the literature regarding the existing artefacts used to facilitate medical device localisation in LMICs.

Keywords: localisation, medical devices, innovation system,

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1 INTRODUCTION

Appropriate health technologies are essential for any functional health system. However, due to economic constraints experienced by several developing countries, the health sectors of these countries have to rely heavily on donated equipment. Many of these donations are sent with good intentions but do not appropriately meet the contextual needs, i.e. the majority of this equipment is unsuitable for local conditions and cannot be maintained due to a lack of local infrastructure and/or resources [3, 4].

These donations frequently bypass the selection and procurement systems in a recipient country. As a result, insufficient thought is given to the actual local requirements, the prevalence of disease and degree of care, the number of device users (staff members) and their capabilities, and the level of technical skill available to provide maintenance. This oversight thus results in inappropriate technologies being implemented. Further contributing to this, is the poor communication between donors and recipients about their contextual needs [4].

The outbreak of the COVID-19 pandemic in 2020 that shook the healthcare sector of various nations intensified the urgency for African governments to invest in the local production of various medical health technologies like medical devices, vaccines, and diagnostics. This was because there was a high demand for equipment like ventilators to combat the pandemic globally, but they were in short supply. During that period, it was evident that Africa was neither self-sufficient nor adaptable enough to repurpose local pharmaceutical or device capabilities to produce medical health technology at the scale necessary to quickly address the pandemic's concerns, resulting in severe shortages [5].

Investing in the local medical device industry, particularly its manufacturing capabilities, could address the problem of inappropriate medical devices emerging from donations and a lack of preparedness for a health emergency. Hence, this study will design and develop an innovation system framework for strategic decision-making to support the localisation of medical devices in South Africa. Furthermore, insights and policy support guidelines will emanate from this study. This framework will be designed for the South African medical device industry, and can potentially be adapted for other LMICs.

The author conducted a Structured Review (SR) to understand the current state of knowledge and establish a future research direction on the topic of localisation frameworks supporting the medical device IS in LMICs. The SR aimed to **synthesise and investigate the evidence from the literature regarding the existing artefacts that have been used to facilitate medical device localisation in LMICs**. These artefacts could be in the form of frameworks, tools, or models. The following research question was explored: **"What innovation and development artefacts exist to facilitate medical device localisation in LMICs?"**. The gaps identified from the synthesis of the existing artefacts will serve as the foundation for designing and developing a decision-support framework for localising medical devices in South Africa.

2 METHODOLOGY

The SR followed a six-step methodological approach defined by Arksey and O'Malley [6] which involved (1) identifying the research question(s), (2) identifying the relevant studies, (3) study selection, (4) charting the data, (5) collating, summarising, and reporting the data and (6) consultation (optional stage). A bibliometric analysis of the data was conducted to observe the evolution of the scientific literature and identify unique characteristics of the associated knowledge domain. The overall reporting of the SR was guided by the Preferred Reporting Items for Systematic Reviews and Meta-analysis extension for Scoping Reviews (PRISMA-ScR) checklist.

2.1 Selection Process

The literature search was guided by two electronic databases: Scopus and Web of Science (WoS). Both WoS and Scopus provide broad coverage of several disciplines, including nature, medicine, health sciences, engineering, and technology and, therefore, are extensively utilised for academic research [7]. The search was also extended to include a review of grey literature of other documents from organisational websites. The table below indicates the search strings that were used in both Scopus and Web of Science, focusing on the title, abstract and keywords as indicated:

Table 1: Table showing the search strings of the Scopus and WOS databases

Database	Search string
Scopus	TITLE-ABS-KEY (model OR framework OR system OR tool) AND TITLE-ABS-KEY (“medical device” OR “medical equipment” OR “medical technolog*” OR “medtech”) AND TITLE-ABS-KEY (“local manufactur*” OR local* OR benefi* OR self-suffici* OR “localisation”) AND TITLE-ABS-KEY (“africa” OR “lmic” OR “developing countr*”)
Web of Science	[(((TI=(model OR framework OR system OR tool)) AND TI=(“medical device” OR “medical equipment” OR “medical technology” OR “medtech”)) AND TI=(“local manufactur*” OR local* OR benefi* OR self-suffici* OR localisation)) AND TI=(“Africa” OR “LMIC” OR “developing countr*”)] OR [(((AB=(model OR framework OR system OR tool)) AND AB=(“medical device” OR “medical equipment” OR “medical technology” OR “medtech”)) AND AB=(“local manufactur*” OR local* OR benefi* OR self-suffici* OR localisation)) AND AB=(“Africa” OR “LMIC” OR “developing countr*”)] OR [(((AK=(model OR framework OR system OR tool)) AND AK=(“medical device” OR “medical equipment” OR “medical technology” OR “medtech”)) AND AK=(“local manufactur*” OR local* OR benefi* OR self-suffici* OR localisation)) AND AK=(“Africa” OR “LMIC” OR “developing countr*”)]

Articles retrieved were critically evaluated to be included in the SR if they met the following inclusion criteria: (1) articles published in English; (2) articles with accessible full texts; (3) articles that present a model/tool/framework that features the innovation system Articles were excluded if (1) they were non-English language documents; (2) they featured studies not conducted in LMICs; (3) they were focused on the technological development and bench/ clinical testing of a medical device exclusively with no extension to framework development; (4) the articles focused on any other products except medical devices. A total of 236 articles were retrieved from the search, with 218 originating from Scopus and 18 from Web of Science databases. All 236 articles were subjected to a three-stage screening process as indicated in Figure 1 below.

2.2 Data Extraction and Analysis

Using R with the package *bibliometrix* [8], the 47 articles retrieved from both Scopus and WoS and identified before the second and third screenings were analysed. All 47 articles were included in this analysis because of the possibility of discovering valuable trends from their bibliotex data. Data was analysed in terms of document statistics, collaboration index, journal impact, country productivity, document citation analysis, and keywords. The main goal was to uncover the emerging trends and patterns over the years, the collaboration patterns, identifying knowledge gaps, and positioning intended contributions to the field [9]. Further analysis aimed to identify and map any actor-institutional links and information routes used to create, generate, and disseminate innovation [10].

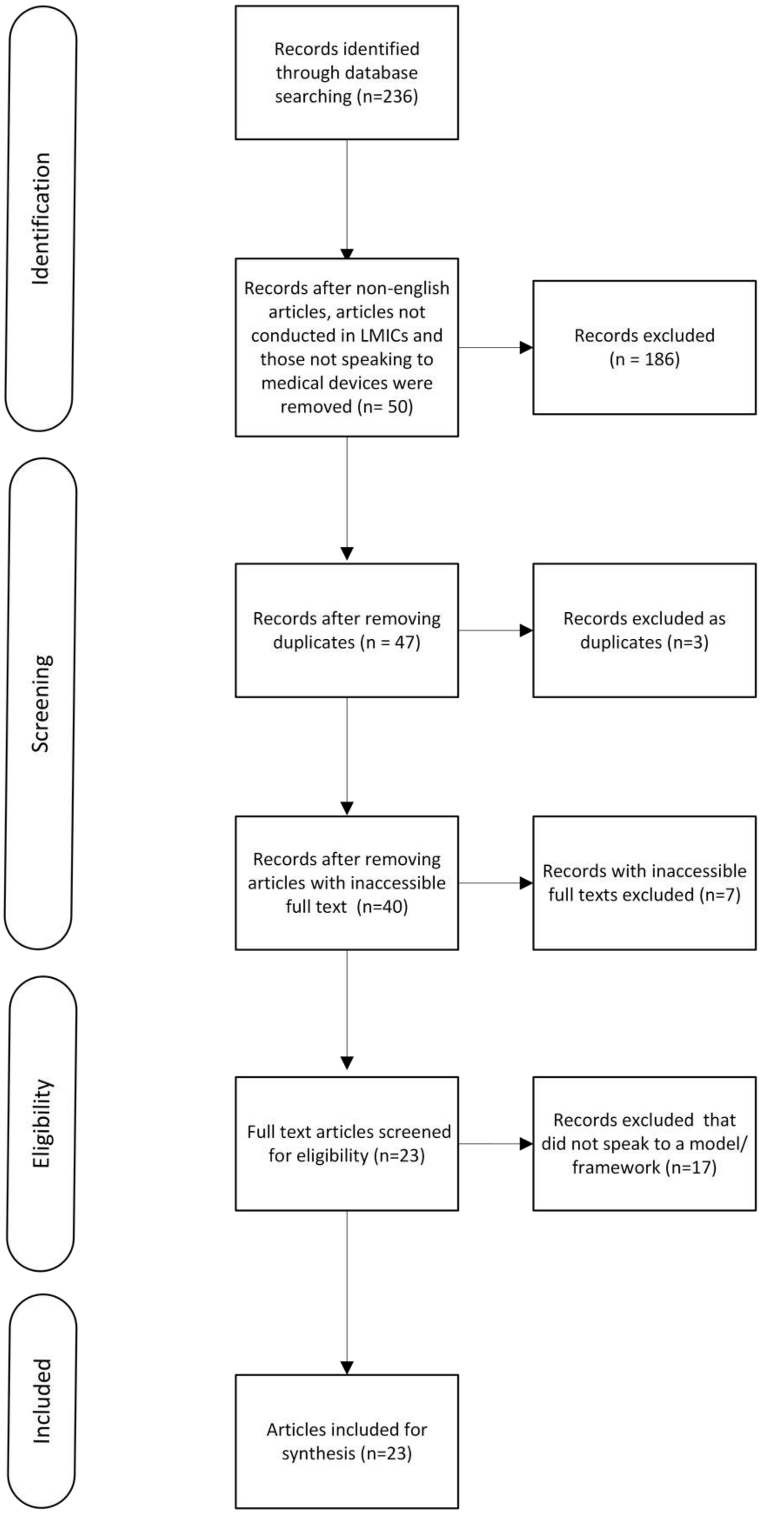

Figure 1: Prisma ScR flow diagram for this structured review

3 RESULTS AND DISCUSSION

Results from the bibliometric analysis are presented in this section to reflect (i) growth and trends of frameworks or models in terms of publication output, distribution, source, and citations; (ii) prolific scholars, affiliations, and social networks; (iii) thematic focus of the field of localisation frameworks.

3.1.1 Descriptive Statistics

Analysis from *Biblioshiny* revealed that the structured review consisted of 29 articles, 9 reviews, 5 conference papers and 1 representative each for the conference proceedings, book chapter, editorial and notes; traversing a timespan from 1995 to 2022. This analysis revealed an 8.48% annual growth rate of scientific production. There was a significant increase in scientific output between 2017 and 2022 and a notable increase in citations per year from 2010, indicating an increased interest in localisation artefacts for medical device development in LMICs.

3.1.2 Science Mapping

Analysing the Top-Author's Production of articles between 2010 and 2022 and their countries of affiliation and keywords revealed that most of the research in this field is conducted in the developed world. Only two LMICs are featured in this map: South Africa and Tanzania, which indicates that there is still limited contribution to knowledge regarding localisation artefacts in LMICs. This is suggestive of both a mushrooming discipline and the necessity for LMICs to invest in the creation of localisation-related knowledge, as they have a greater awareness of their setting than developed nations.

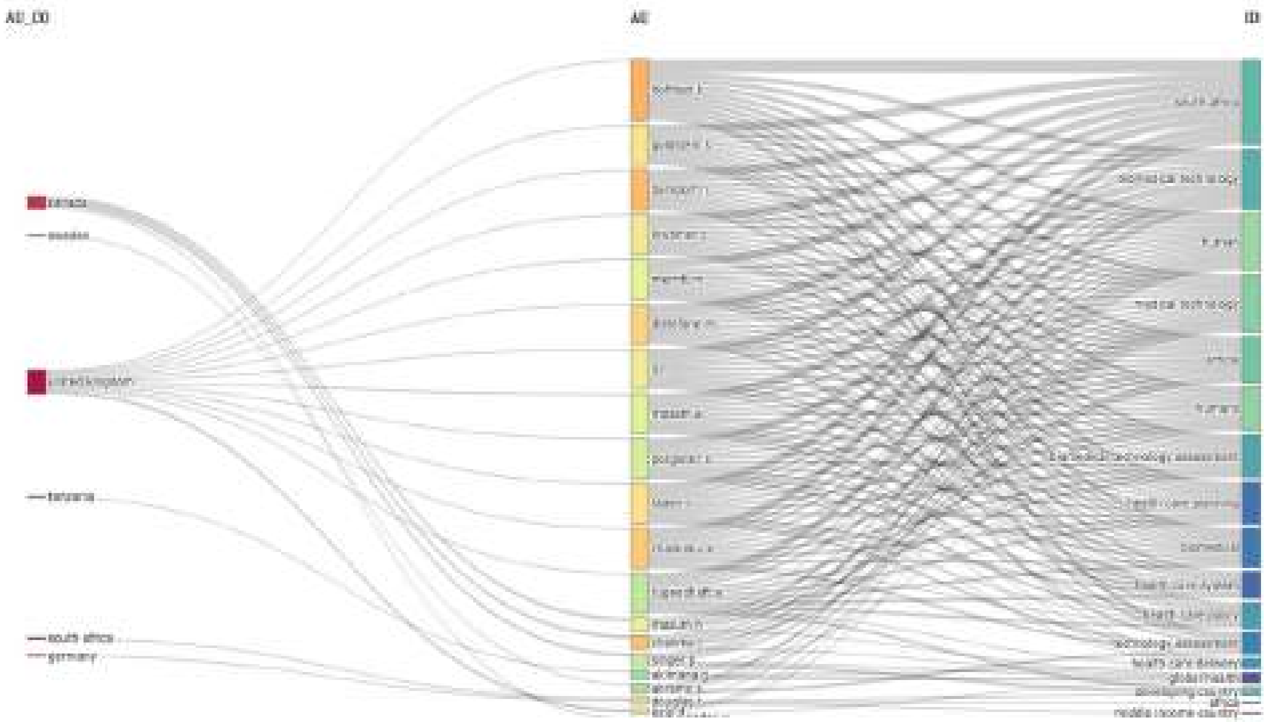

Figure 2: A three-field plot of countries, authors, and identified keywords: The emphasis is placed on the height of each box and thickness of the connecting lines; the taller the box, the more significant; and the thicker the lines' correlation, the more information or volume of work was produced [1]

Notably, Figure 2 above reveals that a lot of work is being done in South Africa regarding the localisation of medical devices owing to the thickness of the connecting lines as well as the highest height of its box. This could be attributed to the fact that South Africa has a well-established medical device sector in terms of companies registered to sell medical devices, compared to several other LMICs [5]. This rightly positions South Africa as a study setting for this research.

An analysis of the top 20 organisations contributing to the dataset further revealed that there were 8 LMIC institutions featured among the top 20 contributing to this dataset. A holistic analysis of Figures 2 and 3, demonstrates that collaboration exists between LMICs and non

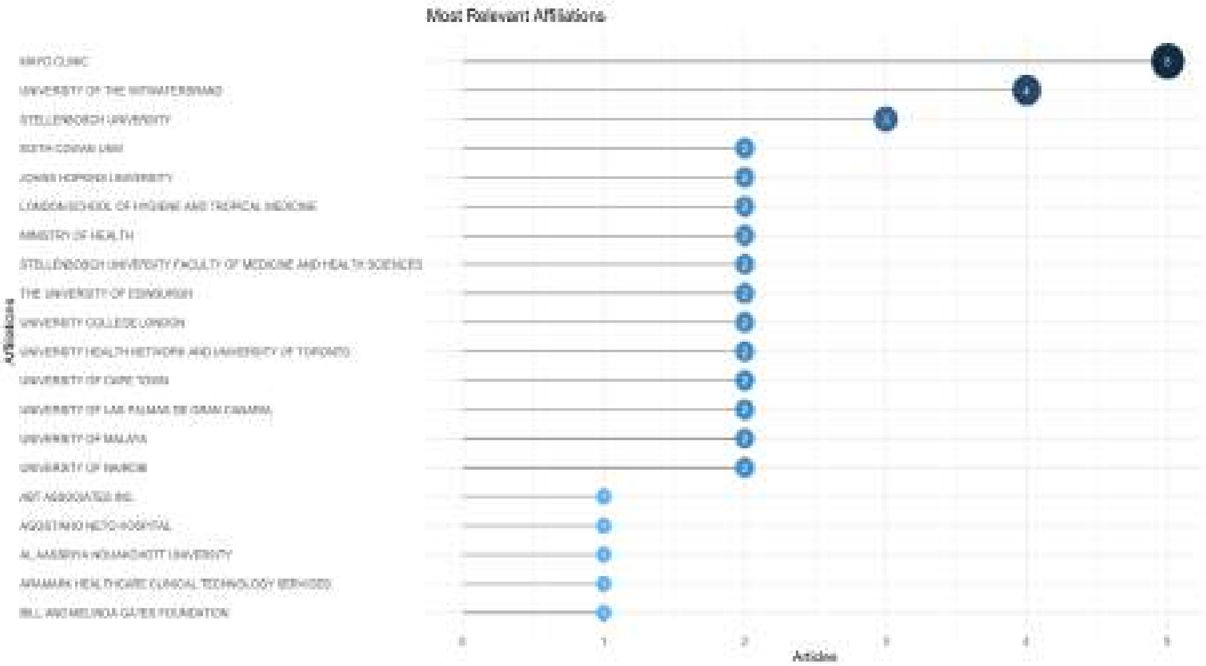

Figure 3: Most relevant institutions and affiliations.

LMICs however with the field dominated by non-LMICs. Notably, universities and authors from non-LMICs make up the majority of contributors. According to the innovation system framework, universities play a key role as drivers in the knowledge-economy, which could potentially be their lead role played in this context [11].

3.1.3 Thematic Mapping and Categorisation

ATLAS.ti software [12] was used to assemble, disassemble and reassemble the data. Grounded theory methodologies were utilised and preferred during the coding cycles because of the meticulous attention paid to the process of theorisation [13]. The first coding cycle produced 88 codes which were later reviewed and iteratively coded into 43 codes that finally generated five themes/categories namely: localisation artefacts, localisation requirements, defining localisation, localisation case studies and rationale for localisation.

Table 2: Table showing the representation of frameworks across three time slices

Frameworks	1995 - 2010	2011 - 2016	2017 - 2022	Totals
Business models	6	0	1	7
Decentralisation	0	3	0	3
Frugal innovation	0	0	9	9
Health Technology Assessment	1	12	14	27
Maker Hub	0	0	5	5
Medical Technology Score (MTS) by WHO	0	2	0	2
Open source - open science architecture framework	0	5	1	6
Path following, skipping and creating	0	1	0	1
Platform based framework	0	0	3	3
TIS framework	0	0	3	3
Totals	**7**	**23**	**36**	**66**

Table 2 above indicates that the subject on frameworks began building up between 2011 - 2016 and became exceedingly apparent during the later time slice of 2017-2022. This indicates that the field has been developing since the first time-slice. Some of the identified artefacts were focused on steering innovation at the onset of device discovery and risk analysis; for example, the concept of “frugal innovation”, “path following, skipping and creating” whereas the majority were employed post-device production (ready for deployment) and focused on aspects like procurement and device usability. The “Health Technology Assessment (HTA)” tool and the Medical Technology Score (MTS) by WHO are examples of such. Table 3 further elaborates on the frameworks that were focused on steering/guiding innovation.

Table 3: Table describing the frameworks obtained from the Coding process

Framework	Description	Author and year
Frugal innovation	This involves applying the concept of doing and achieving more with less [14] and being able to develop appropriate, cost effective, adaptable, and accessible solutions for users in resource constrained settings [15].	Chakravarty (2022), Waran et al., (2022)
HTA	Health technology assessment (HTA) is a multidisciplinary approach that uses clinical effectiveness, cost-effectiveness, policy and ethical perspectives to provide evidence upon which rational decisions on the use of health technologies can be made. It can be used for a single stand-alone technology (e.g. a drug, a device), complex interventions (e.g. a rehabilitation service) and can also be applied to individual patient care and to public health.	Blaauw et al., (2022), Chakravarthi (2013), Dang et al., (2016), Edney et al., (2022), Govender (2011), Krubiner et al., (2022), Simiyu et al., (2010), Kumar et al., (2014), Mukherjee (2021), Patterson et al., (2019)
Maker Hub	A model designed to address challenges in the social sector through creative collaboration, leadership and governance processes for management of locally based physicians, nurses and biomedical engineers. The funding approach used allowed for mechanisms for problem-solving to ensure its long-term sustainability.	Ayah et al., (2020)

Open source - open science architecture framework	Utilising a hybrid approach of integrating agnostic. This framework entails setting specialised environments for fruitful interaction especially between the open-source technology, healthcare interoperability standards and Total Quality Management principles. Such platforms include for example the 3D Slicer ecosystem and the UBORA E-platforms [16]. Such platforms provide opportunities for medical and engineering education, training and for biomedical research translation.	Harding (2016), Ruiz-alzola et al., (2018)
Medical Technology Score by WHO	The WHO Priority Medical Devices Project also makes use of the "availability matrix," which relies on WHO survey technology to determine the list of preventive, diagnostic, therapeutic, and assistive medical devices needed for the treatment of 15 diseases.	Fatunde & Bhatia (2012)
Path following, skipping and creating	According to this model, countries are firstly divided into three categories of technological capabilities, namely low, average and high. Then, each country attempts to absorb and localise technology based on its level of technological capability. In other words, countries with low capability start their path towards localisation of technology by focusing on mature technologies thereby adapting the path following approach. Similarly, the acquired technologies will be changed into new and emerging technologies due to an increase in technological capabilities; thereby employing the path - skipping model for average capabilities and the path creating for the high technological capabilities [17].	Shafia et al., (2015)
Platform based framework	This framework is characterised by a holistic understanding and combination of innovation and transaction platforms. It draws from the synergism between the engineering and economic perspectives to derive meaning from an ecosystem.	Herman (2020)
Context-specific TIS framework	According to Carlsson and Stankiewicz [18], a Technological Innovation System (TIS) is a "network of agents interacting in a specific economic/industrial area under a particular institutional infrastructure or set of infrastructures is involved in the generation, diffusion, and utilisation of technology". This framework incorporates aspects of context as technology generally develops differently in various contexts. Also, it is defined in terms of knowledge/competence flows rather than flows of ordinary goods and services.	Salie at al., (2019)

3.3 Thematic Mapping and Categorisation

ATLAS.ti software [12] was used to assemble, disassemble and reassemble the data. Grounded theory methodologies were utilised and preferred during the coding cycles because of the meticulous attention paid to theorisation [13]. The first coding cycle produced 88 codes, which were later reviewed and iteratively coded into 43 codes, finally generating five themes/categories: localisation artefacts, localisation requirements, defining localisation, localisation case studies and rationale for localisation.

Some of the identified artefacts were focused on steering innovation at the onset of device discovery and risk analysis; for example, the concept of “frugal innovation”, “path following, skipping and creating” whereas the majority were employed post-device production (ready for deployment) and focused on aspects like procurement and device usability. The “Health Technology Assessment (HTA)” tool and the Medical Technology Score (MTS) by WHO are examples of such.

The HTA was significantly outlined in several papers as a preferred decision support tool for guiding the medical technology industry. The HTA tool has successfully been employed in several developed countries and produced significant results, especially when embedded with economic evaluation and considering the contextual and social aspects [19, 20]. Its use in the LMICs is still limited but is rather increasing with continuous representation of the HTA agents in international HTA networks [21].

In practice, HTA is constrained in that it pays less attention than is necessary to the systematic assessment of significant social, organisational, and ethical consequences of the health technology in question and instead focuses primarily on economic evaluations of cost-effectiveness and budget impact [22]. Also, HTA is primarily focused on product development instead of the holistic sectoral/system development. According to Mukherjee [21], a systems approach to HTA could be used to evaluate health innovations holistically, assisting policy makers in determining which innovations improve the health system and fill gaps. Additionally, HTA would allow for efficient utilisation of existing resources and wastage reduction allowing for equity gains. Gains realised in equity and efficiency would significantly lessen the trade-offs associated with sustainability.

The review highlights the potential for HTA to be used as a decision support framework aiding localisation in LMICs. However, this would involve incorporating a relatively new concept called the “early HTA” that allows for the potential value of a new health technology to be determined at an early stage of its development. The early HTA concept extends the traditional HTA that informs coverage/reimbursement decisions at the latter stages of device development. The early HTA thus informs early research, development, and investment decisions. There have been numerous methodological studies and implementations of early HTA in recent years. However, it is still unclear how early HTA can be included in the innovation process and fit in with routine healthcare decision-making, which presents a research gap [23].

Other artefacts that were identified as decision support tools and were predominantly context-based include the concept of frugal innovation that involves developing appropriate, cost-effective, adaptable, and accessible solutions for users in resource constrained settings [15]. The frugal innovations are further characterised by significant cost reduction, focusing on core functionalities and optimal performance [24].

To address shortage of technological capabilities which is key for localisation of medical devices, models such as the “Maker Hub” were introduced aimed at addressing challenges in the social sector through creative collaboration, leadership and governance processes for management of locally based physicians, nurses and biomedical engineers [25]. Another such platform was the Open source - open science architecture framework focused on setting specialised environments for fruitful interaction especially between the open Source technology, healthcare interoperability standards and Total Quality Management principles. Such platforms include the 3D Slicer ecosystem and the UBORA E-platforms [16]. These platforms provide opportunities for collaborative engagement between stakeholders in the innovative space, medical and engineering education, training and biomedical research translation using best practices, ensuring improved research, product and service delivery outcomes [26].

The "Path following, skipping and creating" model was designed to ensure that countries develop and increase their technological capabilities [27]. According to this model, countries are firstly divided into three technological capabilities categories: low, average and high. Then, each country attempts to absorb and localise technology based on its technological capability. In other words, countries with low capability start their path towards localisation of technology by focusing on mature technologies thereby adapting the path following approach. Similarly, the acquired technologies will be changed into new and emerging technologies due to increased technological capabilities; thereby employing the path - skipping model for average capabilities and the path creating for the high technological capabilities [17].

Herman, et al. [28] elucidated on the concept of "technology platforms" defined as technology that provides a software foundation for interactions and transactions between several actors and can be used in healthcare to foster communication, data analysis, and opportunities to increase patient healthcare education, especially in resource-constrained settings. This platform-based tool was used to inform and support platform owners in designing, developing and implementing healthcare-related platforms and the ensuing ecosystems. They can potentially improve the quality and accessibility of healthcare, particularly in the rural areas of developing countries.

The Context-specific TIS framework introduced by Salie, et al. [29] was tailored towards understanding how well the functions of an orthopedic TIS are performing over time hence being able to gauge the capacity of the TIS. This framework incorporates aspects of context as technology generally develops differently in various contexts. Also, it is defined in terms of knowledge/competence flows rather than flows of ordinary goods and services which are important factors to consider in localisation. The "Medical Technology Score" metric designed by WHO was developed as a comparative metric to judge the levels of technology available in health facilities and ascertain whether the existing technologies meet the disease burden locally [30]. This metric was contextualised around the disease burden and inclined towards being product-centered as compared to the TIS framework which is system-centered.

3.4 Research Gap and Future Direction

This review found that most of the existing literature regarding localisation artefacts focuses on the TIS and mainly gravitates toward post-device production (ready for deployment) and aspects like procurement and device usability. There was scanty literature on how the Sectoral IS has been used to understand the flows between actors in the medical device sector [31] as opposed to the conventional focus on the dynamics of technological development. Therefore, the SIS can be used as a framework to measure the performance of technology change in the medical device sector over time, which presents a focus for this research project [32].

According to Hekkert, et al. [31], there is a need to influence both the speed and direction of innovation and technological change, whereby technological change incorporates the holistic development of the technology concerning its innovation system, a process called "the innovation process". Steering innovation and technological change as pointed out by the existing literature largely involves developing the technological capabilities of the concerned actors and stakeholders. The term "technological capability" refers to a set of skills, equipment, knowledge and all attributes that can aid an organisation in the production, learning, improvement and development of manufacturing and operational processes [33].

Although the requirement for actors to possess appropriate technological capabilities for localisation has been highlighted, there was scarce literature on the specific actors' capabilities required as well as their corresponding functions needed for the successful localisation of the medical device IS. This demonstrates the need to identify and match IS functionality to actor capabilities, particularly when focusing on the South African medical device IS. This knowledge would guide various actors on the appropriate path to take regarding the localisation of medical devices in SA.

4 CONCLUSION

Further study following this structured review will involve conducting an industry survey to identify the existing policy priorities for localisation in the medical device industry in South Africa and thereafter, various case studies will be conducted of failed medical devices. This will all be in a bid to identify how various IS functions emerge over time and support the relevant actors. Using Events History Analysis, event-based narratives will be obtained and utilised to gain an in-depth understanding of the positive and negative significant milestones that led to a particular outcome and, more importantly, to uncover valuable insights that will be utilised for framework development [34].

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IMPROVING ASSET INFORMATION MANAGEMENT IN THE SOUTH AFRICAN CONSTRUCTION INDUSTRY USING BUILDING INFORMATION MODELLING

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ABSTRACT

The innovation of technologies to assist the construction industry with asset information management has gained attention since the complexity of projects is also increasing, making it difficult to correlate data without computer systems. Hence, the construction industry is shifting from the traditional method of managing information that involves handwritten and printed documents into the modernised technique that entails digitalising data. However, the South African construction industry is slowly adopting digital transformation that can be initialised by implementing Building Information Modelling (BIM) due to factors not limited to ambiguous economic benefits and not knowing where to start. The main contribution of this paper is to highlight the need for modernisation in the South African construction industry and demonstrate the benefits of using BIM through a comparison of BIM with traditional methods using Multicriteria Analysis (MCA). The MCA evaluates five objectives: the Top Strategic Initiatives for the SA construction industry, Cost and Expenses, Quality, Asset Information Management Processes, and Outputs.

Keywords: Asset Information Management, Building Information Modelling (BIM), Multicriteria Analysis (MCA)

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1 INTRODUCTION

The process of acquiring, organising, and integrating asset data is vital in ensuring the smooth operation of construction projects, and most countries have invested in advancing asset information management to enhance the performance of construction projects generally [1]. According to [2], the Western world is improving asset information management through the use of BIM implementation that results in a digital transformation strategy by merely organising and digitalising information.

Digital transformation has been accelerated in different industries nowadays and it involves using technology in numerous processes. The United Nations (UN) highlights that in the past two decades, digital technology has been embraced by 50% of the developing world's population, and it believes that the 17 Sustainable Development Goals (SDGs) can be achieved more quickly owing to digital advancements [3]. With this, BIM implementation can help in the fulfilment of several SDGs namely, SDG 3 for good health and well-being, SDG 6 for clean water and sanitation, SDG 8 for decent work and economic growth, SDG 9 for industry, innovation and infrastructure, SDG 11 for sustainable cities and communities and SDG 12 for responsible consumption and production. This paper, therefore, outlines how BIM helps achieve these SDGs, thus explaining the need for immediate modernisation of asset information management techniques and the benefits of BIM over the traditional approach of asset information management that involves the use of hard copies.

The multicriteria analysis (MCA) is used to explicitly compare the BIM method to the traditional technique due to its suitability to filter options before applying more in-depth quantitative analysis as well as to compare options when implications are difficult to quantify as outlined by [4]. Hence, it is the best tool that can be used to analyse the two options, particularly BIM and the conventional method for asset information management.

2 LITERATURE REVIEW

The need to extensively increase awareness of the importance of managing and maintaining existing infrastructure as well as considering its full-service life has globally increased owing to the necessity to improve the poor service performance of construction projects as well as the loss of asset value due to poor maintenance. According to [5], South African municipalities are worried about the deterioration of the infrastructure that is built as well as the one that already exists with the challenge of balancing the demand and the supply of infrastructure. As a result, there is an increase in abandoned infrastructure, high informal settlements, poor municipality service delivery like the health facilities, constant load-shedding, collapse of infrastructure and poor quality of infrastructure. These challenges are immensely significant in a large population of impoverished people like the township areas in South Africa. Most of these challenges are merely due to poor asset information management.

Asset information management can be effective and efficient if it allows proper time and resource management to produce the desired results and the right people to use the correct information at the right time to make the right decisions [6]. Moreover, the correctly stored information facilitates effective management, planning, monitoring and controlling, operations, maintenance and reporting to improve the value of the asset information. With this, the poor asset information management in the South African construction industry, as well as substandard information storage, has led to the construction of inferior quality infrastructure and poor infrastructure maintenance that give rise to the collapse of the built assets, buildings to be abandoned as well as ineffective and inefficient energy infrastructure resulting in increased power cuts. If asset information is up to standard, then the resources would be properly managed to produce the desired output, and the right people would make the right decisions using accurate information.

According to [7], asset management (AM) generally helps provide the required infrastructure by enabling asset assessments, creating, and maintaining asset registers, defining roles and responsibilities for the AM process, maintaining and protecting assets through accounting, managerial, and information systems of the organisation. The study by [1] highlights that assets are analysed in two aspects namely, the financial perspective for the economic value of an asset such as focusing on its financial value, reducing costs as well as increasing return on investment and engineering perspective for establishing information systems and facilitating decision making throughout the asset lifecycle, particularly in asset scheduling, maintenance and reliability. As a result, effective asset management creates opportunities for the provision of affordable, effective and efficient infrastructure in a transparent and accountable manner. In order to achieve this, an asset management toolkit, illustrated in Figure 1, is used to assist the construction industry in managing infrastructure assets accordingly.

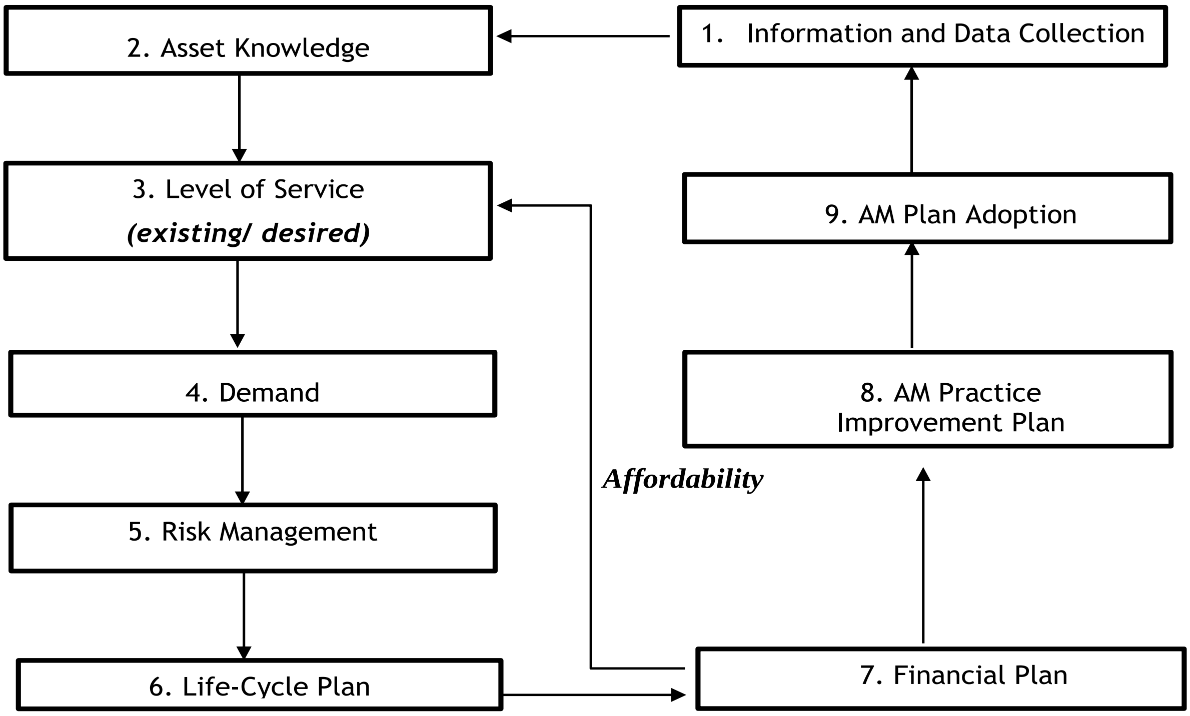

Figure 1: Basic AM Toolkit (Adopted from [5])

The AM toolkit outlines the elements of infrastructure asset management (IAM) in chronological order. According to [5], IAM starts with gathering information and data, which involves identifying what information is already available, assessing its relevance and validity, highlighting any information gaps and assumptions, and maximising the use of information that is already available. This immensely affects the asset knowledge which results in the initial information and data collection element of the toolkit. Due to the unstructured, inconsistent and unstandardised information and data collection methods that result in the use of traditional method of asset information management, the first two stages of the toolkit produce substandard results.

The level of service consists of the existing and the desired levels that are influenced by stakeholders. These include customers' needs as well as technical and legal requirements; the difference between the two levels needs to be minimised by the asset management strategies [7]. However, a lack of advanced technologies in the asset management strategies makes it even more difficult to reduce the service level gap due to the low performance associated with the deficiency of innovative practices to improve efficiency, reliability, quality, comfort, sustainability and affordability which are the main criteria to determine the acceptable service life of an asset as outlined by [5] & [7].

According to the AM toolkit, the affordability of an asset is determined by the level of service and the financial plan. This is due to the budget restrictions associated with the financial plan which in turn affect the quality of the construction of an asset, one of the criteria for service life. The study by [8] discusses the importance of the project management iron triangle that highlights the importance of quality and that it is constrained by scope (features, functionality), time (schedule) and cost (resources, budget). In the toolkit, the financial plan assesses the economic viability of infrastructure using a financial forecast that details an asset's costs and revenues; preference is given to construction projects with less costs than revenue [5].

Moreover, the life cycle plan is an intentional response to the strategic vision of the organisation's demands, gaps in the level of service, pattern of anticipated future demand, demand management activities, and risks [5]. The plan details how the project is connected to each requirement, and it shows the approach taken to manage the asset life cycle from the pre-construction phase to the post-construction phase of the built asset. With this, the demand element of the toolkit ensures the right balance between the supply and demand of the infrastructure and its services, while the risk management helps in the identification, analysis and evaluation of the risks as well as providing the risk responses/ treatments [5].

Similarly, all levels of the asset lifecycle require a continuous process of improving infrastructure management practices. Hence, the AM practice improvement plan allows continuous infrastructure improvement, and it requires a sufficient budget and reasonable schedule to achieve the infrastructure asset management plan milestones [5]. The AM plan is then adopted and implemented when the comprehensive infrastructure plan which includes infrastructure overview, issues and risks, level of service targets and financial forecasts has been consolidated [5].

Considering the AM toolkit for the South African construction industry, some of its elements can be drastically enhanced by adopting technology to facilitate its functionality, through modernising the information and data collection, asset knowledge, level of service and the aspects of the asset life cycle as well as the financial attributes. The study by [2] has already established a relationship between AM and BIM, an innovative practice that assists AM by providing a digital transformation strategy. This relationship is outlined in Figure 2.

According to [2], organisational information requirements (OIR) entail identifying and categorising the necessary information to enable asset management at an organisational level, which may include posing questions that may help an organisation determine whether the objectives will be accomplished or not. As a result, asset information requirements (AIR) entail providing answers to questions identified in the OIR at the asset level as well as identifying and capturing the data needed to create and maintain the asset [2] & [1]. Moreover, information management for construction projects always starts with capturing the client's information needs to make sure the project is completed in a way that satisfies the client. With this, Employer's/Exchange Information Requirements (EIR), which specify the data that must be provided along with the practices and standards to be used for building projects, are the requirements needed for projects that use BIM to ensure that the project is delivered as per contract and to the satisfaction of the client [6].

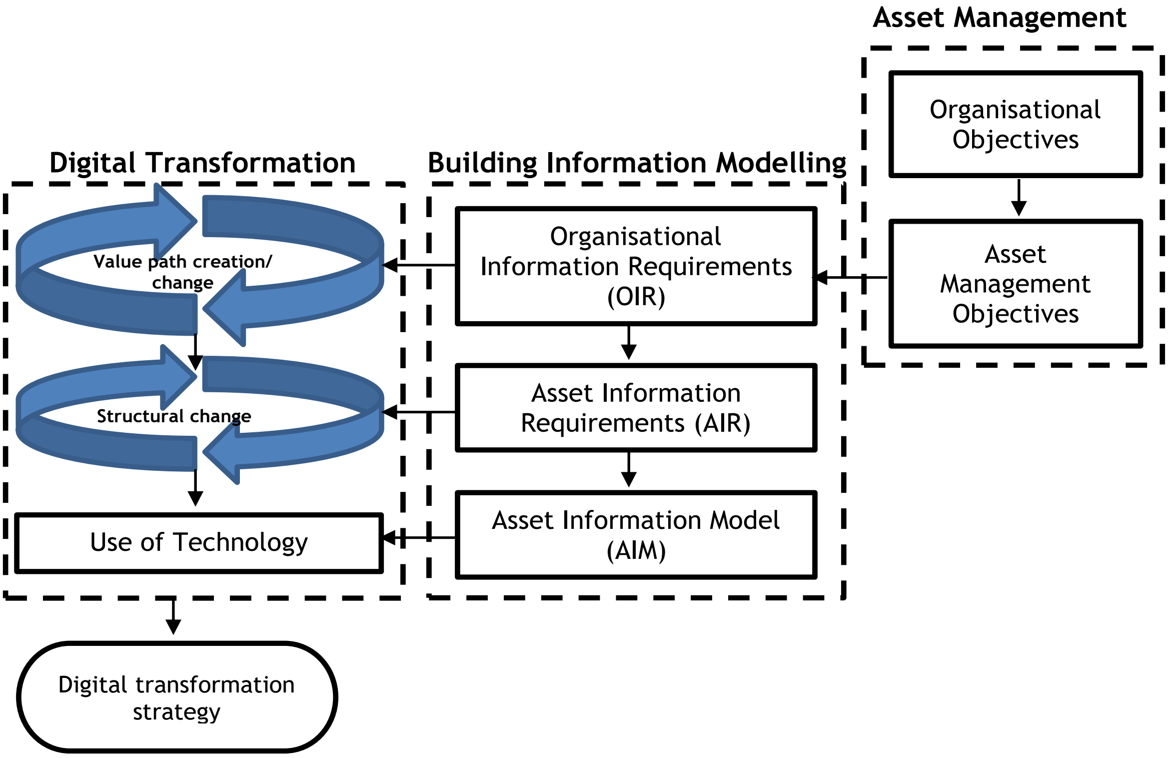

Figure 2: Digital transformation framework for BIM (Adopted from [2])

According to [9], the asset information model (AIM) results from the project information model (PIM) which stores structured digital data for the design and construction phases to improve infrastructure asset management in the post-construction phase. When the project has been completed and accepted, it is then handed over and the PIM is transferred into AIM. This involves the use of technology to provide the digital transformation strategy which results in changes of how the structures are created and managed as compared to the traditional method. Table 1 provides an overview of the BIM requirements and their respective outputs.

Table 1: Overview of BIM Requirements (Adapted from ([9] & [2])

	Level	Requirements	Deliverables
Stakeholders based	Organisational	Organisational Information Requirements (OIR)	Organisational Objectives Asset Management Objectives
Contract based	Asset	Asset Information Requirements (AIR)	Asset Information Model (AIM)
	Project	Employer's Information Requirements (EIR)	Project Information Model (PIM)

It is possible to list the vital distinctions between the implementation of BIM and the conventional approach to managing assets by comparing the world of traditional corporate to modern digital business, and Figure 3 outlines this comparison. According to [10], the world of digital business Is dynamic with high levels of competition, uncertainty, knowledge creation, innovation and multiple ways of doing business. As a result, this provides the basis of the dynamic capabilities of a firm which is the ability to adjust to changing environments, thus supporting factors not limited to the company's market penetration and continuous adaptation to the increased complexity of projects, technology and shifting environments. On the contrary, the world of traditional business is stable with low levels of competition and ways of doing business [10]. Moreover, it focuses on knowledge utilisation rather than creation, unlike the world of digital business.

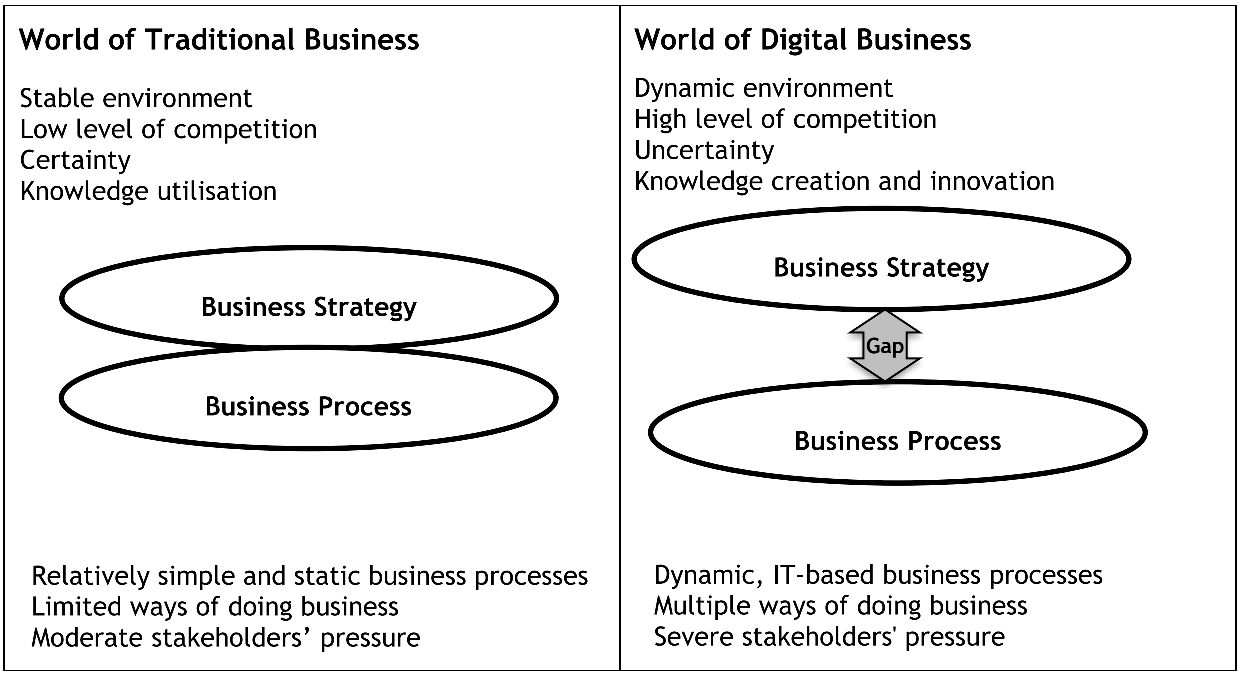

Figure 3: Comparison between the world of traditional and modern digital business (Adopted from [10])

The MCA is additionally used to compare the BIM method to the traditional technique since their influence and impact are difficult to quantify, and an in-depth quantitative analysis of the MCA outcome is done in the result analysis section of this paper. There are five objectives of the MCA namely, the top strategic initiatives for the South African construction industry, asset information management processes, asset information management outputs, cost and expenses and quality.

2.1 The top strategic initiatives for the South African construction industry

The company [11] identified critical strategic objectives that would assist the development of the South African construction industry, which include ***expanding business offerings and geographic reach***, ***implementing lean construction concepts***, and embracing ***digital transformation***. The study by [12] explains that the extension of geographic reach allows an organisation to grow its market by targeting new clients while expanding business offerings allows a corporation to grow by offering new products and services. The economic growth will also increase due to the growth and success of the entire construction sector if the South African construction industry expands its business offerings and geographic reach. On the other hand, lean construction eliminates unnecessary value-adding processes, thus lowering waste production while improving overall project performance by reducing costs and speeding up project completion [13], and digital transformation involves adopting various digital technology to improve the effectiveness of traditional processes [14].

With this, BIM is an enabler of all these strategic initiatives. It offers the digital transformation strategy as outlined in Figure 2, it catalyses lean construction as outlined by [15], and it uses cloud computing which is effective for collaboration regardless of physical location [16], thus allowing the expansion of geographical reach. It also enables the growth of business offering through offering structural changes as well as creating the new required value path [2]. However, traditional asset information management is limited to all the required strategic initiatives. Hence, BIM implementation is essential in the construction industry.

Using BIM to achieve strategic initiatives for the South African construction industry will additionally help in the fulfilment of SDG 8, SDG 9, and SDG 12. The fulfilment of SDG 8 focuses on target 8.2 which favours increasing economic productivity through innovation, technical advancement, and sector-specific attention to high-value added and labour-intensive industries (in this case, the construction sector) [17], and target 8.1 may be accelerated by achieving target 8.2 since the economy of South Africa is immensely affected by the development of infrastructure as outlined by [18]. Target 8.1 entails sustaining economic growth per capita in accordance with national circumstances, particularly at least 7% GDP growth per annum in the least developed countries [17].

The link between target 8.2 and target 8.1 is through fulfilling SDG 9, particularly target 9.2 which entails fostering sustainable industrialisation, and significantly increasing the sector's employment and GDP share (construction sector) by 2030 as per the national conditions as well as doubling its share in the world's least developed countries [17]. Similarly, SDG 12 is satisfied by ensuring that chemicals and wastes throughout the lifecycle are reduced significantly in the environment in compliance with accepted international frameworks to minimise their drastic effects on human health and the environment, thus achieving target 12.4 [17].

2.2 Asset Information Management Processes and Outputs

The South African AM toolkit highlights the fact that asset information management starts with information and data collection which essentially involves ***data capture***. Data capture also includes ***standardising information*** to improve data consistency. As a result, ***information accuracy and standardisation*** are enabled by data capture and standardising information. The study by [1] outlines that asset information management generally involves the process of acquiring, ***organising*** and integrating asset data which requires ***effective collaboration***. Moreover, how ***information is stored*** affects factors not limited to ***information security***, ***data retrieval***, ***information accessibility and transparency***.

According to [19], the traditional strategy only allows for the transfer of data amongst the concerned parties while offering data in an unstructured form which results in unstandardised and inconsistent data that is difficult to manage. Instead, all stages of construction must replicate the data, and the data has no backups to be restored when using conventional means. Therefore, when reports are lost or damaged, information is not easily retrieved. This has an impact on information accessibility and availability, which are typically constrained by conventional techniques. Moreover, the unstandardised information as well as numerous files stored in different databases makes data organisation a challenge.

On the other hand, BIM has room for improving the asset information management processes and outputs. BIM can organise structured data from a single source of information, which facilitates better information availability and accessibility when needed [19]. It additionally enhances collaboration, thus allowing open and accurate stakeholder communication while fostering standardisation. Data visualisation provided by BIM enables clear pictures of project communications that improve the data capture process, unlike the traditional method. Moreover, the computer software used to store information is an enabler for information retrieval when data is lost. However, information security in BIM is reduced due to hacking opportunities and viruses, unlike traditional methods. With this, BIM generally improves information management in the construction industry.

2.3 Cost and Expenses

There are two types of IAM expenditures, namely capital expenditures ***(CAPEX)*** which involves expenses for new construction, upgrading, and renewal as well as disposal and operating expenses ***(OPEX)*** which considers only the operations and maintenance costs [5]. Each construction project has its stipulated budget known as ***project cost/ contract cost*** that can be direct or indirect. Moreover, projects are executed by skilled labourers who acquire their skills through training, and the ***training costs*** can be paid by the employee or the employer.

The CAPEX of BIM is increased by purchasing hardware and software needed to implement it whereas OPEX is increased by the employment of information managers who design, create and maintain BIM. However, the project cost is usually reduced by implementing BIM [2] due to several factors including a decrease in errors and faults, project delays, and material waste. Nowadays, people are also interested in equipping themselves with BIM expertise; hence the training costs for BIM employers are not too much since some employees pay for their training. Besides, adequate training is mandatory for any new employee so that they can easily adapt to how things are done in the organisation. With this, training costs must not hinder BIM implementation.

2.4 Quality

The ***completion of a project within the required budget***, ***time***, ***and scope***, as well as the ***satisfaction of all engaged stakeholders***, constitutes both project quality and project success [20] & [21]. With this, a project is considered successful with superior quality if it is completed within budget, schedule and scope while the stakeholders are satisfied with the outcome of the project. Moreover, ***sustainability*** as well as the protection of the environment is imperative in the construction industry since it consumes a significant amount of resources which have a large impact on the environment and ***construction healthy and safety*** of workers and the environment affected by the construction project must be considered as one of the aspects of sustainability [18]. The ***maintenance of built infrastructure*** also affects the sustainability of infrastructure. This is supported by the study by [15] that outlines infrastructure asset maintenance correctly promotes resource conservation, lowers energy consumption, improves the energy efficiency of operational buildings, and offers a safer and cleaner environment for people.

Similarly, ***adaption to complex projects*** affects project quality. The study by [14] states that *"our challenges are becoming more complex and more technical. What we build isn't simplistic anymore. We're beyond the point where the old mechanisms and the standard training are sufficient. The people involved are not able to correlate all the data in their heads without the assistance of systems. So, digitalisation is no longer an option."* The quote highlights that digitalisation which is enabled by BIM can help improve the adaption to complex projects. BIM also generally helps with other aspects of quality, like completing a project within the required budget, scope and time by reducing project cost and increasing productivity [2]; improving maintenance of built infrastructure in the operations and maintenance stages [15]; enhancing sustainability by supporting the overall concept of sustainable construction through delivering verifiable results and making a significant contribution to the three pillars of sustainability, namely social, economic, and technology aspects [22] & [22] further elaborates that BIM tools and technologies can be used to advance construction health and safety. All this directly affects the satisfaction of stakeholders. As a result, the chances of the stakeholders being happy with the outcome of the construction project increase.

Moreover, SDG 3, SDG 6, SDG 8, SDG 9, SDG 11, and SDG 12 will be fulfilled by implementing BIM in the construction industry. BIM can help achieve target 3.9 which requires the reduction of deaths by 2030 due to water, air and soil pollution that results in the production of dangerous chemicals. BIM helps in reducing carbon dioxide emissions [22], thus reducing air pollution and it reduces soil and water pollution by reducing the contaminants that are produced in the construction industry through catalysing lean construction [15]. This additionally drives the success of providing sustainable management of water and sanitation by fulfilling target 6.3 of improving water quality by reducing pollution and target 6.6 of protecting water environments. Consequently, adopting BIM generally creates opportunities to achieve SDG 8: decent work and economic growth; SDG 9: industry, innovation and infrastructure; SDG 11: sustainable cities and communities and SDG 12: responsible consumption and production through enhancing sustainability as well as health and safety. When these SDGs are achieved, they can additionally help fulfil other SDGs since they are interlinked. As a result, BIM can generally help enhance the quality of life, unlike the traditional method. However, BIM implementation also has issues which are merely political and legal, economic and technological and cultural and individual that affects its impact. The MCA will therefore help quantify the impacts of the identified criteria to explicitly compare the two methods.

3 METHODOLOGY

This paper uses a multicriteria analysis approach to evaluate the benefits of implementing Building Information Modelling (BIM) in the South African construction industry, and the technical guideline of the Australian government made by Infrastructure Australia that outlines the assessment framework of the multicriteria analysis is used as the guideline. The qualitative data are gathered from the Google Scholar database, while the quantitative data of the scores are facilitated by the scoring system shown in Figure 4. The criteria scores and their weights are based on simplicity and intuitiveness as suggested by [4], while the results from communicating with professionals on LinkedIn through a poll determine the weight of the objectives, and the outcome of the poll is in the appendix section. Using both methods enables the subjectivity brought by the qualitative approach to be compensated for by the objectivity of the quantitative analysis [23]. Moreover, the necessary steps taken to complete this study are summarised in Figure 5.

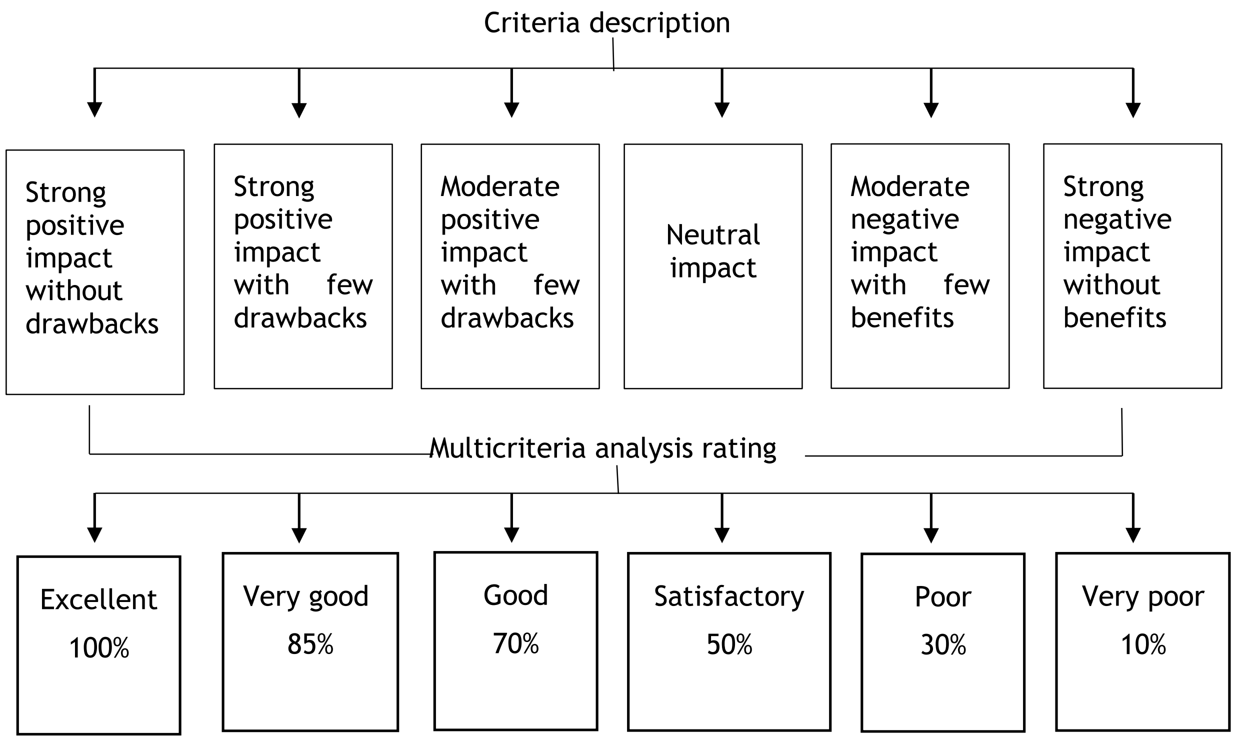

Figure 4: Proposed scoring system applied to multicriteria analysis.

Steps Taken	The Objective of the Step
1. Indentify the problem	To select the appropriate research approach
2. Develop key words	To identify relevant literature
3. Collect and analyse data	To understand the concept of BIM and asset information management
4. Develop the MCA	To compare the BIM and traditional approach of asset information management using Microsoft Excel tools

Figure 5: Flowchart of research methodology

The development of the MCA is done by initially identifying the objectives and the criteria using the literature study. Subsequently, the objectives' weights are determined, as well as the criteria scores and weights. Finally, the BIM and traditional approaches of asset information management are ranked using the MCA method outlined by the technical assessment framework of the multicriteria analysis guideline of the Australian government, as made by Infrastructure Australia.

4 RESULTS ANALYSIS

This section summarises the MCA results findings and provides a discussion of the statistical analysis for MCA outcomes. Table 2 provides an overview of the MCA scores, objectives, criteria and weights.

Table 2: The Multicriteria Analysis Matrix

Objectives and Criteria	Weights	Option Scores	
		Traditional Method (%)	*Digitalised (BIM) Method (%)*
Objective 1: Top Strategic Initiatives for SA construction industry	**0.1**	**20**	**92.5**
Criterion 1: Expansion of business offerings	0.1	30	85
Criterion 2: Expansion of geographic reach	0.1	30	85
Criterion 3: Implementation of Lean construction	0.3	30	85
Criterion 4: Digital transformation	0.5	10	100

Objective 2: Asset Information Management Processes	**0.2**	**40**	**71.5**
Criterion 5: Data capture	0.1	30	85
Criterion 6: Organising information	0.3	30	70
Criterion 7: Standardising information	0.1	30	70
Criterion 8: Effective sharing of information/ collaboration	0.3	50	70
Criterion 9: Information storage	0.2	50	70
Objective 3: Asset Information Management Outputs	**0.2**	**45**	**74**
Criterion 10: Information transparency	0.2	50	85
Criterion 11: Information accuracy and standardisation	0.2	30	85
Criterion 12: Information accessibility	0.2	30	85
Criterion 13: Information security	0.2	85	30
Criterion 14: Information retrieval	0.2	30	85
Objective 4: Cost and Expenses	**0.1**	**80**	**48.5**
Criterion 15: CAPEX	0.3	100	30
Criterion 16: OPEX	0.3	100	30
Criterion 17: Project cost/ Contract cost	0.3	50	85
Criterion 18: Training cost	0.1	50	50
Objective 5: Quality	**0.4**	**30**	**85**
Criterion 19: Stakeholders satisfaction	0.2	30	85
Criterion 20: Completion within required budget, scope and time	0.2	30	85
Criterion 21: Sustainability	0.2	30	85
Criterion 22: Maintenance of built infrastructure	0.1	30	85
Criterion 23: Adaption to complex projects	0.1	30	85
Criterion 24: Safety	0.2	30	85
Total Score		**215**	**371.5**

Total Weighted Average Score		**39**	**77.2**
Ranks		**2**	**1**

4.1 Statistical Analysis of MCA

This section transforms the multicriteria analysis into graphs which helps to check score variability and the trends of the multicriteria analysis. This helps deduce if the multicriteria analysis can be reliable or not. However, it must be noted that multicriteria analysis is a generally less reliable data decision-making tool. Despite that, multicriteria analysis can be successfully used to compare the AIM techniques with the influences of statistics. Figure 6 gives the score variabilities for the traditional and modernised techniques.

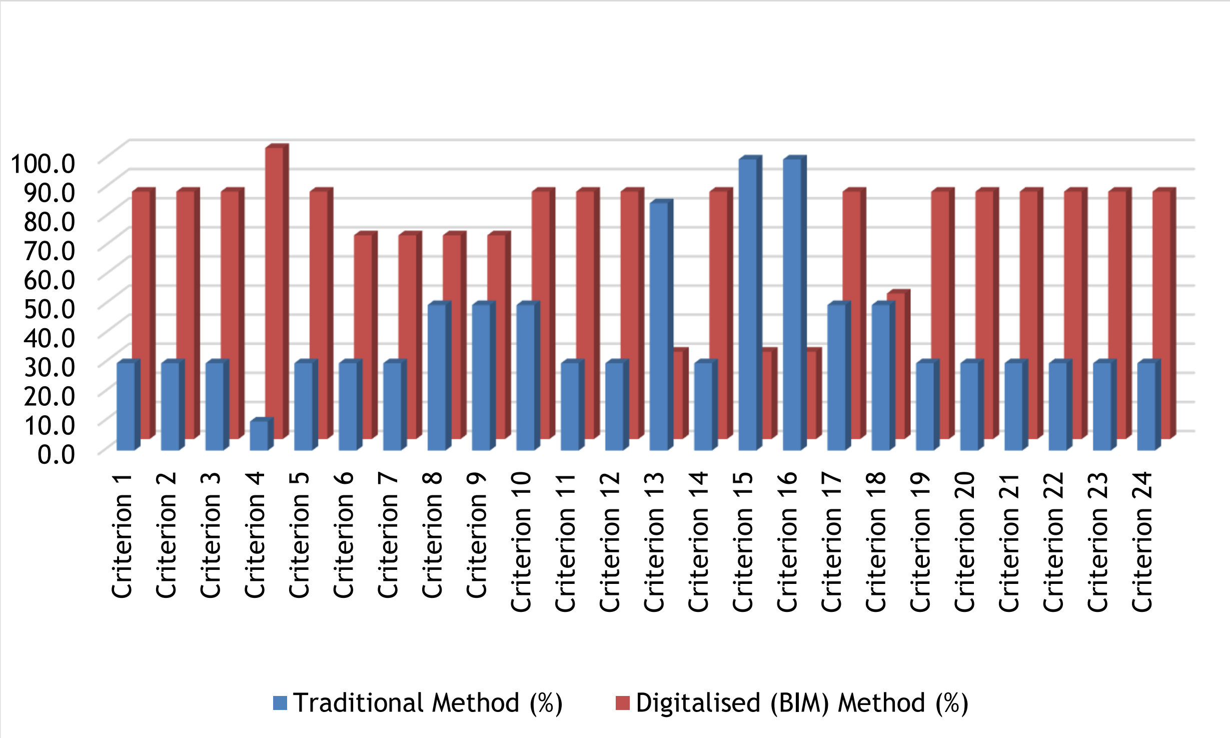

Figure 6: Score Variability of the MCA

In Figure 6, traditional method has wide-ranging values with a skewness of 1.7, a range of 90%, an average of 41.5% and a standard deviation of 22.9. The high range and standard deviation indicate that data is spread out around the mean. Moreover, the positive skewness shows that there are outliers that are distant from the mean on the right while they are closer to the mean on the left. The results show that there are three outliers, and the outliers are in criterion 13: information security, criterion 15: CAPEX and criterion 16: OPEX. The lower and upper outlier scores are 0 and 80, respectively where Q1 is 30 and Q3 is 50. This suggests that there may be errors in data collection of the multicriteria analysis due to factors not limited to human error, particularly inaccuracies in reasoning skills. Hence, it is imperative to check the percentage error of the weighted objectives to see whether these outliers are problematic or if they represent naturalism in the multicriteria analysis data.

On the other hand, the data of the digitalised (BIM) method in Figure 6 has a mean of 74.8%, a standard deviation of 19.7, a range of 70% and a skewness of -1.6. Just like the traditional technique data, the BIM data has spread out data around the mean due to the high range and standard deviation. On contrary, the modernised data has a negative skewness which indicates that there are outliers that are distant from the mean on the left while they are closer to the mean on the right. Similarly, the digitalised technique has three outliers in the same criteria i.e., criteria 13, 15 and 16. The lower and upper outlier scores are 47.5 and 107.5, respectively where Q1 is 70 and Q3 is 85. This shows that the percentage error of the weighted objective 3: Asset Information Management Outputs and Objective 4: Cost and Expenses are crucial since criteria 13 is for objective 3 whereas criteria 15 and 16 are for objective 4. The percentage error will help analyse the closeness of the measured value to an actual value and outline a comprehensive error analysis.

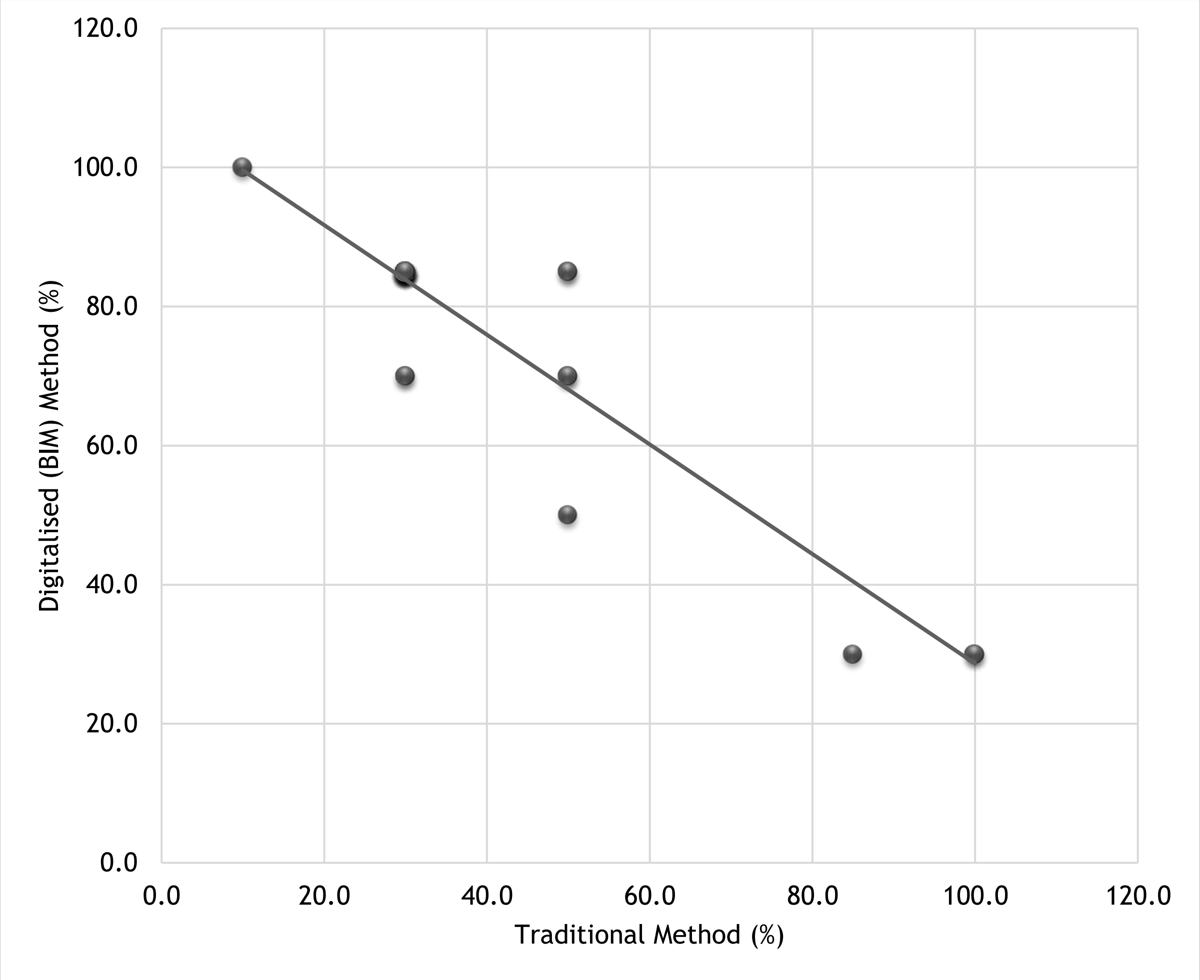

Figure 7: Correlation Graph

The multicriteria data analysis shows a strong correlation between the digitalised BIM method and the traditional method. Figure 7 shows the correlation graph between the two techniques. The correlation coefficient of the two AIM practices is -0.9. This is a high number, which emphasises the high correlation. The negative sign indicates that the more you implement the digitalised BIM method to manage asset information, the less you implement the traditional method or vice versa. The results show that there is no effective implementation of the traditional method and digitalised BIM technique simultaneously. This is in line with what is expected in the real world because BIM is believed to be a disruptive innovation, which significantly changes how the construction industry operates. Hence, the South African construction industry needs to understand that if it is to implement BIM innovation, information regarding how to transition from the traditional method to digitalised practices, such as the frameworks and the guidelines for BIM information models, is crucial. The frameworks and guidelines that South Africa may create to help their construction industry adopt BIM must also consider the challenges that arise with adopting BIM as well as how they can be resolved so that a smooth digital transformation may be promoted.

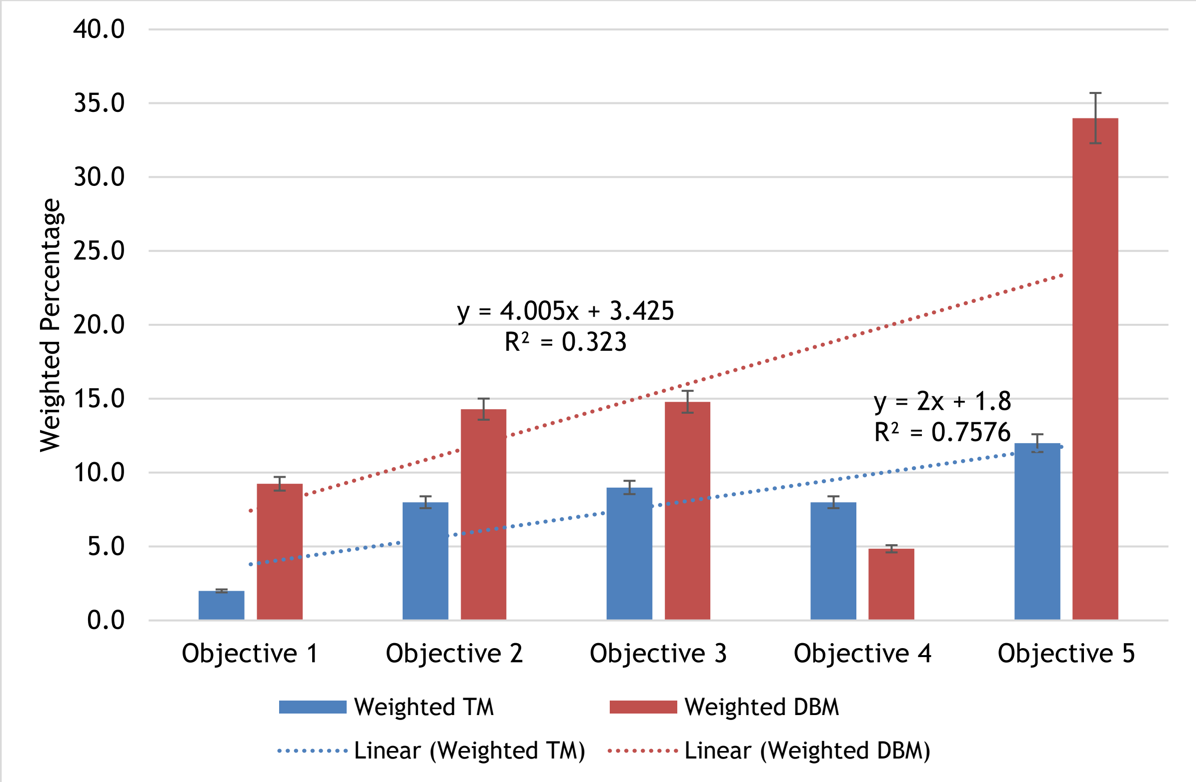

Figure 8: Traditional Method VS Digitalised BIM Method for Objective Weighted Average Score

The comparison of the weighted objectives of the traditional method and the modernised technique is shown in Figure 8. Accurate information is essential when managing data, and the IIMM recommends a 5% data accuracy review as a quality assurance measure [5]. Hence, the acceptable percentage error of the weighted objectives must be in the range of ±5%. As mentioned earlier, the percentage error, particularly for objectives 3 and 4 are crucial in deducing whether the outliers are problematic or not. The percentage errors for all the weighted objectives are generally in the range of ±5% in Figure 8. It can therefore be deduced that the three outliers identified in the multicriteria analysis do not highlight the inaccuracies of data collection. Instead, they illustrate the naturalism of the collected data.

The graph in Figure 8 shows that the multicriteria analysis model framework fits the collected data because the R^2 values are between 0.3 and 0.7 [24]. However, the multicriteria analysis model fits the weighted objectives of the traditional method (R^2=0.7576) more than those of the digitalised BIM method (R^2=0.323). This explains the generally lower percentage of errors in the traditional method than in the digitalised BIM method. The trendline equations also suggest that for any variable of x, the digitalised BIM method results will always be approximately double those of the traditional method. Additionally, this cements the fact that the implementation of BIM in the South African construction industry can lead to significant improvements in asset information management. The multicriteria analysis conducted in the study found that the BIM method consistently outperformed the traditional method in terms of the identified criteria, including the expansion of business offerings, and the expansion of geographic reach as the top strategic initiatives for the South African construction industry. The study concludes that the methods used to manage assets need to be modernized in the South African construction industry, and that BIM can produce approximately double the results of the traditional method for any variable of x. However, more research is required to confirm the trend and relationship shown in Figure 8.

Moreover, the radar chart in Figure 9 shows that the BIM method is generally better than the traditional method in all objectives excluding Objective 4: Cost and Expenses. This is due to the high initial cost of purchasing BIM hardware and software as well as the operational costs associated with managing and operating BIM. However, these are short-term disadvantages, and in the long-term, the company benefits more by improving project delivery and productivity through adopting BIM, thus increasing their profit margins.

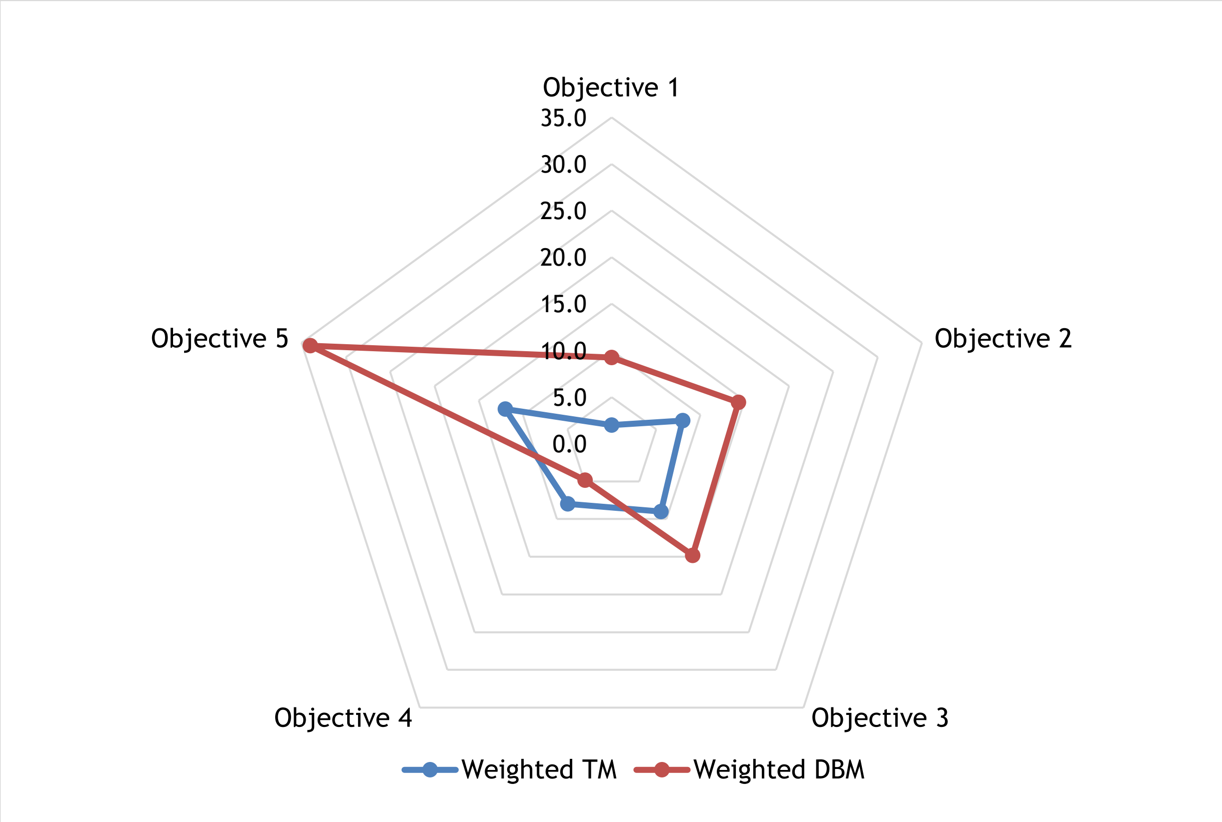

Figure 9: The Radar Chart of the MCA

5 CONCLUSION

It can be concluded that the results of the multicriteria analysis can be accepted because they show naturalism, the skewness of the graphs is within a range of ±3, the percentage error of the weighted objectives is within a range of ±5%, the multicriteria analysis model structure fits the data well and there are significant relationships that have been recognised by the multicriteria analysis. As a result, it is evident that the methods used to manage assets need to be modernised in the South African construction industry since the BIM technique will always produce approximately double the results of the traditional method for any variable of x. Moreover, the multicriteria analysis is not biased, or if there is any, the bias is insignificant, as the sample results, i.e., the multicriteria analysis results represent what is expected in the population, namely, the construction industry. The high standard deviations and ranges of data are in line with the theory that the multicriteria analysis is generally a less reliable decision-making tool. However, in this case, the results may be trusted and reliable due to acceptable accuracy and insignificant bias. Hence, BIM is the future of asset information management in South Africa, as per the MCA results of this paper.

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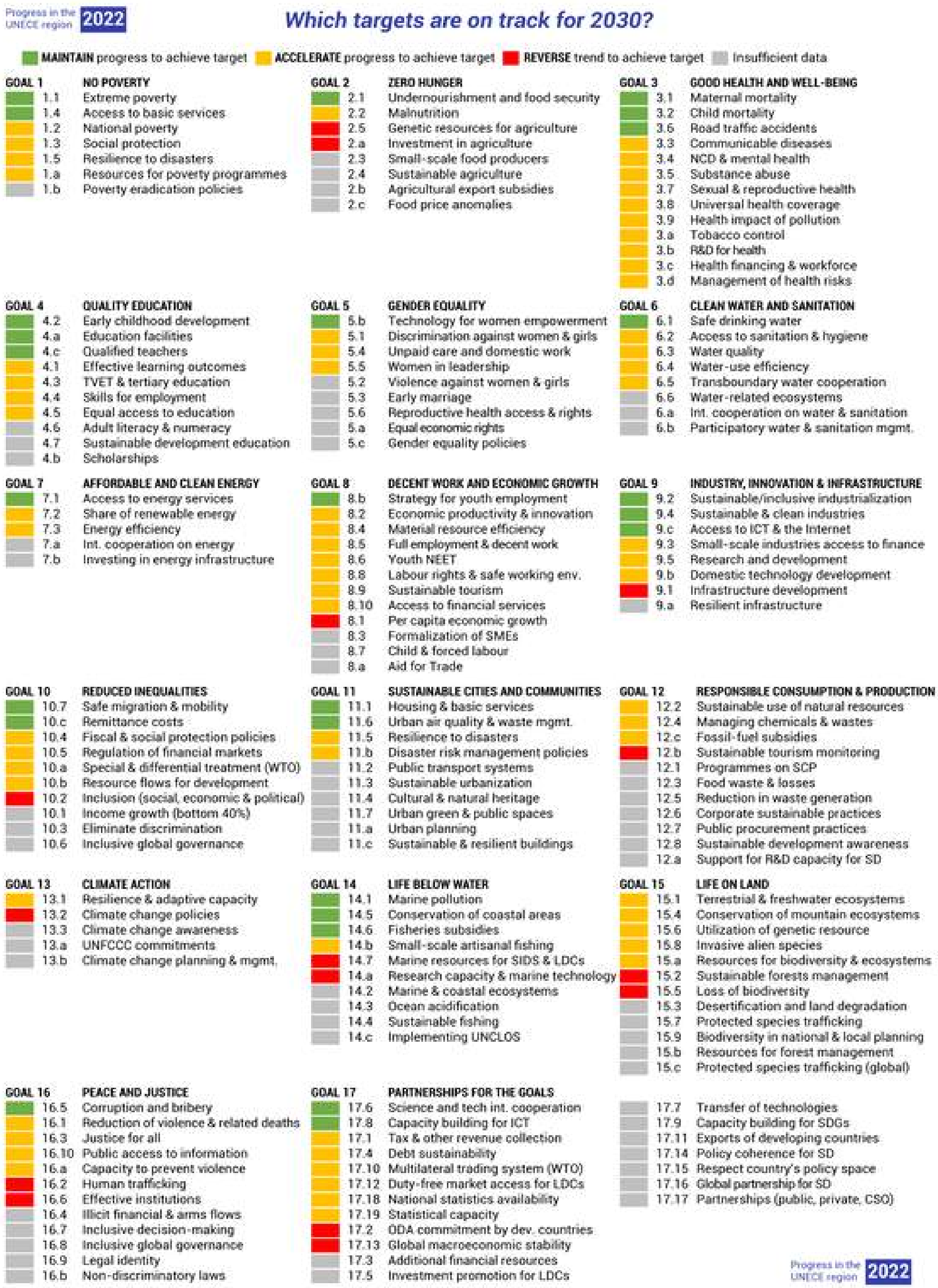
APPENDIX A: 17 SDG



APPENDIX B: POLL RESULTS

Factors	Score Percentage (%)	Additional Comments
Top strategic initiatives	14	• All are important. • They are all interrelated, so all of them and many more. • Quality maintains customer trust and company reputation. • Information management includes the other 3 and more. The other 3 require information and data management to be efficient.
Information management	37	
Project Quality	38	
Cost and expenses	11	

APPLICATION OF SYSTEM DYNAMICS IN THE INDUSTRY – SYSTEMATIC LITERATURE REVIEW 1981-2022

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ABSTRACT

To explore the common System Dynamics (SD) research approaches applied to solve the engineering problems. The outcome shall be used in the development of Dust and Ash plant maintenance SD model. SD studies were identified from 1981 to 2022. This was done through systematic literature review research methodology and Thematic Analysis Framework. These studies (21) were reviewed for the type of research problems, report structure, frameworks applied, instruments used to build the model, type of publication, trends and SD software used. Studies (70%) made use of Forrester SD research framework. Theoretical framework was found to be vital for the prediction and explanation of the plant maintenance phenomenon. Studies (42%) made use of mixed research instruments and interviews were common in all studies. Five different types of software were identified and Vensim SD (50%) was the most common. These learnings shall be applied in development of SD model in the future.

Keywords: System dynamics, Data, Dust and Ash plant and Studies.

* Corresponding Author

1 INTRODUCTION

System Dynamics (SD) is a suitable approach for modelling homogenous systems, which is described by interactions among variables and their feedback structure at an aggregate level [1] while Agent-based (AB) approach allows all individual building blocks to carry their individual characteristics. In this study, system dynamics approaches used to solve a wide variety of the industrial problems shall be explored with the objective to extend the learnings to dust and ash handling plant maintenance problem.

Sterman [2] argues that the behaviour of a system arises from its structure and Amen ([3] and [4]) who is practicing psychiatry argues that behaviour is an expression of a problem and not a problem. Amen makes use of single-photon emission computed tomography (SPECT) to identify loop that is accountable for the behaviour while Sterman makes use of the Systems Dynamics computer tool. These two academics are miles apart, but their arguments are in harmony. Martin [5] reasons that the underlying relationships and connections between the components of the system is called the structure of the system. Full understanding can only come when one dives beneath the plant maintenance behaviour to understand the structure causing the behaviour. Below in figure 1 is some of the common modes of behaviour in a dynamic system.

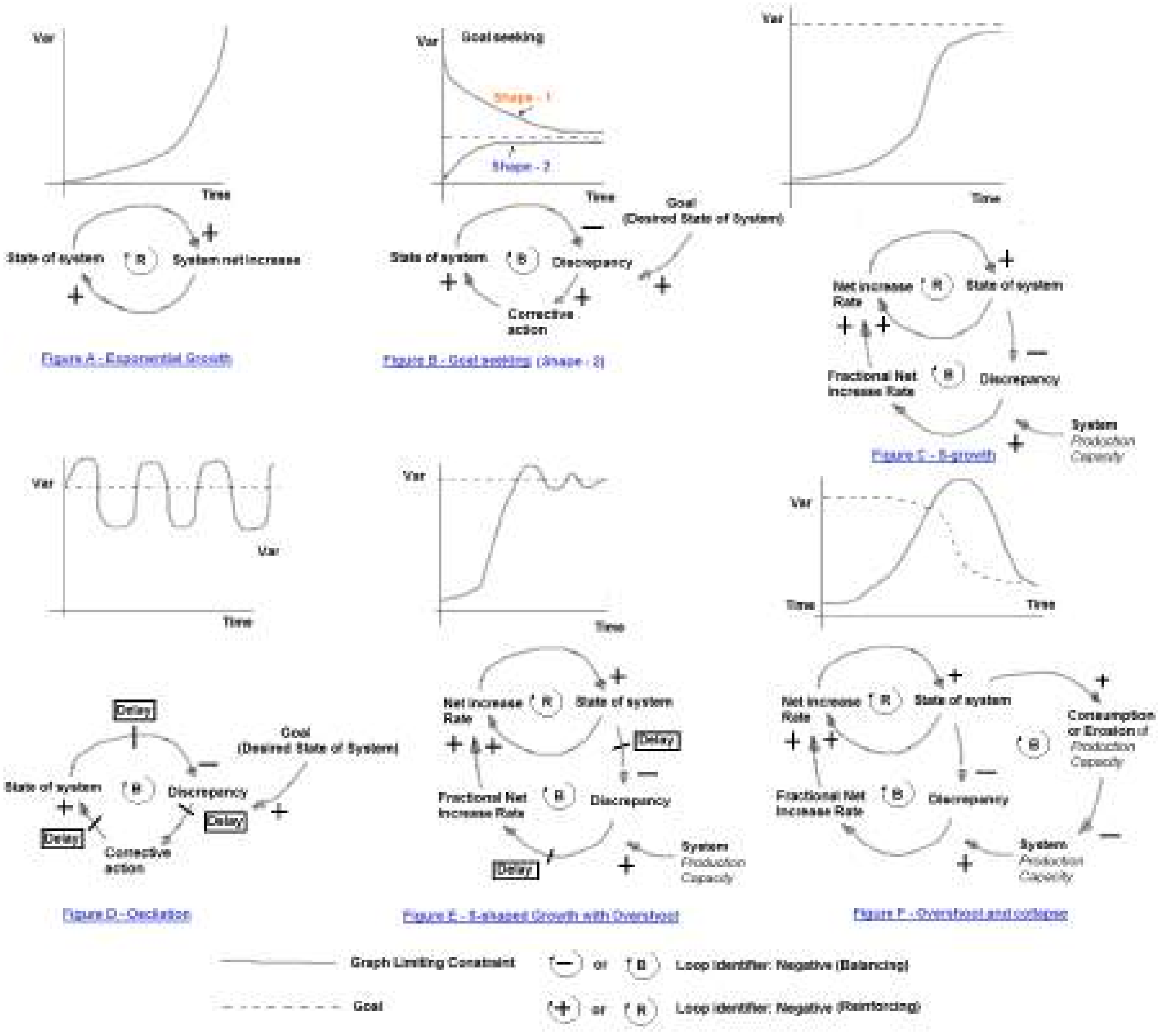

Figure 1: The common modes of behaviour in a dynamic system, Source: [2]

According to Sterman [2] "*growth, goal seeking, oscillation and their combinations are not the only behaviours that dynamic systems express. He argues that (1) Statis or equilibrium: state of the system remains constant over time, (2) Randomness - Sterman cautions the system dynamics student not to assign randomness when they cannot characterise the system behaviour and (3) Chaos.*" these form part of the common modes of the system behaviour in a dynamic system. He argues that individual components in a maintenance system do not contain the most complex behaviours, but the interactions of the components contain the most complex behaviours. Systematic Literature Review (SLR) will be done on the system dynamics topic with the objective understand the model building steps and attributes that define best SD model. The above-mentioned complex behaviours form part of what the future system dynamics maintenance model will attempt to unravel in the future.

2 RESEARCH OBJECTIVE

The researcher was tasked to improve the health of the dust and ash plant in a coal-fired power plant and a need was to learn from the work of the researchers who have travelled this route of solving problems using system dynamics approach. The study is based on the work conducted by various researchers dating 1981 to 2022. Therefore, the objective of the study is:

- To establish as to how system dynamics tool was applied using systematic literature review methodology.
- To present a summary of the implications of the systematic literature review findings for industry practitioners, researchers, and policymakers, offering insights into the potential benefits and challenges associated with the application of System Dynamics.

These best attributes obtained in these studies will be transferred to the future SD maintenance model.

3 RESEARCH QUESTIONS

Based on the stated background, systematic research methodology has been adopted to learn from the system dynamic research that had been conducted in the past. This study seeks to answer the following question:

- How to apply system dynamics methodology so that the dust and ash plant poor performance can be enhanced?

In addition to tackling this question, the study shall characterise the studies (21) by paying attention on the following themes: *Report structure, Software applied, Type of problems tackled, Types of data sources used to build model, Type of publications and Theoretical Research Frameworks* that was adopted by the researchers in the studies. The outcome of this study shall be used to aid the authors to build the dust and ash plant system dynamic model with the objective to enhance plant uptime.

4 RESEARCH METHODOLOGY

A systematic literature review (SLR) methodology was adopted, google scholar was indexed on the 28th of April 2023 to extract relevant journals, conference papers, theses and books that were applicable for system dynamics problems. Then, data was coded and extracted from the manually and included studies to synthesize and appraise the results, describe how the system dynamics was applied in practice, and highlight any gaps or discrepancies. Total of about 21 system dynamics articles were mapped in this study. The investigation process made use of explicit and replicable search strategy, studies were excluded or included, based on the inclusion criteria.

The benefits and shortfalls of this methodology were known; hence research controls were put in place to eliminate bias. The ability of this study was to explore a number of system dynamics cases from various socio-cultural contexts and present a holistic view as its main strength. There were several restrictions to be aware of in addition to its strength, researchers provided country-specific cases that were subject to their own interpretation and may be subjective [6].

5 SEARCH STRATEGY AND SELECTION PROCEDURE

Modified Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) systematic review principles [7] have been used for assessing and reporting the system dynamics studies to identify the best practices of SD applications. The research methodology that was followed is represented in figure 1 below. The authors made use of PRISMA 2020 for abstracts checklist and in cases where the abstract was not comprehensive, the authors had to review the entire article so that value could be extracted from the selected papers. The search engine made use the following search string: *application of system dynamics*. Due to lack of structured research in the system dynamics application, it was burdensome to select the appropriate search words, total of 40 articles were identified for the systematic review, to select the final articles to be included in this review, a practical screening was conducted, this was based on the setting of inclusion criteria.

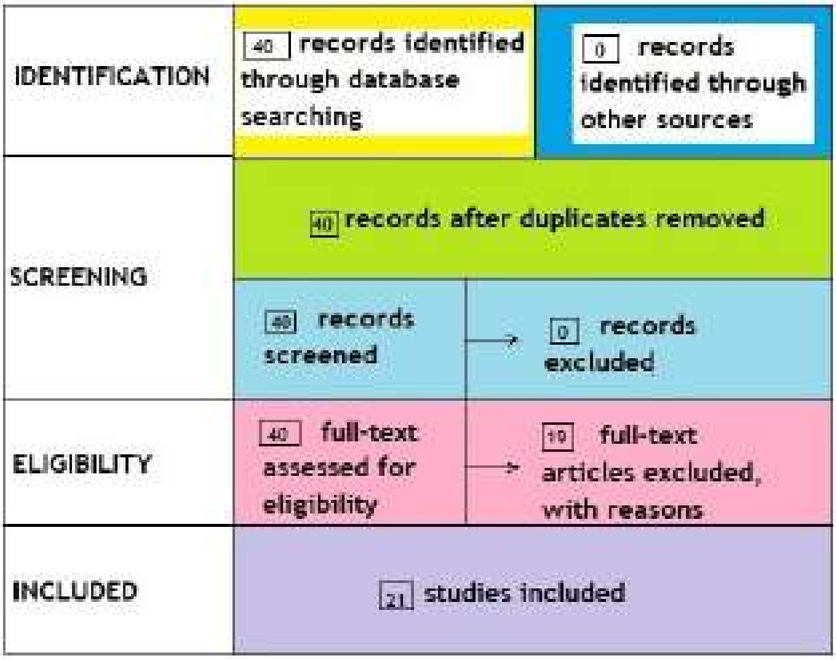

Figure 2: Systematic review flow diagram. Source: Adapted from [7].

6 INCLUSION CRITERIA

The initial search yielded 40 records through general internet search and manually. Total of 19 studies were removed for other reasons, leaving 21 studies that were then screened, applying the inclusion/exclusion criteria (see figure 2). Only English studies were selected (Table 1). Studies were included if they were published between 1981 and 2022. This included 21 journal articles, theses and conference papers. This process was followed to assist the peer-reviewers to able to easily establish the replicability of this study for confidence building in the research outcomes. The studies covered system dynamic models that were applied in the general industry.

Table 1: Inclusion criteria

Item	Description
Database searched	Google scholar and manual search
Date of search	28 April 2023
Person searching	Sello David Koloane
Database settings	Open to all areas that had researched about system dynamics application in the general industry
Language	English
Timespan	1981-2022
No. of records obtained	40
Search string	"system dynamics application"
Questions	**Review focus**
Population – who?	System Dynamics application models locally and internationally.
Intervention – what?	System Dynamics application models that had been duly developed and tested so that the learning could be transferred to dust and ash plant uptime enhancement project.
Comparator/s – compared to?	Best system dynamic plant model with high availability internationally.
Outcomes – expected result	Identification of the system dynamics model levers that can be explored and transferred to the dust and ash plant model for an enhanced plant uptime.
Time – when?	1981-2022
Setting – where?	In the power plant and general industry setup

7 STUDIES SELECTION

A total of 40 relevant papers in all were found in Google Scholar at first. But after looking at the titles and the abstracts, it was discovered that 19 of these publications largely dealt with systematic literature and did not clearly highlight the application of system dynamics. To assess the use of system dynamics in general industry, a detailed analysis of the remaining 21 articles was conducted. These articles were distributed over 21 various theses, journals, and conferences. Most of them were published in fourteen theses from different universities across the world.

Using the qualitative data analysis, all articles that had met the requirements were examined and coded [8]. Thematic analysis, according to [9], "is a method for identifying, analysing, and reporting patterns (themes) with data." *SD report structure, SD Software applied, Type of problems tackled, Type of publication, Types of data sources used to build model, Type of publications and Theoretical Research Frameworks* used were the themes that were adopted. This was the culmination of a six-step procedure, as seen in figure 3 below.

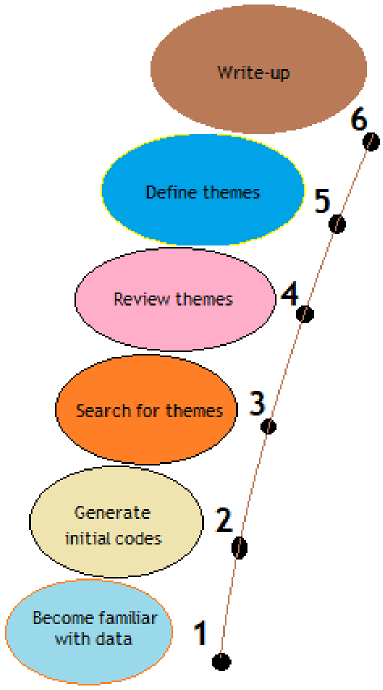

Figure 3: Framework for doing thematic analysis. Source: Adapted from [8,9] and [10].

The results of the thematic analysis have been captured under appendix A ([27] to [48]). During the application of the research methodology, it became evident that the studies were not well structured as abstracts could not be used to obtain all thematic data required to prepare for the building of dust and ash plant SD model, for this reason and others, meta-analysis could not be applied as the SD studies were heterogeneous and did not meet PRISMA guidelines requirements.

8 STUDY CHARACTERISTICS

8.1 TYPE OF RESEARCH PROBLEMS

Majority (29%) of the problems that were under review came from the energy related sectors, this was followed by the project management type (19%). The study has also revealed that application of system dynamics covered wide spectrum of studies as ten different fields were covered. These included: Water management, Supply chain, Quality, Manufacturing, Maintenance, Sustainability, Technology Change Management and Scheduling. Forrester [11] reasoned "*that our social systems are far more complex and harder to understand than our technological systems. Why, then, do we not use the same approach of making models of social systems and conducting laboratory experiments on those models before we try new laws and government programs in real life?*". Application of this tool in these diverse sectors has confirmed the visionary work of SD founding father.

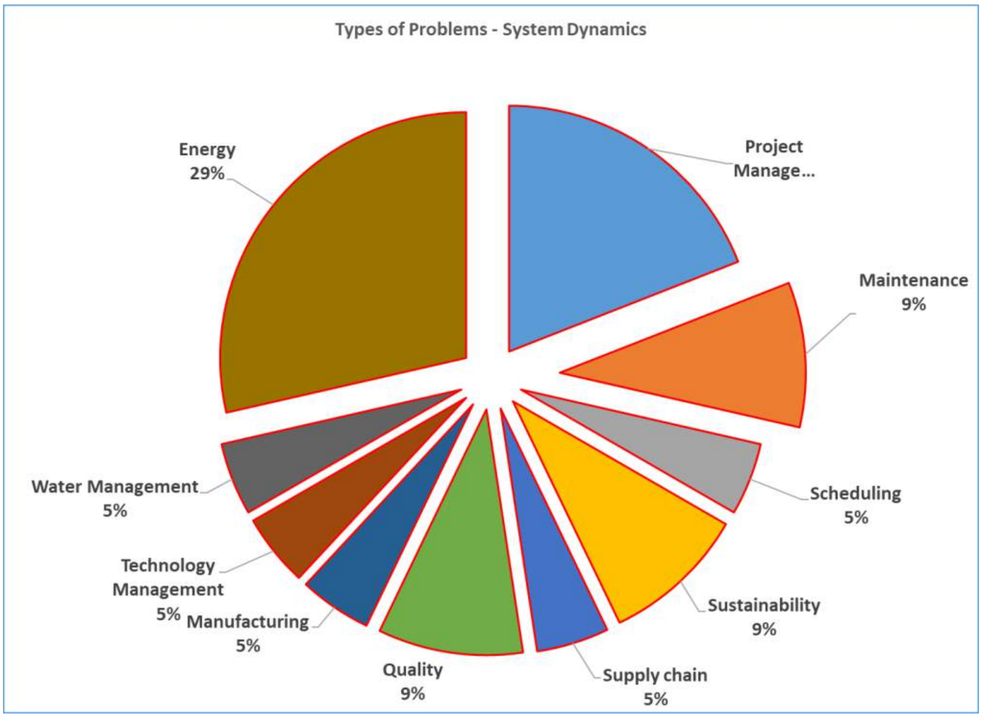

Figure 4: Types of problems solved using system dynamics modelling.

8.2 PUBLICATION REPORT STRUCTURE

Most of the literature that was reviewed had five sections (38%). Eleven of the Ph. D theses had structure divided into eight sections (24%). The least number of sections in SD report was four while the highest was nine. The study has also revealed that SD lacked systematic tool to aid the researchers to report SD modelling results uniformly across the fields to eliminate replication crisis.

Table 2: Types of problems solved using system dynamic modelling.

Publication Type	Four Sections	Five Sections	Six Sections	Seven Sections	Eight Sections	Nine Sections	TOTAL	Type of Publication Contribution
M.Eng Thesis	0	3	0	0	0	0	3	14%
PhD Thesis	0	2	2	1	5	1	11	52%
Licentiate Thesis	0	1	0	0	0	0	1	5%
Journal	1	2	0	2	0	0	5	24%
Conference	0	0	0	1	0	0	1	5%
TOTAL	1	8	2	4	5	1	21	TOTAL
Publications with X sections	5%	38%	10%	19%	24%	5%		

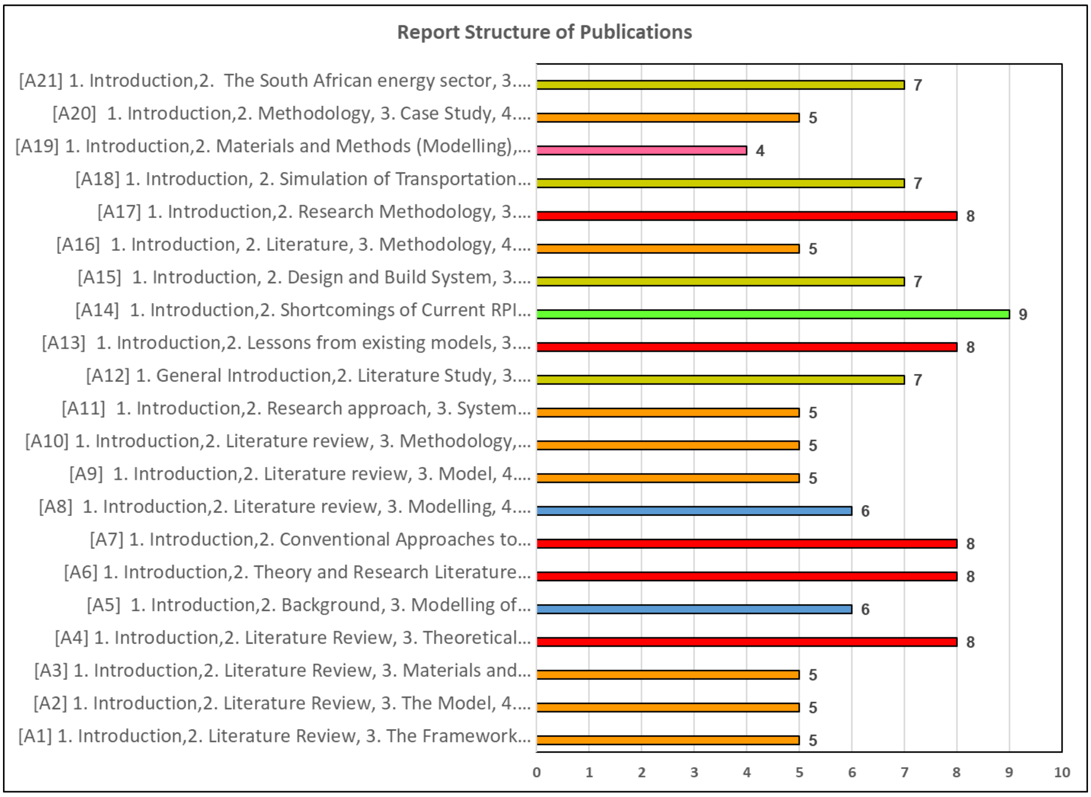

Figure 5: Study - Number sections in the SD report structure.

8.3 RESEARCH FRAMEWORKS APPLIED

Scientific inquiry objective is to find an explanation and prediction about the world of dust and ash system in a coal-fired power plant, to achieve this enlightenment; scientific methods must be applied with rigour so that theory can be developed to provide phenomenon's description and prediction. Popper [12] sums up the criterion for the theory's scientific status as its falsifiability, or refutability, or testability. Glassman [13] argues that a theory is a hypothesis with at least one non-trivial validating datum while Glanz, Rimer and Glanz *et al*. [14] defines theory as a set of interrelated concepts, definitions, and propositions that present a systematic view of events or situations by specifying relations among variables, in order to explain and predict the events or situations. Table 3 below provides more insight based on the work of the various researchers.

Table 3: Theory definitions

Definition	Source
Theory is an organized body of concepts and principles intended to explain a particular phenomenon.	Leedy and Ormrod [15]
A scientific theory is a set of statements that, when taken together, attempt to explain a broad class of related phenomena.	Eastwell [16]
Theory has four components: Definitions, domain, relationships, and predictive claims to answer the natural language questions of who, what, when, where, how, why, should, could and would.	Wacker [17]

The most applied theory in the systematic literature study that was reviewed is systems thinking theory which is the foundation of the system dynamics founded by Forrester. Boulding

[18] argues that periodic table that was discovered by Dmitri Mendeleev in 1869 can be used to support the general system theory. Development of the periodic table was able to indicate to the scientists that certain *elements existed* and were *unknown* and this opened a room to search for these missing elements [19]. Systems theory also seeks to serve as a periodic table in the republic of engineering to identify and predict the missing theories so that the body of knowledge can be enhanced.

Arnold and Wade [20] critically examined various definitions offered by different experts and based on the strength and weaknesses that they had identified, they developed a new definition: "*System thinking is a set of synergistic analytic skills used to improve the capability of identifying and understanding systems, predicting their behaviours, and devising modifications to them in order to produce desired effects*". The same definition shall be applied to explore the Dust and Ash plant performance to understand the system dynamics involved, predict the plant behaviour in order to drive the plant availability to the highest level.

This plant is complex as it contains numerous items, different types of technologies, operated by different people, maintained by different people, processing different types of ash and so on. These parts have a complex intra- and inter-relationship structure with the performance of the whole plant as the cause and effect are not close in time and space [20]. Systems theory is vital for this research owing to the interaction and interdependencies that exist within Dust and Ash plant.

Kivunja [21] argues that a theoretical framework is made up of the theories put forth by experts in the system dynamics, which the researcher draw from to give a theoretical framework for your data analysis and result interpretation. Articles (21) studied made use of general system dynamics theoretical framework without describing the theoretical coat [21] that had been adopted while 57 % the articles had a section in their publication that was dedicated to the description of the theoretical framework. Below in Table 4 is a list of the frameworks that were used by the various researchers in this study.

Table 4: System dynamics - theoretical frameworks applied in the studies

ID	Theoretical Framework Applied
A1	System dynamics in general
A2	System dynamics in general
A3	Grounded theory, Narrative enquiry (interviews, observation and evidence from literature) and System Dynamics
A4	Theory of project management, Complexity aspect in the Project Management Research, Interaction of Risks in Mega Projects (STEEP) and System Dynamics
A5	System dynamics in general
A6	System dynamics in general
A7	Social-Ecological System Framework (SESF). Complex and Systems Thinking Theory
A8	System dynamics in general
A9	System dynamics in general

ID	Theoretical Framework Applied
A10	System Dynamics and Participatory Action Research - SyDPAR approach is a modelling process design resulting from the integration SD and PAR. Technology driven theory for guiding SD model building and validation (critical rationalist theory of science), and organizational decision choice theory for guiding decision making on HE quality issues (Garbage Can Model of Organizational Choice).
A11	Theory of Structure, Project management, Complexity aspect in the Project Management Research, Interaction of Risks in Mega Projects (STEEP) and System Dynamics
A12	System dynamics in general
A13	System dynamics in general. This is based on explicit causal theory of the economic behaviour. Behavioural theory of the decision-making at the microeconomic level.
A14	Systems theory, Complexity theory and Decision Theory. Group model-building (GMB), Dynamic Synthesis Methodology.
A15	Agent-based Model -System Dynamics-Building Information Modelling (AFM-SD-BIM) framework and Theory of Reasoned Action (ToRA).
A16	System dynamics in general
A17	Top-to-bottom-to-top dynamic systems modelling method (DSM) - Dynamic Synthesis Methodology Research Design. System Dynamics.
A18	The hybrid modelling framework - System dynamics (SD) and agent-based (AB) modelling. Mathematical modelling of agents - Interlinked modules for studying the diffusion of AFVs (Alternative Fuel Vehicles).
A19	System dynamics in general
A20	System dynamics-multiple objective optimization (SD-MOO) model-based water supply and demand prediction, dynamic adjustment, and water optimal allocation.
A21	Threshold 21 model - planning tool that integrates the economic, social, and environmental dimensions of a country into a single, comprehensive, transparent, user-friendly analytical framework. This is a system dynamic macro-model, based on the systems thinking approach.

Combination of the various theoretical frameworks that were applied by various researchers listed in the above table shall be applied through system dynamics tool to untangle plant maintenance problem that has dynamic combinatorial complexity.

8.4 RESEARCH INSTRUMENTS USED TO BUILD SYSTEM DYNAMICS MODEL

System dynamics methodology that was developed by Forrester [22] to solve complex feedback systems is explored by delving into the research instruments that were applied in the field. This methodology was originally designed to close the gap between real world observations (i.e., cause-effect relationship) by the users of the system and the policies that have been implemented to achieve certain outcome.

This methodology makes use of both qualitative and quantitative methods to build the system dynamic model. Qualitative approach is used to articulate problem statement, causal loop diagram and development dynamic hypothesis. Quantitative approach is used to formulate the simulation model using the stocks, flows, variables, etc. In solving these complex problems, the following sources of data are vital in the development of the model ([22] and [23]). Sterman [23] provided categories of the data sources that were essential in building the system dynamic model.

Table 5: Sources of data for modelling process. Source: [23]

Type of data source (s)	Description
Mental data (Most valuable for modelling process)	Information in people's mental models, such as their impressions, tales they tell, their understanding of the system and how decisions are made in practice versus how decisions are made in theory, how exceptions are handled, and so on. Interviews, observations, focus groups, Delphi methods and other methods are used to gather information.
Written data (Valuable for modelling process)	Records include operating instructions, organizational charts, media reports, e-mails, and other archival items.
Numerical data (Least valuable for modelling process)	Time series and cross-sectional records in various databases (E.g.: SAP PM maintenance data, etc.).

In this systematic literature review study, it was found that archival data (25%) was the most used research instrument, and this was in contradiction with the Sterman and Forrester's findings [24]. Group modelling with experts, observations and individual interviews constituted 42%. This finding agreed with established system dynamic methodology.

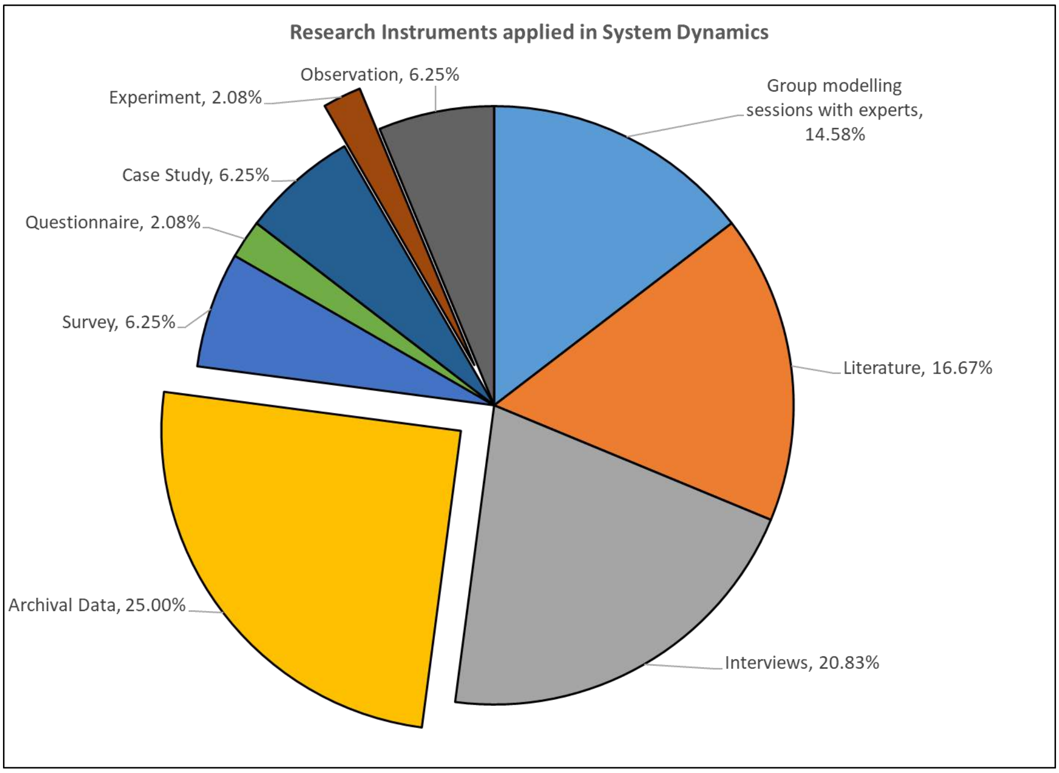

Figure 6: Research instruments applied in the System Dynamics studies

8.5 System Dynamics SOFTWARE applied in the studies

Most of the researchers (50%) made use of the Vensim software in the 21 studies that were reviewed. One study did not indicate the software that was used in study.

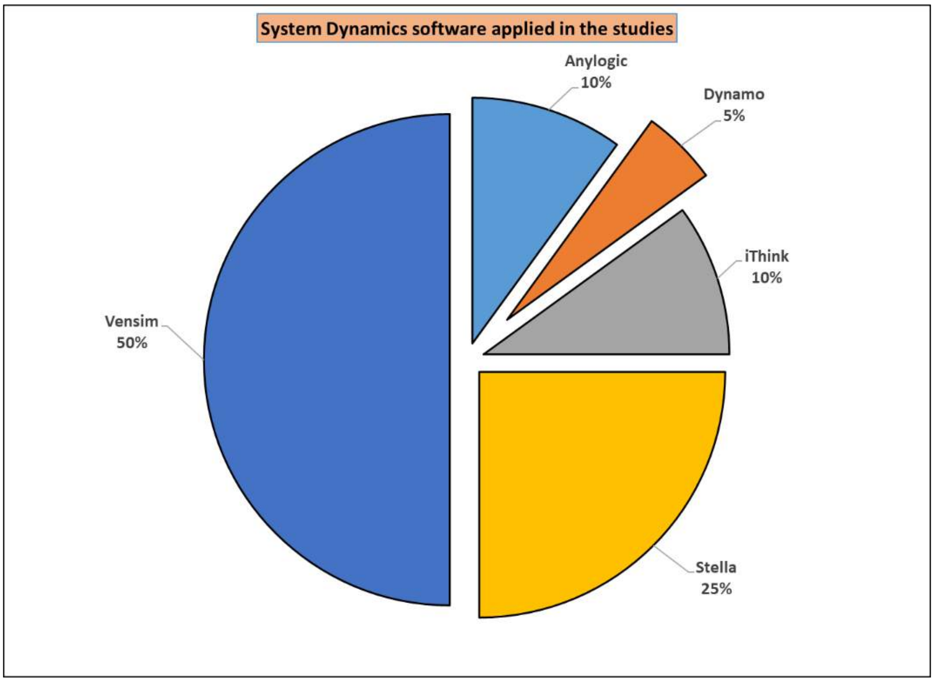

Figure 7: Software that was applied in the studies

According to the study conducted by [25], system dynamics software must be evaluated according to the following:

- Its foundation in the fundamental theory of system dynamics.
- Its usability.
- Support it provides for model development.
- The extent to which models can be documented and explained to the sponsor.
- Facilities it has for model debugging.
- The range of its facilities for designing policies.
- The ease of conducting trials and providing results.

Below in figure 8 is the evolution of the System Dynamics software.

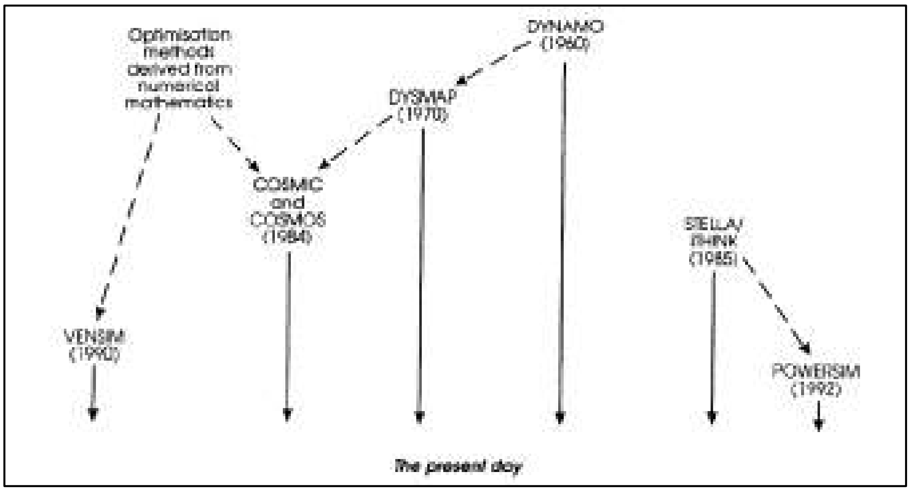

Figure 8: Evolutionary lines of system dynamics software, Source: [25]

8.6 PUBLICATION YEAR

The studies that were selected for the system literature review ranged from 1981-2022 and most of the studies were in 2016. Publications in these studies had stagnated.

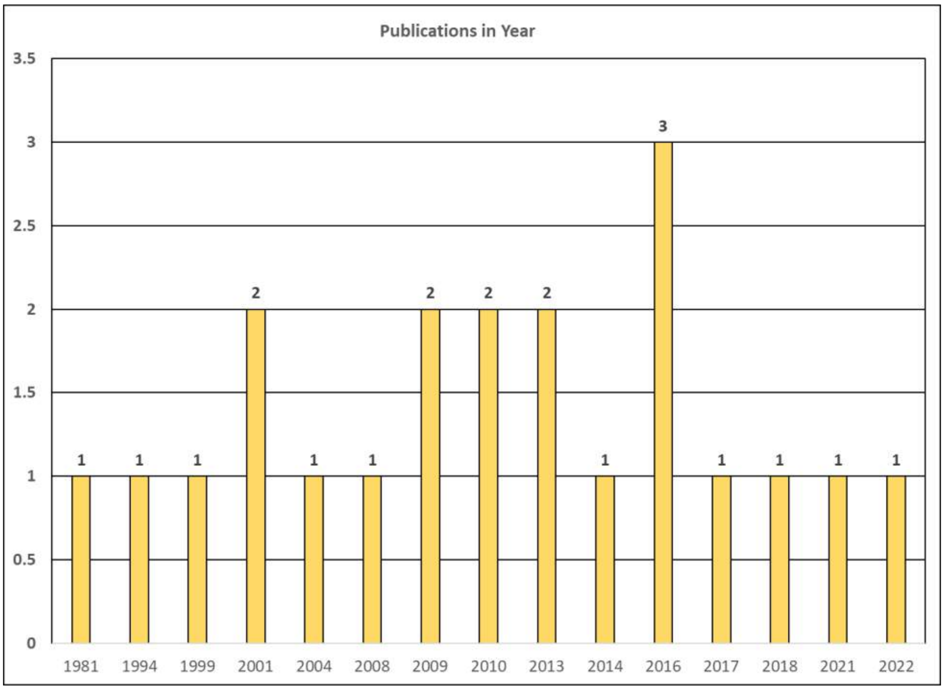

Figure 9: Publications in a year

9 DISCUSSION OF THE RESULTS

Table 6 below provide a summary of the systematic literature review and learnings that are important for the system dynamics practitioners.

Table 6: Summary of the SLR and learnings.

Item	Study Findings	Notes for the System Dynamics model practitioners
Type of research problems	System dynamics tool has been applied in different sectors (10) and energy sector was the leader. Forrester's prediction about the diverse application of this tool has been validated through the SLR outcomes. This was like the work done by Mendeleev regarding the periodic table elements that were yet to be discovered. System dynamics has the potential to predict the missing body of knowledge in the dust and ash plant dynamics. The two scientists' arguments were based on system theory. Amen's work in psychiatry and Sterman's work in engineering have recently produced the same results even though they from came two opposite positions - structure of the system defines its behaviour.	System dynamics is an ideal tool to identify and predict the missing body of knowledge in diverse fields and this has been validated as a good device to study the dust and ash plant problems for safer and higher plant uptime.
Publication report structure	Most of the SD publications (38%) had five (5) sections structure which included: 1. Introduction, 2. Literature Review, 3. The Model, 4. Simulation and Application of Results 5. Conclusion Ph.D. theses (52%) had minimum of eight (8) sections. SD publication structure was important to capture all crucial building block of the research. These blocks will aid in the validation by the peers.	SD publication must have a minimum of five (5) sections to cover all pertinent phases of the research while Ph.D. theses must have a minimum of eight sections.

Item	Study Findings	Notes for the System Dynamics model practitioners
Research frameworks applied	The most applied theory in the studies that were reviewed is systems thinking theory (57%). Application of this theory demands that the student of SD tool must study pertinent facets (people, tools, methods, technology, etc.) of the dust and ash plant to mimic the plant performance behaviour.	Theoretical framework must be developed for the dust and ash plant maintenance problem to provide explanation and prediction of the phenomenon.
Research instruments used to build system dynamics model	Combination of interviews and group modelling with experts constituted 42% while the use of archival data had 21%. This observation in contravention of the positions of Forrester and Sterman (refer to table 5 above). Obtaining data from the mental models of the users was ranked the best by the two pioneers.	Quantitative and qualitative research instruments are vital for the SD modelling process and mental model data was ranked supreme.

10 LIMITATIONS

This study, which was published between 1981 and 2022. It was included in the Google database and conducted using English-speaking lenses. Although the 21 studies were obtained in the Google database, it may have overlooked any additional important studies that were published elsewhere or in languages other than English. Examples of include studies that were conducted in Arabic, Greek, Chinese, Spanish, French, Swahili amongst other languages and this was missed due to the design of inclusion criteria. Therefore, future studies should be mindful of English-based and one index searches and seek to include research from areas previously considered under-represented. This might include using other methods to identify system dynamics literature and making use of translation tools for non-English studies. Some of the studies' abstracts were incomplete as they did not include the salient findings and the author had to review such articles comprehensively to identify themes of interest. This shortfall in the studies could be a source of replication crisis [26] as the author could have been biased.

11 CONCLUSION

In this study, 21 published articles on the application of the system dynamics theory were applied using the systematic literature review and framework for doing thematic analysis were used to identify the above-mentioned themes.

Majority of the research problems were geared to solve the energy issues (29%) followed by project management (19%). The has also revealed that application of system dynamics covered wide spectrum as eleven different fields were covered. These included Water management, Quality, Manufacturing, Maintenance, Sustainability and Scheduling.

The author also found that the system dynamics research lacked structure as there was no alignment amongst the researchers using the same methodology. This could be source of replication crisis as the author could have been biased.

Sources of the publication came from Ph.D. theses (52%), M. Eng. theses (14%), Licentiate thesis (5%), Journals (24%) and Conference (5%) articles.

Theoretical frameworks applied in the studies were based on system dynamics theory. Most the studies (57%) were explicit about the theoretical coat that their studies were relying on while 43% did not come forth with the espoused theoretical coat.

Archival data (25%) was the single most common source of data but combination of interviews and group modelling with experts constituted 42%. Archival data position was in the least preferred according to Sterman while obtaining data from the mental models of the users was ranked the best.

Vensim (50%) was the most used software and the total number of software in these studies were five.

The publication in this study covered a wide spectrum dating from 1981 to 2022. Publications growth in this sample seemed to be stagnant but this is not agreement with the observations of the authors. This anomaly could have been caused by the research design that has yielded a sample that did not have the true characteristics of the main population. This was beneficial for the study as changes in the application could be noted in these studies.

The above-mentioned findings opened the road for the application of system dynamics model in the dust and ash plant based on the above-mentioned summary of the findings. These results are beneficial for future research of SD in the dust and ash plant maintenance modelling.

12 RECOMMENDATIONS

- Future reviews search strategy must be expanded so that the gaps identified in this study could be eliminated, that is to include other databases and languages translated through translation tools.
- Dust and ash plant maintenance model shall be developed in the future based on these learnings.

13 COMPETING INTERESTS

The authors declare that they did not have competing interests.

14 ACKNOWLEDGMENTS

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16 APPENDIX A – SYSTEM DYNAMICS MODEL STUDIES

ID	Author(s)	Type of Research Problem	Report Structure	Theoretical Framework Applied	Research Instruments used to Build the Model	SD Software used	Type of Publication
A1	Pavinder Monga (2001)	Lack of understanding of the dynamic nature of the technology development process undertaken by aircraft-carrier builders and planner. Project management problems.	1. Introduction,2. Literature Review, 3. The Framework Model, 4. Results, Testing, Sensitivity Analysis, Validation and Verification 5. Conclusion	System dynamics in general	Group modelling sessions with experts	VENSIM Professional 4.0 software	M. Eng Thesis
A2	Prasad Iyer (1999)	The effect of maintenance policy on system maintenance and system life-cycle cost. Maintenance.	1. Introduction,2. Literature Review, 3. The Model, 4. Simulation and Application of Results 5. Conclusion	System dynamics in general	The Delphi Approach	VENSIM and C++	M.Eng Thesis
A3	Ashiel Jumman (2016)	Using system dynamics to explore the poor uptake of irrigation scheduling technologies in a commercial sugarcane community in South Africa. Scheduling in Agriculture.	1. Introduction,2. Literature Review, 3. Materials and Methods 4. Results (Part 1): Evidence from Literature and Narrative Data. 5. Result: (Parts 2) Word of mouth System Dynamics Model 5. Conclusion and Recommendations.	Grounded theory, narrative enquiry (interviews, observation and evidence from literature) and system dynamics	Literature, Semi-structured Interviews and Observations	STELLA software	PhD Thesis
A4	Noah Omondi Ogano (2016)	To develop a means or method of how to manage risk better in the projects in Kenya and Southern Africa. Energy.	1. Introduction,2. Literature Review, 3. Theoretical Framework, 4. Empirical Research, 5. Model development, Modelling and Simulation, 6. Model verification, validation, analysis and policy design, 7. Discussion of results, 8. Conclusion	Theory of project management , Complexity aspect in the Project Management Research, Interaction of Risks in Mega Projects (STEEP) and System Dynamics	Interviews and Archival Data	Vensim	PhD Thesis

ID	Author(s)	Type of Research Problem	Report Structure	Theoretical Framework Applied	Research Instruments used to Build the Model	SD Software used	Type of Publication
A5	Raymond Joseph Madachy (1994)	A software project dynamics model for process cost, schedule and risk assessment. Software Project Management.	1. Introduction, 2. Background 3. Modelling of inspection-based process 4. Knowledge-based risk assessment and cost estimation 5. Model evaluation and demonstration 6. Conclusion	System dynamics in general	Interviews, Literature and Archival Data.	iThink	PhD Thesis
A6	George T Maluleke (2014)	Mining and minerals project development in RSA has been focused on upstream mining and leaving the communities behind. Sustainable mining in South Africa (Manganese).	1. Introduction 2. Theory and Research Literature Review 3. The research theory and concept 4. Research Methodology 5. Construction of system dynamics model 6. Results presentation and analysis 7. A case for system thinking and system dynamics modelling based approach 8. Conclusion	System dynamics in general	Archival data,	Vensim	PhD Thesis

ID	Author(s)	Type of Research Problem	Report Structure	Theoretical Framework Applied	Research Instruments used to Build the Model	SD Software used	Type of Publication
A7	Julius Harrison Kotir (2017)	To develop a computer-based integrated conceptual, dynamic and simulation model that can be used to support decision-making concerning sustainable water resources planning and management and agricultural development in the Volta River Basin of Ghana, West Africa. Sustainability.	1. Introduction,2. Conventional Approaches to Managing and Researching Natural Resource Systems. Contemporary Approach for Natural Resources Management and the Research - A system-based approach, 4. Research Methodology, 5. Drivers of change and Sustainability in linked ecological systems, 6. Systemic Feedback Modelling for Sustainable water resources management and agricultural development, 7. A system dynamics simulation model for sustainable water resources management and agricultural development in Volta River Basin, Ghana, 8. Conclusion	Social-Ecological System Framework (SESF). Complex Systems Thinking Theory.	Literature review. Exploratory interviews. Structured expert judgement technique - interview/questionnaire. Participatory modelling based on causal loop. System dynamics simulation approach.	Stella	PhD Thesis
A8	Roberto Poles (2010)	System dynamics modelling of closed loop supply chain systems for evaluating system improvement strategies. Supply chain.	1. Introduction,2. Literature review, 3. Modelling, 4. Modelling the returns process. 5. Modelling the remanufacturing process. 6.Conclusion	System dynamics in general	Direct observation, Archival data and Interviews	Vensim PLE v5.6d	PhD Thesis

ID	Author(s)	Type of Research Problem	Report Structure	Theoretical Framework Applied	Research Instruments used to Build the Model	SD Software used	Type of Publication
A9	Vishal Kothari (2004)	Objective is to model the maintenance system of a generic technology and to map the causal and non-linear relationships among the key variables to analyze the impact of various maintenance policies on systems' behavior. To understand the dynamics associated with maintenance functions and formulate the best possible policy for maintenance management of a technological system and simulate it in the virtual world to approximate the policy's response in the real world. Maintenance problem.	1. Introduction,2. Literature review, 3. Model, 4. Results, Testing, Validation and Verification, 5. Conclusion	System dynamics in general	Interview of the experts	Vensim	M. Eng Thesis

ID	Author(s)	Type of Research Problem	Report Structure	Theoretical Framework Applied	Research Instruments used to Build the Model	SD Software used	Type of Publication
A10	Benedict Oyo (2010)	To develop a more rigorous participative modelling architecture. The relevance of the new architecture in solving complex practical problems is tested on HE quality problem area. Quality in Education.	1. Introduction,2. Literature review, 3. Methodology, 4. Research Issues and Field Study Findings, Model, 5. Application of SyDPAR to HE Quality Management, 5. Discussions and Conclusions.	System Dynamics and Participatory Action Research - SyDPAR approach is a modelling process design resulting from the integration SD and PAR. Technology driven theory for guiding SD model building and validation (critical rationalist theory of science), and organization al decision choice theory for guiding decision making on HE quality issues (Garbage Can Model of Organization al Choice).	Interviews and Survey	Stella	PhD Thesis
A11	Gary Linnéusson (2009)	To increase an organization's ability to find key leverage points in an industry problem situation by using system dynamics projects for manufacturing systems development. Manufacturing .	1. Introduction,2. Research approach, 3. System dynamics, 4. Findings, 5. Conclusion	Theory of Structure, Project management , Complexity aspect in the Project Management Research, Interaction of Risks in Mega Projects (STEEP) and System Dynamics	Interviews, Literature review, Group model building, Survey, Case Study and Archival Data.	Vensim	Licentiate Thesis
A12	Nalini Sooknanan Pillay (2018)	System Dynamics Simulation of Income Distribution and Electric Vehicle Diffusion for Electricity Planning in South Africa. Energy Planning.	1. General Introduction,2. Literature Study, 3. Research methodology, 4. Short-term Electric Vehicle Simulator (STEVsim), 5. Long-term Electricity Strategy Battery Electric Vehicle (E-StratBEV), 6. Results and Discussion, 7. Summary of results, Validation, Limitation and Future work.	System dynamics in general	Interviews, Archival data and Work Group Meetings.	Stella	PhD Thesis

ID	Author(s)	Type of Research Problem	Report Structure	Theoretical Framework Applied	Research Instruments used to Build the Model	SD Software used	Type of Publication
A13	John David Sterman (1981)	To develop an integrating framework to evaluate the effects of depletion and rising energy prices on economic growth, inflation, and other key economic and energy indicators. Energy and Economy.	1. Introduction,2. Lessons from existing models, 3. Model structure, 4. Depletion and the real economy, 5. Energy and Inflation, 6. An example of policy analysis and 8. Summary and Conclusions.	System dynamics in general. This is based on explicit causal theory of the economic behaviour. Behavioral theory of the decision-making at the micro economic level.	Interviews, Literature review, Group model building, Survey, Case Study and Archival Data.	Dynamo	PhD Thesis
A14	Aminah Zawedde (2016)	How do we model the relationships and the dynamics that exist between the Requirement Process Improvement (RPI) variables in terms of cost, schedule, and quality? Quality.	1. Introduction,2. Shortcomings of Current RPI methods, 3. System Dynamics Modelling, 4. System Dynamics-based Approaches, 5. Factors that characterize RPI success, 6. RPI Model Conceptual Design, 7. RPI Model Building, 8. RPI Model Validation and Evaluation, 9. Conclusion	Systems theory, Complexity theory and Decision Theory. Group model-building (GMB), Dynamic Synthesis Methodology .	Interviews, Literature, Delphi method and Archival data.	Vensim	PhD Thesis
A15	Mohammad Nyme Uddin, Hung-Lin Chi, His-Hsien Wei, Minhyun Lee, Meng Ni (2022)	To uncover the salient aspects of the impact of a building's interior layout on occupants' energy-saving behaviour by proposing a hybrid model. Energy Efficiency Management.	1. Introduction, 2. Design and Build System, 3. Project Scope Definition, 4. Initial Scope Establishment, 5. Study Methodology, 6. Model Simulation, 7. Conclusion	Agent-based Model - System Dynamics-Building Information Modelling (AFM-SD-BIM) framework and Theory of Reasoned Action (ToRA).	Synthetic data and Real data from the experiment were used.	Anylogic	Journal Renewable and Sustainable Energy Reviews
A16	S. Chritamara and S.O. Ogunlana Nguyen Luong Bach (2001)	Investigating the effect of initial scope establishment on the performance of a project. Project Management.	1. Introduction, 2. Literature, 3. Methodology, 4. Results and Discussions, 5. Conclusion	System dynamics in general	Archival data, Interviews	iThink	Journal of Engineering, Construction and Architectural Management

ID	Author(s)	Type of Research Problem	Report Structure	Theoretical Framework Applied	Research Instruments used to Build the Model	SD Software used	Type of Publication
A17	Sezer Uludağ (2021)	Modelling the impact of change in systems and technology in a surface mining environment with system dynamics. Decision-making in technological changes in mining.	1. Introduction,2. Research Methodology, 3. Literature Review, 4. Mine Value Chain Analysis, 5. Conceptualisation of Simulation Model, 6. System Dynamic Modelling of the Mine Production Environment, 7. Discussion of the Model with Case Study, 8. Summary and Conclusion	Top-to-bottom-to-top dynamic systems modelling method (DSM) - Dynamic Synthesis Methodology Research Design. System Dynamics.	Observation and Archival data. No Field Study as per DSM due security clearance issues.	Vensim	PhD Thesis
A18	Ehsan Shafiei , Hlynur Stefansson , Eyjolfur Ingi Asgeirsson , Brynhildur Davidsdottir & Marco Raberto (2013)	To develop conceptual framework for a comprehensive evaluation of the diffusion process of alternative fuel vehicles is introduced. Energy management	1. Introduction, 2. Simulation of Transportation System: Review of Existing Methods and Studies, 3. Conceptual Framework for Hybrid Simulation of Sustainable Mobility, 4. Mathematical Modelling of Agents' Behaviour, 5. An Illustrative Example, 6. Simulation Results, 7. Conclusions.	The hybrid modelling framework - System dynamics (SD) and agent-based (AB) modelling. Mathematical modelling of agents - Interlinked modules for studying the diffusion of AFVs (Alternative Fuel Vehicles).	Literature reviews. Archival data.	Anylogic	Journal Transport Reviews
A19	S. Santharooban (2008)	To understand the dynamics of Batticaloa Lagoon. Water Management.	1. Introduction, 2. Materials and Methods (Modelling), 3. Results, 4. Discussion.	System dynamics in general	Archival data, Literature review	Stella	Journal of JSc EUSL
A20	Xiaoying Zhou, Feier Wang, Kuan Huang, Huichun Zhang, Jie Yu and Alan Y. Han (2013)	Predicting and allocating water resources have become important tasks in water resource management. Sustainable Water Management	1. Introduction 2. Methodology, 3. Case Study, 4. Discussion, 5. Conclusion.	System dynamics-multiple objective optimization (SD-MOO) model-based water supply and demand prediction, dynamic adjustment, and water optimal allocation.	Case Study, Archival data and Estimated data	Vensim	Journal of Water

ID	Author(s)	Type of Research Problem	Report Structure	Theoretical Framework Applied	Research Instruments used to Build the Model	SD Software used	Type of Publication
A21	J. K. Musango, A. Brent, and A. M. Bassi (2009)	To examine a set of policies that the South African government is currently considering, e.g., expansion of nuclear energy production and implementation of more stringent energy efficiency measures. Energy Planning.	1. Introduction,2. The South African energy sector, 3. South Africa energy policy, 4. The South Africa energy modules of the T21 model, 5. Model validation and scenario definition, 6. Results, 7. Conclusion.	Threshold 21 model - planning tool that integrates the economic, social, and environmental dimensions of a country into a single, comprehensive, transparent, user-friendly analytical framework. This is a system dynamic macro-model, based on the systems thinking approach.	Archival data.	Not provided	System Dynamics Conference

EXPLORING THE SPACE FOR ENTREPRENEURIAL ENGINEERS OF THE FUTURE: A SOUTH AFRICAN CASE

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ABSTRACT

South Africa reported an unemployment rate of 30% in Q4 of 2022 of which youth unemployment contributed a staggering 64% to the total unemployment rate. Statistics South Africa estimates graduate unemployment for those aged 15-24 at 32.6% and 22.4% for those aged 25-34 in Q4 of 2022. Youth unemployment is a ticking time bomb, it is not surprising that the June 2021 uprisings befell Kwa-Zulu Natal Province and certain parts of Gauteng Province. Industrious entrepreneurs can revitalize the economy by creating jobs, developing, and deploying new technologies, and increasing efficiencies thereby improving the quality of life in countries. This paper attempts to explore the challenges and opportunities facing the engineering pipeline in the context of entrepreneurship and innovation. The article is envisaged to provide insights on measures that universities could undertake to trigger interest in industrial engineering students to pursue a career in entrepreneurship.

Keywords: Entrepreneurship, unemployment, universities, curriculum.

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1 INTRODUCTION AND BACKGROUND

Unemployment is a socio-economic problem that is difficult to solve due to its complex and interconnected nature. Unemployment constraints economic growth, erodes business confidence, increases the number of dependents on social welfare, reduces productivity and competitiveness of the country; and places the country on a social time-bomb that could trigger a social uprising as the number of unemployed youth soars. The events that led to the July 2022 unrests stem from unemployment, poverty, and inequality.

The aim of this article is to provide a systemic view on the concepts of rising unemployment, perilous youth unemployment in the context of the engineering profession in South Africa which could be useful for policy makers in universities. To accomplish this task, the paper will explore the concept of unemployment, youth unemployment, entrepreneurship, and university curriculum in industrial engineering to instil a culture of entrepreneurship in industrial engineering students to create work rather than seek work.

The main research question is:

What can be done to inculcate the innovation and entrepreneurship culture amongst industrial engineering students?

To answer this pertinent question, the following sub-questions must be answered:

1. What is current entrepreneurship inspired culture in engineering education?
2. Which opportunities can be exploited to assist in solving the societal challenge of chronic unemployment?

2 LITERATURE REVIEW

2.1 Contextualising the phenomenon of graduate unemployment

Oluwajodu et al [1] argue that one of South Africa's most enduring and divisive economic issues is unemployment. The situation is much more dire for young people, endangering social security as well as the nation's long-term plans for economic growth and development. The important findings of studies documenting the worsening job market prospects for graduates in South Africa are consistent with findings from other countries that have suggested structural changes in other labor markets have resulted in a global trend of worsening job market prospects for those with Higher Education (HE) qualifications [2]. Figure 1 depicts a snapshot of the unemployment rates, expanded definition, absorption rate, and labour force participation rates in South Africa and its respective provinces as of 31 March 2023.

According to the precise definition of Statistics South Africa, more than a quarter (32.9%) of the labor force is unemployed. Most of the unemployed persons are Black Africans (32.7%) and Coloreds (22.4%), women (35.4%), residents of rural areas, those without post-secondary education, and young people. Indians sit at 14.3% unemployment rate while whites sit at 7.5% unemployment rate. According to the enlarged definition of unemployment, only 36.1% of 15- to 24-year-olds who are disengaged from the labour market, and they are also not building on their skills base through education and training [3]. This is notably a serious concern and a ticking societal time bomb.

This phenomenon is supported by Graham et al [3] argues that the massification in access to higher education and the worldwide economic collapse of 2008 are suspected to be behind the high rate of graduate unemployment globally, and South Africa is not an island and is affected by the same phenomenon. Graduate unemployment as a very emotive topic should be grounded within the broad context of high levels of unemployment levels in South Africa.

Figure 2 demonstrates that that of the 7,9 million unemployed persons in the first quarter of 2023, as many as 48,3% did not have matric, and 40,7% had completed matric. Almost 8% of the unemployed had other tertiary qualifications, while only 2,7% of unemployed persons were graduates which is a sizable number of graduates just below 216000 persons.

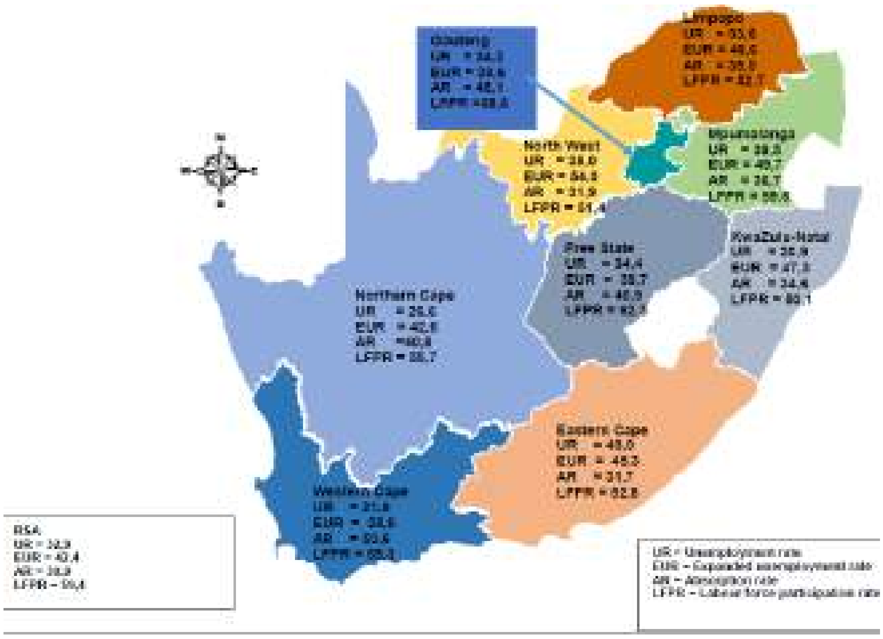

Figure 1: Snapshot of unemployment rate in South Africa

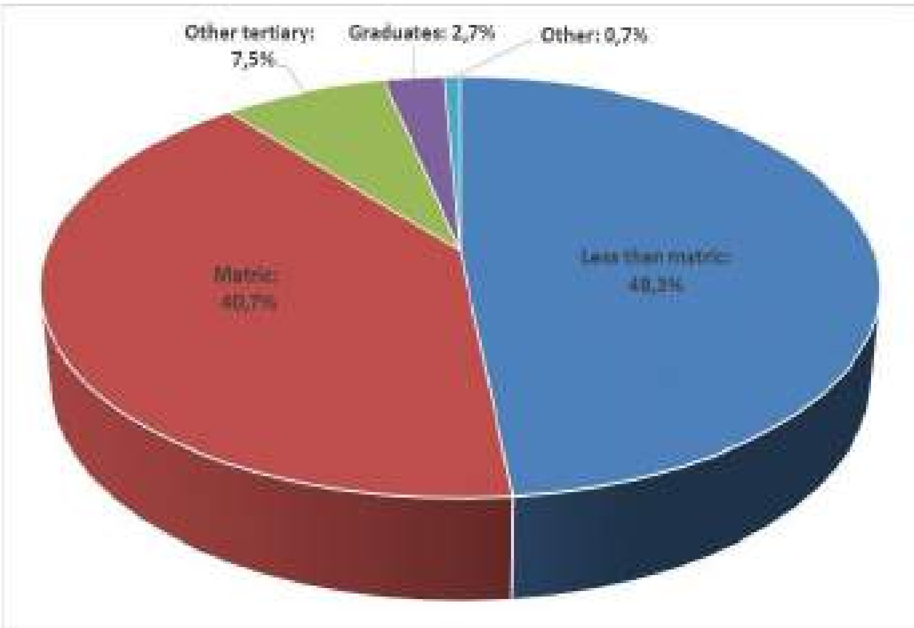

Figure 2: Proportion of the unemployed by education level

2.2 The concept of entrepreneurship education

2.2.1 The engineer

Litchfield et al. [4] advance that engineers have been esteemed for their technical proficiency for centuries. This skill has often distinguished engineers' role as civil servants who design and produce goods, services, infrastructure, and processes for the needs of humanity. Tenopir and

King [5] postulates that engineering products, services and applications are vital to everyday activities in our life. These include housing, transportation, communications, and other industrial processes. Considering safeguarding life, health, and property, and promoting public welfare, the practice of engineering is treated as a learned profession.

Khalid et al. [6] propose that engineers are understood to be authorities in their field of specialization and that is often where their expertise ends. The authors further advance that, engineers are good critical thinkers but often lack communication and interpersonal skills. This lack of interpersonal and communication skills may be attributed to the lack of importance given to these disciplines during their engineering education [6]. This view is supported by McKeag [7] who argues that one of the challenges facing engineering faculties is the matter of entrenching creativity and innovation into undergraduate and postgraduate programmes. He further argues that creativity was and continues to be erroneously perceived to be the realm of the arts, and the general understanding of innovation is any change. Connor et al. [8] take this argument further and challenge the common pedagogies found in STEM education with a particular focus on engineering. The authors argue that the dominant engineering pedagogy remains “chalk and talk”; despite research evidence that demonstrates its ineffectiveness. Such pedagogical approaches they argue, do not embrace the possibilities provided by more student-centric approaches and more active learning.

2.2.2 Entrepreneurial engineer

Davids et al. [9] propose that engineering is a field of study that applies science, mathematics, and technology to the existing world. Entrepreneurship on the other hand entails the introduction of a new product, introduction of a new technique of production, opening of a new market, establishment of a new supply source, establishment of a new industrial structure, and introduction of an innovation are five fundamental components of entrepreneurship. Entrepreneurship is a practice that starts with taking initiative and establishing a new business, a new entrepreneurial paradigm is introduced whenever a person starts a new venture [10]. Osipov and J. Ziyatdinova [11] postulate that education has generally neglected an integral aspect of humans nature, that human beings are moral and spiritual beings, and have to be trained in a positive way to develop the positive, ethical parts of our nature, which are not inherited but are learned. That raises the need to address character cultivation and character training in engineering education as entrepreneurs require character.

Sharma [12] concurs and argues that engineering is a very diverse profession that requires different skills. An engineer must perform various tasks, namely, technical supervision, personal management, project management, diagnostics etc. Moreover, in today’s global world an engineer is to be capable of intercultural communication to work with international partners and run joint projects. Therefore, engineering education aims at training an expert who has all these skills, however, providing technical knowledge in the field of profession obtained is not sufficient. Only humanities education can assist in developing special traits necessary for performing all engineering functions, and it is through humanities that character development and ethics can be incorporated into engineering.

Bruhl and Bruhl [13] advance the notion that engineers being educated and trained today not only be technically competent but must be creative and innovative. An important part of developing creative and innovative solutions is the framework within which students are taught to think and formulate ideas. This assertion points to the gap that exists between engineering and the arts and demands the transition from STEM (Science, Technology, Engineering and Mathematics) to STEAM (Science, Technology, Engineering, Arts, and Mathematics).

Boy [14] hypothesises that the 20th century was grounded on linear thinking to solve complicated problems, however, the 21st century has brought about complex interconnected problems in a connected world, this requires additional skills for engineers to deal with the complex challenges of the 21st century which requires critical thinking, collaborative, creativity and dealing with complexity skills.

3 RESEARCH METHODOLOGY

Khothari [15] proposes that research is a scientific and systematic exploration for relevant information on a specific topic. This research is a scientific and systematics exploration of literature relating to the concepts of unemployment and entrepreneurship education in engineering programmes. The study adopted an interpretivist philosophical worldview followed by an inductive approach. The study further adopted a qualitative methodological choice and a archival research strategy which entailed a review of secondary data from the respective universities.

In this study, a sample of industrial engineering programmes across public South African universities is surveyed. The engineering sciences and engineering technology programmes will be separated so that a fair comparison can be drawn. Three engineering science and three engineering technology institutions were surveyed. The research will only focus on engineering programmes that have full accreditation from the Engineering Council of South Africa (ECSA). Finally, the entrepreneurship related subjects offered in these engineering programmes will then be grouped to allow fair comparison. The limitation of this method is that some of the entrepreneurship curricula could have been incorporated into some modules. If this is true, it is easy that the reviewer could have missed this information. Therefore, the methodology utilized in this study assumes that entrepreneurship knowledge is implemented in the engineering programme as a standalone module.

4 FINDINGS AND DISCUSSION

4.1 Engineering sciences programmes (Entrepreneurship inclined modules)

Table 1 depicts the entrepreneurship inclined modules in the engineering science programmes in industrial engineering at University of Pretoria, University of Witwatersrand, Stellenbosch University and Northwest University.

Table 1: Engineering Science Programmes

Programmes & modules	WITS	UP	NWU	SUN
Industrial Engineering	Business Studies	Business Engineering 321	Business Engineering	-

4.2 Engineering technology programmes (Entrepreneurship inclined modules)

Table 2 depicts the entrepreneurship inclined modules in the engineering technology programmes in industrial engineering at the Cape Peninsula University of Technology, University of Johannesburg, University of South Africa, Tshwane University of Technology, and the Durban University of Technology.

Table 2: Engineering Technology Programmes

Programmes & modules	CPUT	UJ	UNISA	TUT	DUT
Industrial Engineering	-	Entrepreneurship 3B	Engineering entrepreneurship 3701	-	-

5 DISCUSSIONS

The results point to variations in entrepreneurship-inclined programmes in universities, these variations are not only between engineering science programmes and engineering technology programmes, but variations exist within the respective programmes as standalone. The section below discusses the programmes as standalone.

5.1 Engineering science programmes

University of Pretoria (UP) and Northwest University (NWU) offer business engineering in third year which to smaller extent covers some aspects of entrepreneurship while Wits University (Wits) offers Business studies which also covers to a smaller extent aspect of entrepreneurship. The curriculum of Stellenbosch University (SUN) does not reflect any entrepreneurship module or an entrepreneurship inclined module. UP, NWU, and Wits offer their entrepreneurship inclined modules at the third-year level of the Bachelor of Engineering (BEng) programme.

5.2 Engineering technology programmes

The same variations that exist in the engineering science programmes exist in the engineering technology programmes with University of Johannesburg offering Entrepreneurship at third-year level in their Bachelor of Engineering Technology (BEng Tech) programme while the University of South Africa offers Engineering Entrepreneurship at Advanced Diploma level which is at third-year level. The curriculum of Cape Peninsula University of Technology (CPUT), the Tshwane University of Technology (TUT), and the Durban Institute of Technology (DUT) do not reflect any entrepreneurship module or an entrepreneurship inclined module.

It is noteworthy that the University of Johannesburg and the University of South Africa offer tailor made entrepreneurship modules in their respective programmes, University of South Africa offers engineering entrepreneurship which attempts to steer entrepreneurship from general entrepreneurship to technology inclined entrepreneurship. However, this module still requires improvement to incorporate innovation, a cornerstone of entrepreneurship.

6 RECOMMENDATIONS AND CONCLUSION

The world is faced with far-reaching revolutionary changes shepherded by the digital age, which is changing the world as we know it. The engineering profession is not immune to these sweeping changes driven by VUCA. Engineers trained today should be able to deal with this volatile, uncertain, complex, and ambiguous world. One of the leading wicked problems faced by South Africa is chronic high unemployment The literature reviewed points to the lack of a standard approach to embedding entrepreneurship in engineering programmes from both engineering science and engineering technology perspectives. The modules offered that are entrepreneurship-inclined are a good start but not sufficient to instil a culture of entrepreneurship amongst engineering students. Entrepreneurship is a mindset that requires inculcation of a culture of innovation and seeking to succeed in business.

It is noteworthy that (1) Some of the universities have stated to move in the right direction to train students in the exciting field of entrepreneurship (both engineering science and engineering technology) to respond to national challenge faced by South Africa, however none (2) of the universities integrates innovation and creativity in their respective modules.

Innovation is the foundation of successful entrepreneurship as entrepreneurs are in the business of finding gaps in the market and filling the gaps with the necessary speed of execution.

The gap acknowledged in this study is a fragmented approach towards engineering entrepreneurship in the engineering curriculum. The embedding of entrepreneurship together with innovation will develop the creativity and innovativeness character of the student, a systems view of entrepreneurship module will develop a character of students that can deal with complexity, uncertainty, and ambiguity.

As a recommendation for an effective and efficient Science Engineering Technology and Entrepreneurship (SETE) programme in universities, a technology entrepreneurship module should be considered for implementation in engineering science programmes and engineering technology programmes and should cover the following topics:

- Team dynamics
- Elevated pitching and presentation skills
- Entrepreneurial ethics
- Creativity and innovation
- Navigating from idea to opportunity
- Patent engineering
- Technology venture financing
- Marketing for engineers
- Strategic management dynamics

Incorporating the proposed topics is likely to develop an entrepreneurial industrial engineer of the future during their journey in university and this will potentially contribute towards dissolving the wicked societal problem of unemployment.

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ON THE FIXED CHARGE SOLID LOCATION AND TRANSPORTATION PROBLEM WITH TRUCK-LOAD CONSTRAINT: A CASE OF UNSUPERVISED LEARNING MEETS OPTIMISATION

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ABSTRACT

Advances in machine learning have made optimisation methods receive more intelligent inputs to give more reliable outputs. In this paper, the Fixed Charge Solid Transportation Problem with Truck-load Constraint (FCSLTP-TLC) is studied. This problem considers that shipment cannot be done in one lot, decides on the facility location, and obtains its demand input through clustering of demand predictions. Using an adapted K-means clustering technique, the demand predictions are used to select the final demand and compared to possible final demand obtainable from measures of central tendencies such as the mean and mode. The optimisation model is solved and results from the different demands are analysed to determine possible cost savings and more importantly other learnings from the data input technique. This model is useful to academics and industry practitioners in gaining insight into the impact of selected unsupervised machine learning models on optimisation decisions.

Keywords: machine learning, clustering analysis, fixed charge solid transportation problem, Facility location, mathematical optimisation

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1 INTRODUCTION

Machine learning methods have continued to digitally revolutionise business operations in the form of making good predictions to support business operations. For example in the manufacturing and logistic sector, the prediction of failure rates of production processes [1], Strengthening supply chain resilience [2] and predicting road traffic accidents [3] has been beneficial to the sector.

These predictions have taken the form of a supervised learning method which essentially involves training the machine using selected features of inputs and corresponding output/labels. On the other hand, unsupervised learning rather than making predictions for a course of action, analyses unlabelled datasets. For example, clustering analysis (an aspect of unsupervised learning) suggests hidden patterns within the dataset thus opening the decision-maker to a wide range of possibilities than predicting a specific value.

Optimisation models essentially are concerned with selecting the best course of action or decisions given certain constraints and input variables [4]. Often, sensitivity analyses are conducted to ensure the model becomes robust through different constraints and input variables. These input variables could be known with certainty (deterministic) or without certainty (stochastic or following some probability distribution). For example, demand uncertainties in distribution problems have been studied by [5]. Furthermore, distribution problems in which certain route-limiting constraints are imposed during the shipment were studied by [6] and [7].

Uncertainty in input data for decision-making could be handled through sampling probability distributions such as the Monte Carlo sampling, the use of stochastic programming, and the use of measures of central tendency such as the mean [8]. However, the Monte Carlo simulation and stochastic programming may become intractable as data size increases [8], [9]. In addition, these methods may not well reveal patterns in a dataset which are obtainable using the knowledge extraction powers of unsupervised learning techniques such as clustering [10].

Moreover looking at the current advancement in capturing large amounts of data as noted by [11] in their study (using the case of logistics, where the use of smart data sensors such as RFID(Radio Frequency Identification), wireless adapters, vehicle tracking sensors, GPS (Global positioning system) could provide a vast amount of varied data) the possibility of using other intelligent techniques to understand and quantify the complexity in such datasets becomes important. The datasets having been further understood could be fed into optimisation models to provide more robust decisions. Furthermore, with the possibility of running digital/web surveys for experts in a certain domain (within or outside a business enterprise) to capture their opinions, the need to rely on intelligent methods such as clustering techniques that could reveal hidden patterns within the data collected arises.

We state the research question of this study as "*What are the possible learnings in applying an unsupervised learning technique such as K-means clustering in determining uncertain data parameters in an optimisation model?*". Therefore, this article seeks to investigate the impact of a selected unsupervised learning technique (K-means clustering) on a typical optimisation decision. Specifically, the distribution problem where the shipment cannot be done in one lot and considers the facility location decisions is studied. The aim is to demonstrate this concept and possible learning that could be achieved from this case of unsupervised learning meets decision. The term "unsupervised learning meets decision" refers to capturing some form of data science techniques into traditional decision-making problems for better decision-making. This concept is generally known as data-driven decision-making [12].

2 METHODS AND DATA GENERATION

In this section, we first present the optimisation approach and later discuss our data collection procedure. The optimisation model is a rehash of the FCSLTP-TLC described in [13]. Our data collection procedure is primarily based on random number generation. The model parameters for the unit cost and capacities follow probability distributions as obtained from [13], [14]. In this study, we have assumed demand is uncertain and only obtained from different expert opinions about previously known demand. The basic approach we followed was to cluster the expert demand predictions and adapt the clustering results as inputs into our optimisation model. Figure 1 shows the optimisation problem while Figure 2 shows how the clustering meets the optimisation model by fitting into each demand destination respectively.

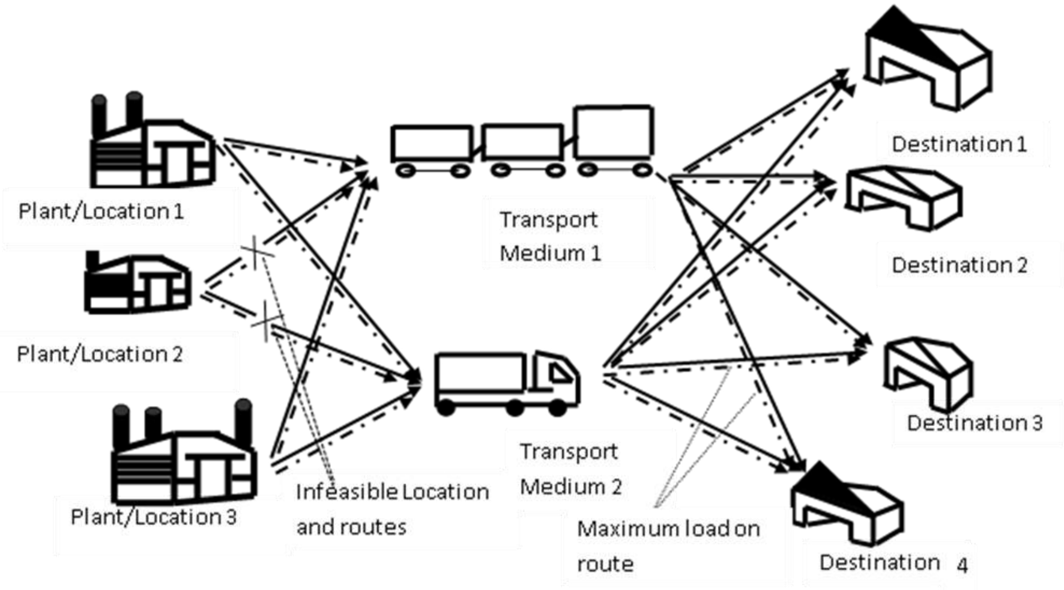

Figure 1: Fixed Charge Solid Location and Transportation Problem with Truck-load Constraint [13]

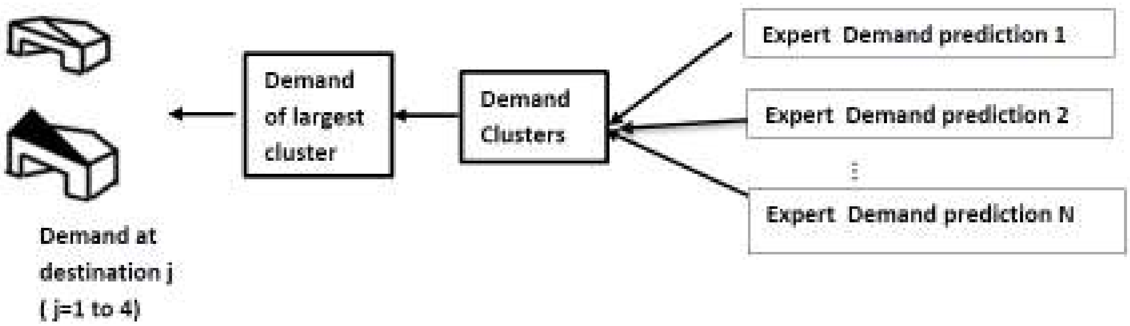

Figure 2: How the unsupervised learning meets the optimisation model

2.1 Optimisation model for the FCSLTP-TLC

2.1.1 Optimisation model parameters

i: Index representing source locations such as manufacturing sites, distribution points warehouse etc.)

j: Index representing demand points such as clients, customers, other warehouses etc.)
r: Index representing capacitated transport vehicles or mediums.
m: representing the number of source locations.
n: representing the number of demand or destination points.
a: representing the number of capacitated transport vehicles or mediums.
c_{ijr} : per unit cost of shipment on route (i, j) by transport vehicle r.
S_i : representing the capacity of source i $for\ all\ i = 1 \dots m$.
D_j: representing Demand at destination j $for\ all\ j = 1 \dots n$.
T_r : Capacity for the transport vehicle r $all\ r = 1 \dots a$.
F_i: Source location fixed cost at i.
H_{ijr} : route fixed cost of shipping through(i, j) by transport vehicle r
W_{ijr}: Maximum shipping permitted through route (i, j) transport vehicle r

2.1.2 Optimisation Model Decision Variables

x_{ijr}: Product quantity shipped from source (i) to demand point (j) using transport vehicle (r)
y_i : Binary variable (0,1) representing opened (1) or closed (0) source location i
z_{ijr}: Integer variable representing one or multiple fixed charges incurred on route (i, j, r)

2.1.3 Objective function of the FCSLTP-TLC

This is given as

Minimize (FCSLTP-TLC):

$$\sum_{i=1}^{m} F_i y_i + \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{r=1}^{a} c_{ijr} x_{ijr} + \sum_{i=1}^{m} \sum_{j=1}^{n} \sum_{r=1}^{a} H_{ijr} z_{ijr} \quad (1)$$

Subject to

$$\sum_{j=1}^{n} \sum_{r=1}^{a} x_{ijr} \leq S_i y_i \qquad \forall\ i = 1 \dots m \quad (2)$$

$$\sum_{i=1}^{m} \sum_{r=1}^{a} x_{ijr} = D_j \qquad \forall\ j = 1 \dots n \quad (3)$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} x_{ijr} \leq T_r \qquad \forall\ r = 1 \dots a \quad (4)$$

$$z_{ijr} = \begin{cases} Integer\ part\ of\ \left({x_{ijr}}/{W_{ijr}}\right) + 1 & if\ x_{ijr} > 0\ and\ remainder\ \left({x_{ijr}}/{W_{ijr}}\right) > 0 \\ Integer\ part\ of\ \left({x_{ijr}}/{W_{ijr}}\right) & if\ x_{ijr} > 0\ and\ remainder\ \left({x_{ijr}}/{W_{ijr}}\right) = 0 \\ (\ 0\ ) & if\ x_{ijr} = 0 \end{cases}$$

$$\forall\ i = 1 \dots m,\ \forall\ j = 1 \dots n,\ \forall\ r = 1 \dots a \quad (5)$$

$$y_i = 0\ or\ 1 \qquad \forall\ i = 1 \dots m \quad (6)$$

$$x_{ijr} \geq 0 \qquad \forall\ i = 1 \dots m,\ \forall\ j = 1 \dots n,\ \forall\ r = 1 \dots a \quad (7)$$

(1) is an expression that represents the minimization cost function of the FCSLTP-TLC.

The first term represents the total facility location cost. The second term represents the route variable cost (transport vehicle dependent). The third term represents the route fixed cost incurred per conveyance type due to truckload constraint.

Equation (2) is a constraint that makes the supply capacity not exceeded.

Equation (3) is a constraint that makes the demand to be met at each destination.

Equation (4) is a constraint that makes the conveyance capacity not exceeded.

Equation (5) is a constraint that represents the maximum shipment per route requirement (the truckload constraint).

Equation (6) represents the facility location requirement.

Equation (7) refers to the non-negativity constraint for the continuous variables.

2.2 Demand values for the FCSLTP-TLC

2.2.1 Generation of Expert demand predictions

The continued importance of demand to the continued operations of any business venture has led our focus on isolating the demand (Dj) as a variable to be generated through expert opinions.

In this study, we have assumed the possibility of experts providing an opinion based on knowing previous values of the demand. As this study is focused on showing the workings and impact of unsupervised learning (K-means) on our optimisation procedure, we have randomly generated the experts' considerations and predictions using mathematical expressions.

The expert demand prediction is generated using a combination of the multiplicative congruential random number generation method [9] and an adaptation of a method for generating discrete random variates [15].

We used the multiplicative congruential method to generate the different expert probabilities around a given previous demand, while the discrete random number generation was used to obtain discrete values that represent expert demand forecast. The expressions below describe the expert demand generation.

Step 1: Randomly obtain the number of experts to use. (This in real cases often depends on the available experts or the number of experts from a survey that can provide a representative sample to the study). For the study 100 was used.

Step 2: Multiplicative congruential random number generation method.

This is given using the recursive function:

$$X_n = (b * X_{n-1} + c) \text{ Modulo m} \quad \textbf{\textit{(8)}}$$

$$Rn = Xn/m \quad \textbf{\textit{(9)}}$$

Expression (8) generates a sequence of random integers $X_1, X_2, \ldots, X_n$ with the starting X_0 defined as a seed. In this study, the X_0 represents the previous actual demand.

Expression (9) finally converts the random integers into a number between 0 and 1 to represent the expert probabilities. The terms b is a constant multiplier, c is the increment and m is the modulus.

These values are carefully selected to ensure the stream of random number generation is not cycled. For this study, b = 13, c =64 and m = 150 is arbitrarily selected to ensure the random numbers obtained are not cycled. It will be interesting to consider in future studies the effect of varying these numbers on the quality of the numbers generated.

Step 3: Adaptation discrete random variates generation

To arrive at the Expert demand (Y) representing their predictions,

$$Y\ (predicted) = X_0 + INT\ [(100 - X_0 + 1) * R_n] \quad if\ R_n >= 0.5 \qquad \textbf{(10)}$$

$$Y\ (predicted) = X_0 - INT\ [(100 - X_0 + 1) * R_n] \quad if\ R_n < 0.5 \qquad \textbf{(11)}$$

0.5 or 50% in equations 10 and 11 is used as a threshold for R_n to ensure predictions above and below the previous real values were obtained.

2.2.2 Demand (Dj) *from Expert Predictions*

K-means Clustering

The K-means clustering algorithm as an example of unsupervised learning was selected due to its popularity in clustering studies[12], its fitness to our numeric data and its relative ease of implementation. The K-means clustering was implemented to understand hidden patterns in the expert demand (Y) dataset. The k-means clustering groups a dataset by iteratively optimizing a particular similarity/dissimilarity measure or distance function such as the Euclidean distance. We refer readers to [16] for more detailed discussions of the workings of the K-means algorithm. The K-means require the determination of the number of groups or clusters in the data set before clustering. We used the method of NbClust [17] to obtain the number of clusters. The NbClust uses 30 validity indices and a majority rule to select the best number of clusters.

Prediction of Demand

Since clustering as a form of unsupervised learning does not make predictions but shows hidden patterns we used a method similar to the operations of the K-nearest neighbour classification method [18]to obtain the predictions by considering the cluster with the largest size and using the cluster means (centroid) obtained as the label of the entire clusters of data points. Ties between similar cluster sizes are broken by finding the average of the cluster means of their respective clusters. Means. Fractional K-means values and the mean of the expert predictions were rounded off to the nearest whole numbers. Figure 3 below presents a description of the major steps in the methods of this study.

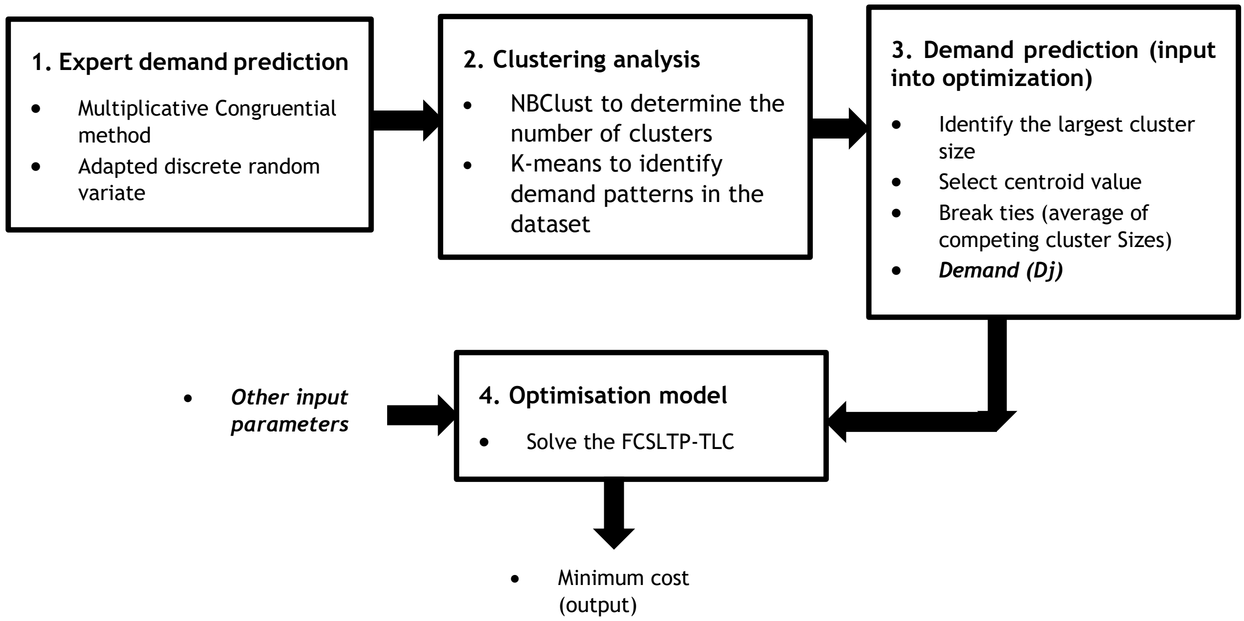

Figure 3: Summary of research methods in the Study

2.3 Data Generation

2.3.1 Other parameters apart from the demand

The cost inputs such as the facility fixed cost (F_i), unit cost (c_{ijr}), fixed route cost (H_{ijr}) and other inputs parameters were obtained from probability distributions from the literature [13], [14] and presented in Table 1 below:

Table 1: Input data into the optimisation model

Parameter Distribution
S_i : U(200, 400) T_r : U(200, 500) c_{ijr} : U(20, 150) H_{ijr} : U(200, 600) $F_i = U(0,90) + \sqrt{S_i}\, U(100,110)$ $W_{ijr} = \ x\,\%\ of\ \ Max\ \ D_j$ $0 < x < 100$ $x = 50\%$ (selected for experimentation) D_j => Current demand obtained using the approach in section 2.2.2 D_p => Previous demand at each destination j U(40, 100).

3 EXPERIMENTATION

3.1 Experiments conducted

The main aim of our computation experiments in this study is to test the approach of using K-means clustering as a method of deciding certain input parameters into our optimisation model.

Furthermore, this approach is compared to using measures of central tendencies such as Mean and Mode to see the robustness of the clustering algorithm in providing hidden data patterns that could provide some noteworthy measures. The optimisation model seeks to obtain the minimum cost which in most cases is used as a measure of profitability for business ventures. Given different approaches to obtaining the demand it is our interest to see the possible cost trade-offs with these methods.

To demonstrate the workings of this method we present a simple problem size of 5 sources, 5 demand points and 2 Transport vehicles. We specifically note that clustering results in addition to the specific clustering tuning parameters selected can be skewed to the type and size of data obtained. Hence running multiple problem sizes due to the random nature of this method are by no means exhaustive and may not be sufficient to show the superiority of any of the demand-generating approaches we have considered. Rather, the workings of this method are presented as the potential to show positive or negative interesting results that could be obtainable when inputs generated from data mining are used. The input parameters specific to this problem are represented in Table 2 below. The numbers have the same units and represent any measure of capacity used in transporting commodities e.g. kilograms.

Table 2: Input Parameters of the case studies

Capacity at Source (S_i)	Transport vehicle capacity (T_r)	Previous demand at destination j ($D_{p,j}$)
298	200	50
245		60
201	250	70
286		80
256		40

3.2 Instrumentation

The optimisation model was written on the Eclipse development platform using Java and the IBM ILOG CPLEX version 12.8 as the mixed integer programming solver. As noted in [19], the CPLEX solver uses methods such as the branch and cut in optimally searching the solution space for a certain class of combinatorial problems such as linear programming, mixed-integer programming, and mixed-integer quadratic problem. The NBClust and K-means were performed using the R studio version 4.2.0. Other data analysis was performed on Microsoft Excel.

4 RESULTS AND DISCUSSION

4.1 Results

The clustering results obtained for the 100 predictions representing the expert opinions based on previous actual demands are represented in Table 3 below. This also includes the mean and mode of the predictions. The abbreviations in Table 3 are defined as follows:

The index for the demand or destination point is represented by j. Previous demand at demand point j is represented by Dp,j. The number of observations of expert prediction at demand point j is represented by Np,j. The best number of clusters suggested per demand point (using NBClust) is represented by Cluster No. (j). The value of the largest-sized cluster is represented as K-means. The arithmetic mean of all the expert demand predictions is represented by Mean. The highest recurring value of the expert predictions is represented by Mode. Lastly, the Naïve value represents using the previous demands directly as the current demand.

Table3: K-means clustering result, mean and mode of demand predictions

j	Dp,j	Np,j	Cluster No. (j)	K-means	Mean	Mode	Naïve value
1	50	100	2	39	62	88	50
2	60	100	14	92	70	96	60
3	70	100	2	93	78	91	70
4	80	100	8	73	85	73	80
5	40	100	2	26	53	27	40
Total demand j(1…5)				323	348	375	300

The table further shows the possibilities of different numbers of clusters that can be obtained for the 100 observations of each demand point. As illustrated in Figure 4 below, The K-means means and mode all present varying demand predictions across the five demand points, with the K-means showing close similarity to the Mode compared to the Mean (The Mean tends to present a central or average measure across the dataset). The comparison among the different predicted values is further illustrated in Figure 4.

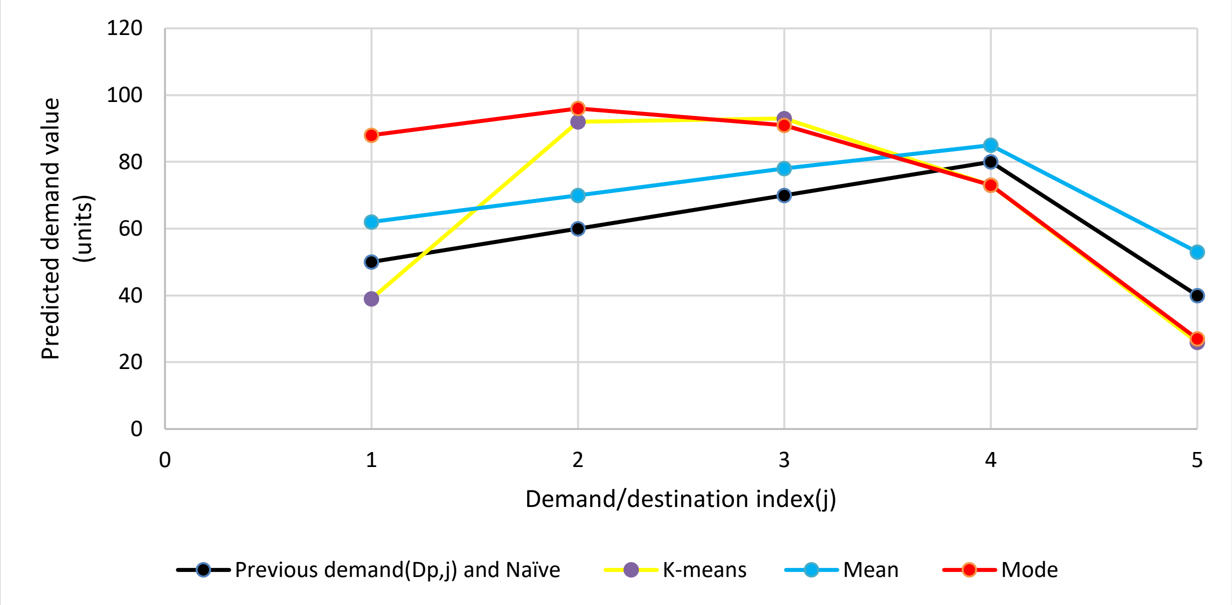

Figure 4: Predicted demand comparison among the four demand prediction methods

Table 4 below shows a comparison of the minimum cost obtained using three demand prediction methods including the Naïve forecast.

Table 4: Optimisation results

Method of obtaining demand	Optimisation result (minimum cost function)
K-means (largest cluster)	20 092
Means of the dataset	20 517
Mode of the dataset	21 816
Naïve (previous demand)	18 423

In this result, the Mode is shown to perform worse than the K-means and Mean(average) in predicting demand values for the minimum cost optimisation problem.

4.2 Discussions

Looking at the results of Table 3 we can see how different demand values are obtainable using selected measures of central tendencies and the K-means. The K-means also tries to provide a central or centroid value for the different clusters obtained from the dataset.

Data-sensitive studies such as this often depend on the type and number of data points used. Therefore, due to the limited datasets used, we would emphasize the possible learnings and gains from this technique rather than the limited gains or losses from an instance of the demand prediction methods.

The utility of our demand prediction methods is such that we have a range of possible demand values to consider when the real or actual demand is not known. On one hand, this could act as a technique of providing an objective sensitive analysis due to the uncertainty in demand. For example, If we consider that all the demand is met by the source location at a unit selling price of 100, then the largest profit will be provided by the mode. This might show a higher bound of profit tending towards being unrealistic compared to a lower bound from the K-means that might be more realistic or closer to the Naïve prediction that would use the previous actual demand as the value for the new prediction.

On the other, the use of methods that can further reveal hidden patterns in the data set might provide more interesting results for optimisation input data as well as the objective function, rather than using a conventional Mean or average of possible demand prediction values, the choice of selecting the mean of the largest cluster from the K-means could reveal a group of experts that provide good similar predictions. These predictions can give a higher confidence in accepting their predictions rather than just a general average of all predictions that might be naïve of certain intricacies in the dataset. Furthermore, when the actual results are known, more research or investigation could be conducted on the rationale behind the expert's selection of a certain range of values for the prediction. This is necessary because only the values of the expert predictions are considered and not the methods of arriving at their predictions.

5 CONCLUSION AND FUTURE DIRECTION

An integrated distribution problem where the shipment cannot be done in one lot and considers the facility location decisions were studied. The focus of the study was on the impact of unsupervised learning methods such as clustering in providing a technique to understand input data into optimisation problems. Considering the fact that there could be different observations of data which we have termed expert predictions around a previously known value creates a problem that could hide certain patterns in the data which might be relevant for the optimisation in providing a more reliable result.

The example we have considered shows the K-means as providing the minimum cost but can contribute to a lower realistic profit, compared to the possible higher cost and profit from the mode which can tend towards being unrealistic. Ultimately the results obtained will depend on the type of real data being studied.

It will be interesting to apply the demand-generating methods we have utilised on a range of actual datasets. Also given real expert predictions, the use of different unsupervised learning techniques such as clustering analysis, principal component analysis, and factor analysis can be implemented. In addition to the K-means clustering, other clustering analysis methods useful for numeric data such as hierarchical clustering, K-medoid, and K-mode can be further tested on their impact on the input data and the optimisation decisions. Lastly, different problem sizes can also be implemented using the methods considered in this study to compare how this technique works in a pattern of datasets.

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IMPACT OF INDUSTRY 4.0 ON TRADITIONAL QUALITY MANAGEMENT PRACTICES IN THE MANUFACTURING SECTOR: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Industry 4.0 technologies are transforming manufacturing processes globally, with potential implications for quality management (QM) practices. A systematic literature review was conducted to investigate the impact of Industry 4.0 on QM practices, using PRISMA to gather data from reputable databases. Out of 29 papers selected for the final quantitative analysis, the study found a significant increase in publications on the topic since 2016. The study revealed that Industry 4.0 could significantly impact three QM practices: evidence-based decision-making, process management, and customer focus, by enabling real-time quality monitoring and control and improving traceability and transparency. The study also identified challenges associated with the integration of Industry 4.0 technologies, such as data accuracy, cybersecurity, employee training, and integrating technologies into legacy processes and systems. The findings in this study are beneficial for manufacturing professionals and researchers in the field of quality management.

Keywords: Industry 4.0, Quality Management, Quality 4.0

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1 INTRODUCTION

Studies have claimed that manufacturing is the backbone of any country's economy and globalization provides firms with worldwide access to markets. Consumers are now confronted with a broader range of available products and, as a result, their requirements are becoming more fluid, and they have begun to scrutinize the quality and value of the goods and services on which they spend their money [1], [2]. Consequently, businesses use quality to set themselves apart from their competition.

According to Najmi et al. [3], Hurta and Noskievičová [4], and Chouchene et al. [5], the concept of quality is not new and the popularity of managing quality stretches back more than four decades. Throughout modern history, several quality management (QM) initiatives have emerged, typically in response to industrial revolutions. However, quality management has been stagnating for a long time. Manufacturers' constant product recalls and loss of consumers demonstrate the stagnancy in quality management.

The risk is that over the last decade, engineering and manufacturing techniques, processes, and technology have changed, and these developments are expected to result in the resurrection of engineering and manufacturing operations [2], [5], [6]. This phenomenon is known as the fourth industrial revolution (Industry 4.0/4IR), and it is characterized by major enablers such as big data and analytics, cyber-physical systems, blockchain technology, autonomous robotics, artificial intelligence (AI), virtual reality and the internet of things (IoT), which enable vertical and horizontal integration and interconnection [1], [2], [7].

These Industry 4.0 technologies enable, inter alia, mass production and product customization and, as a result, production processes become more complicated, necessitating the creation of new QM techniques [6], [7], [8]. Firms find it challenging to rely on prior successes and traditional strategies in the present business environment. As a result, recent articles suggest that current QM strategies are out of date and must be revised to respond to new quality concerns resulting from this new revolution [9], [10], [11]. Several studies have even advocated the digitization of quality management practices to address quality challenges in the fourth industrial revolution, dubbed Quality 4.0 [2], [11], [12].

The objective of this research is to examine the impact of digitizing quality management procedures in the manufacturing industry. It emphasizes the need for gathering data and identifying common themes to comprehend the effects of Industry 4.0 on conventional quality management practices. The ultimate aim is to motivate manufacturers to incorporate 4IR technologies into their existing quality management approaches, thus boosting operational efficiency and enhancing product quality for consumers. This study adopts a systematic literature review to analyse the impact of 4IR in the manufacturing sector.

2 THEORETICAL BACKGROUND

2.1 Industry 4.0

The expression "industry 4.0" denotes the fourth industrial revolution (4IR), which was initiated by technological progress and the integration of computers and the internet into industrial processes, facilitating instantaneous information dissemination and a significant level of independence and automation across the entire value chain. Cyber-physical systems (CPS) are leading the charge in 4IR, merging the physical world with advanced information technology to improve future industrial production [1], [6], [11], [12],[13]. However, it is important to acknowledge the three prior industrial revolutions.

The first industrial revolution (1IR), which Britain pioneered and monopolized from 1760 to 1830, was ignited by the development of steam power. This started the move from an emphasis on human labour to an emphasis on machines. This led to a socioeconomically significant increase in manufacturing [14], [15].

Electricity, assembly lines, and the invention of steel were among the innovations that brought about the second industrial revolution in the nineteenth century. This influenced manufacturing activities, boosting outputs and cutting costs. Automation increased as a result of the development of electronics and information technology in the third industrial revolution around the 1950s [16].

Unlike the previous industrial revolutions that relied on a single dominant technology, the fourth industrial revolution (4IR) is a convergence of cyber and physical technologies. Various technologies such as Artificial Intelligence (AI), machine learning (ML), 3D printing, IoT, augmented reality (AR), cloud computing (CC), big data and analytics (BDA), and blockchain technology have emerged since 2011, and they have significantly impacted industrial operations [9], [12], [16]. AI can optimize production processes, predict equipment failure and enhance product quality, while ML can be used to analyze data to improve process efficiency and quality. Furthermore, 3D printing can create prototypes, produce personalized products, and minimize waste.

IoT can monitor equipment and processes in real-time, enabling predictive maintenance and optimization. Augmented Reality can provide real-time information and guidance, improving safety and efficiency. Cloud Computing can store and analyse large amounts of data, providing real-time access to production information. Big Data and Analytics can analyse data to improve decision-making, optimize production processes, reduce waste, and improve quality. Blockchain technology can track and verify the origin and movement of products and materials, improving supply chain transparency and efficiency. The smart manufacturing sector is characterized by 4IR's capacity to affect product design, production, quality, and delivery.

2.2 Quality and quality management

Although the idea of quality is not new, there is still no agreed-upon definition; however, fitness for purpose is a universally acknowledged criterion. On the other hand, quality management refers to a set of procedures that entails planning, coordinating, and regulating activities geared towards ensuring that a given product or service meets or surpasses customers' expectations [7], [10], [11]. This involves establishing quality benchmarks and objectives, monitoring and evaluating the product's or service's performance, identifying areas that require improvement, and implementing corrective and preventive measures to achieve the intended level of quality. The primary aim of quality management is to consistently enhance the quality of products or services to promote customer satisfaction and loyalty. Quality management had important development stages, moving from statistical quality control (SQC) to quality assurance (QA) and ultimately, as concerns about quality increased in the 1970s and 1980s, to total quality management [7], [8], [9], [16].

There have been several quality revolutions, largely driven by the Industrial Revolution. Quality 1.0 was characterized by measurement and quality control, while Quality 2.0 emphasized quality control. Quality 3.0, during the third industrial revolution, adopted quality management as a strategy, based on principles such as customer focus, process management, and information-based decision-making. Currently, Quality 4.0 integrates digitization and cyber-physical systems (CPS) into established quality management systems and procedures, utilizing the features and technologies of 4IR [7], [8], [9], [11]. Quality 4.0 is a subcategory of Industry 4.0 and aims to enhance quality through intelligent systems and smart solutions without replacing existing quality management practices [15], [17].

3 RESEARCH OBJECTIVES

The systematic adoption of Industry 4.0, as 4IR is also known, has in the last decade addressed the limitations of traditional quality management practices. As a result, this paper aims to conduct a systematic literature review to assess the impact of 4IR on traditional QM practices, and to identify similar trends, consensus, and gaps in the literature.

4 METHOD

The time frame, the research topic, the sources or databases from which the data is gathered, the methodology, and the inclusion and exclusion criteria were all factors considered when determining a search strategy that would yield the best results.

4.1 Time span

This study had a time span of 10 years.

4.2 Research terms and databases

The primary search terms utilized in this study were "Industry 4.0" AND "Quality Management" AND "Manufacturing”. The study also considered related combinations such as "Quality 4.0", "Quality Management 4.0" and "Digitalization of Quality Management". Additionally, the study included articles that concentrated on "Industry 4.0" and "Quality Control/Quality Assurance". A literature search was carried out across the following reputable databases: Scopus, Emerald, and IEEE Xplore.

4.3 Inclusions and exclusions

This study included only articles that answered the research question, were published in the above-mentioned databases, and were published in English. The study did not include publications that tackled sectors other than the manufacturing sector or were incomplete.

The study also utilized a quality assessment technique followed by Maganga and Taifa [16] and Javaid et al. [17], which requires that the completeness of each included publication be evaluated. The publications' study design, research technique, and conclusion were evaluated using the criteria of "yes," "no" and "partially”.

4.4 The research methodology

To find peer-reviewed publications and conference papers, Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), as shown in Figure 1, were used to collect articles from different sources. The first search, applying all the above-mentioned inclusions and exclusions, yielded 141 papers on IEEE Xplore, 9 papers on Emerald, and 1055 papers on Scopus. A further 32 papers were found on Google Scholar, another field whose results were accepted.

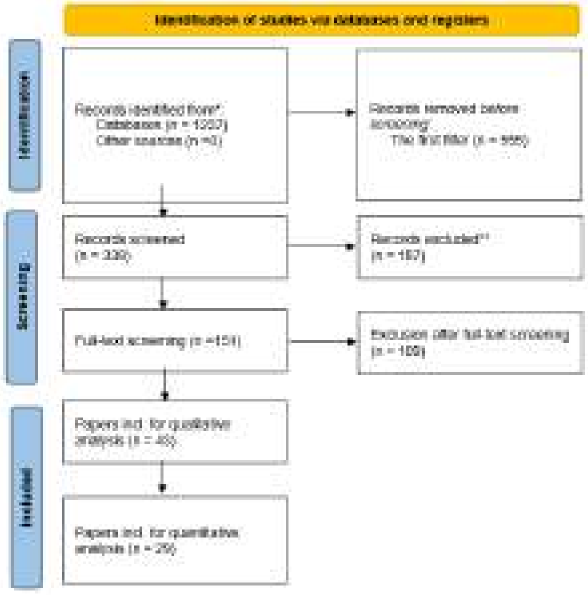
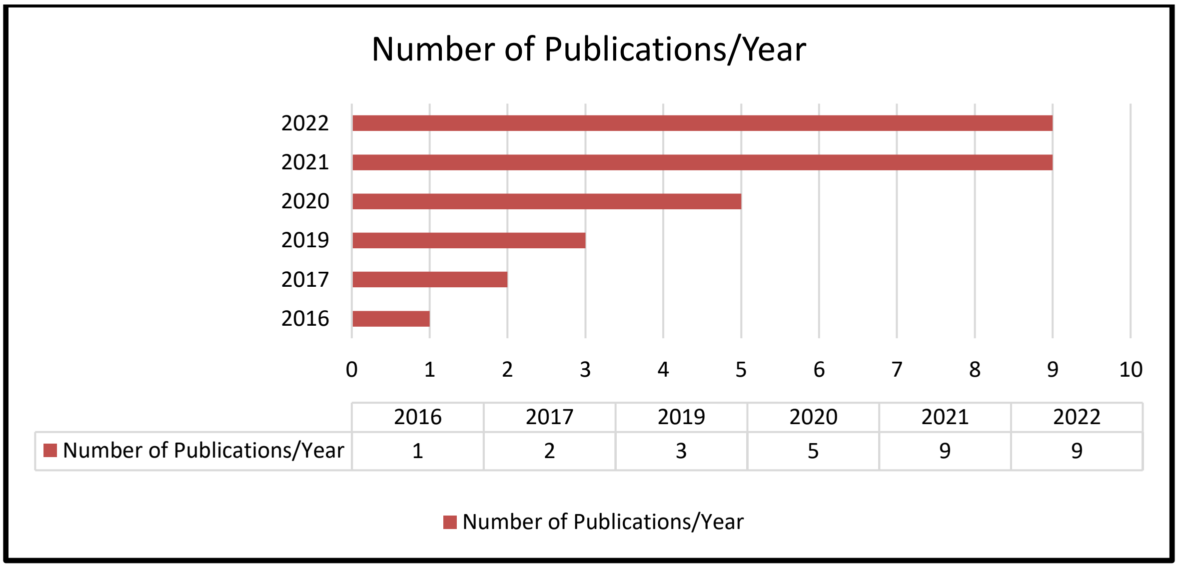


Figure 1: Number of papers identified by PRISMA

The articles were then screened using the title and abstract and those not related to the research question were eliminated, leaving 555 papers in total. Duplicates, and articles that did not review the manufacturing sector were also eliminated leaving 338 papers to screen further. The methodology and findings of each paper were read, and more papers were eliminated if their findings would not contribute to this study, leaving 151 papers that were then screened in their entirety. Of these papers, 43 were included in the final qualitative study, of which only 29 papers were used in the final quantitative study.

The text was analysed using both quantitative and qualitative methods. In this situation, qualitative procedures included reading the articles with comprehension and identifying and grouping themes/similar patterns that emerged during the investigation. Quantitative approaches were used to summarize the grouped themes and numerically represent the articles per year, per journal, and per appearance of 4IR technologies.

5 FINDINGS AND DISCUSSION



	2016	2017	2019	2020	2021	2022
Number of Publications/Year	1	2	3	5	9	9

Figure 2: Number of accepted papers by year

Figure 2 depicts the year-by-year progression of publications to date. Although the field is still in its early stages, this topic proves to be of growing interest among researchers as most publications included in the study were from 2021 and 2022, being nine each.

Table 1 depicts how frequently 4IR technologies were discussed in the papers and the impact they have on quality management in manufacturing respectively. Artificial Intelligence, big data and analytics, and cyber-physical systems were the most covered technologies, appearing 18 times apiece, followed by the Internet of Things (14 times), autonomous robotics (10 times), and machine learning (9 times). 3D printing, augmented reality and virtual reality, blockchain technology, and cloud computing were all mentioned 29 times. This clearly indicates 4IR technologies that have a significant impact on quality management techniques.

Table 1: Industry 4.0 elements and their impact on quality: summary of accepted papers

Industry 4.0 Features and Technologies	Impact on Quality Management Practices	Frequency	Cited Publications
Big Data and Analytics	• Improves quality of design • Improves quality of conformance • Improves performance of quality when used with AI • Influence predictive maintenance	18	[2], [3], [6]-[9], [12], [13], [15]-[17], [21]-[27]
Robotics	• Increased accuracy and efficiency • Real-time monitoring • Minimizes human intervention thereby improving safety • Standardization	10	[8]-[13], [16], [21], [23], [26]
Internet of Things	• Real-time monitoring and data collection • Predictive maintenance • Enhanced collaboration • Cost savings by reducing the risk of defects and equipment failure	14	[2], [3], [6], [8], [9], [12], [13], [15]-[17], [21], [23], [26], [27]
Cyber-Physical Systems	• Improved process control • Enhanced data analysis • Real-time monitoring • Increased efficiency • Customization	18	[2], [3], [6]-[9], [11]-[13], [15]-[17], [21], [23]-[27]
3D Printing	• Improved design and prototyping • Enhanced customization • Reduced production lead times	8	[3], [6], [13], [16], [17], [21], [23], [26]

Industry 4.0 Features and Technologies	Impact on Quality Management Practices	Frequency	Cited Publications
	• Improved sustainability by reducing waste		
Artificial Intelligence and Machine Learning	• Improved product design • Predictive maintenance • Enhanced collaboration • Improved sustainability by optimizing production processes	18, 9	[2], [3], [5], [8], [9], [11]-[13], [15]-[17], [21], [23]-[27]
Augmented and Virtual Reality	• Improved training • Enhanced collaboration for remote workers • Improved prototyping and testing • Improved visualization	7	[11], [12], [16], [17], [21], [23], [26]
Blockchain Technology	• Improved traceability • Enhanced transparency • Increased efficiency • Improved security • Improved collaboration	7	[9], [15]-[17], [21], [23], [26]
Cloud Computing	• Increased accessibility • Improved scalability • Improved sustainability	7	[9], [11], [16], [17], [21], [23], [26]

Figure 3 shows how frequently quality management practices were mentioned in the publications. Papers addressed process management the most (19 times), followed by customer focus and evidence-based decision-making (18 times each).

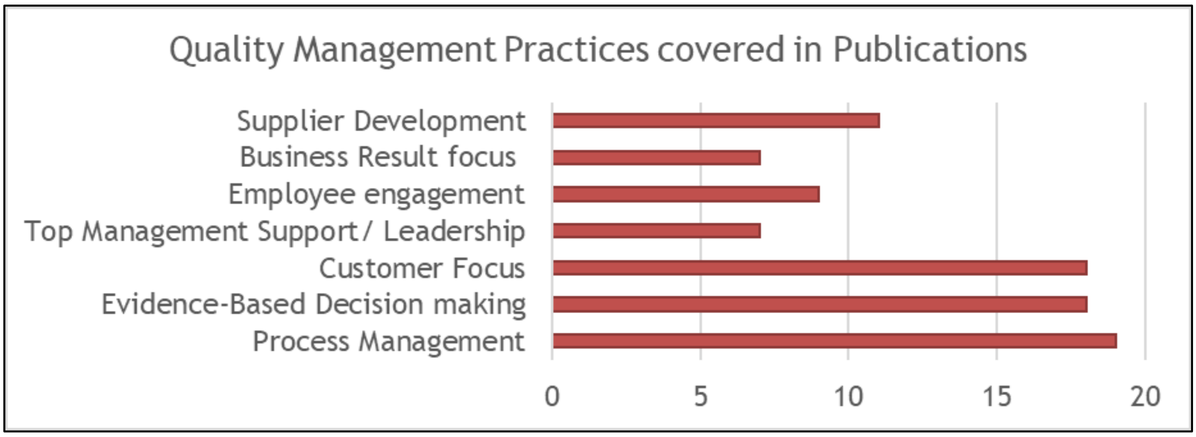


Figure 3: Appearance of quality management practices accepted for publication

Supplier development appeared 11 times. Employee engagement was mentioned 9 times, and top management support and business result focus were mentioned 7 times each.

Table 2: The main impact of Industry 4.0 technologies on quality management practices

QM Practices	Industry 4.0 Impact	ID	Frequency	Cited Publications
Process Management	Rapid process adjustments, processes are self-learning and correcting	P1	19	[1]-[9], [11]-[19], [21]-[26]
	Reduced downtime, advanced maintenance prognostication	P2	19	[1]-[9], [11]-[19], [21]-[24], [26]
	Shop floors are connected to the entire business units and to the customers	P3	18	[2]-[9], [11]-[19], [21], [22], [23], [26]
Evidence-Based Decision making	Enhanced data and insights encouraging improved decision making	I1	18	[2]-[15], [17]-[19], [21]-[23],[25]
	Improved defects prediction and proactiveness	I2	18	[2]-[9], [11]-[15], [17]-[19], [21]-[25]
	Early evidence can be used to correct or confirm decisions.	I3	18	[2]-[9], [11]-[15], [17]-[19], [21]-[25]
Customer Focus	Quick response due to machines and processes being self-learning.	C1	18	[2]-[4], [6]-[9],[11]-[16], [18]-[26]
	Personalised products are produced at a rapid rate	C2	18	[1]-[13], [21]-[26]
	Accurate market demand forecasting enabled by big data analytics and AI	C3	16	[2]-[4],[7]-[9],[11]-[16], [18], [19], [21]-[26]
Business Result Focus	A change-motivating environment	B1	8	[4], [9]-[12], [15], [16], [20], [26]
	Proactive dynamic interaction with market demands	B2	11	[4], [7], [9]-[13], [15], [16], [18], [19], [25], [26]
	Immediate re-configuration of production processes in response to improvement requests	B3	8	[4], [7], [9], [12], [13], [18], [25], [26]

QM Practices	Industry 4.0 Impact	ID	Frequency	Cited Publications
	Overall business efficiency	B4	11	[4], [5], [7], [9]-[13], [15], [16], [20], [25], [26]
Employee Engagement	Facilitating innovation and idea sharing through enhanced communication and collaboration.	E1	7	[10], [12], [13], [14], [16], [17], [20], [24], [26]
	Enhance/augment human intelligence by preserving prior knowledge and tailor-making career developments	E2	8	[7], [10], [12], [14], [16], [19], [20], [24]
	Transparency, traceability, and auditability are all improved.	E3	8	[10]-[14], [16] [17], [20], [24]
	Improves employee culture and transformation	E4	9	[10]-[17], [20], [24], [26]
Supplier Development	Complete supply chain transparency	S1	8	[11], [12], [15], [18], [19], [22], [24], [25]
	Easy-to-use tools for identifying and communicating with stakeholders	S2	7	[11], [12], [15], [18], [22], [24], [25]
	The opportunity to hire stakeholders based on their priorities	S3	5	[11], [12], [15], [18], [22]-[26]
	Stronger engagement with providers and partners to stimulate continual development	S4	5	[11], [12], [15], [18], [22]-[26]
Top Management Support/ Leadership	Effective resource allocation enabled by interconnectedness and integration	T1	7	[11]-[14], [16], [17], [20], [24]-[26]
	Increased coordination among all levels of the company	T2	6	[12], [13], [14], [16],[17], [20], [24]
	Comprehensive results evaluation enabled by big data and analytics	T3	5	[11], [12], [16], [17], [20], [24]
	Pre-production acceptance testing	QPC1	15	[1]-[6], [8], [9], [12],[13], [15],

QM Practices	Industry 4.0 Impact	ID	Frequency	Cited Publications
Quality Planning and Control				[16], [17], [19],[21]-[26]
	Failure detection before the final product is released	QPC2	16	[1], [2], [3], [5]-9], [11], [12], [13], [15], [16], [17], [19], [21]-[26]
	Quality control systems that are intelligent	QPC3	16	[1]-[9], [12], [13], [15], [16], [17], [19], [21]-[26]
	Real-time quality inspection	QPC4	17	[1-[6], [8], [9], [11]-[13], [15]-[17], [19], [21], [22], [24]-[26]

Table 2 presents the primary 28 themes or factors that indicate the effect of Industry 4.0 technologies on quality management practices, as identified during the data extraction process. The data was sorted, and the graph was created using Microsoft Excel. The results illustrate the frequency with which the code emerged during the data analysis.

As can be seen in Figure 4, P1-P3, I1-I3, C1-C3, and QPC1-QPC4 makeup 80% of the quality management elements that Industry 4.0 technologies greatly impact. Simply expressed, the majority of the publications discovered that integrating modern technologies with quality processes enhances process management (as a result of rapid process changes, self-learning and correcting processes, reduced downtime, advanced maintenance prediction, and shop floors connected to the entire business units and customers), evidence-based decision making (as a result of greater data and insights enabling better decision making, improved fault prediction and proactiveness, and early evidence that can be utilized to correct or confirm decisions), customer focus (owing to quicker responses due to self-learning machines and processes, the ability to develop customized products at a rapid rate, and precise forecasting of market demand), and quality planning and control the most. Companies aiming to implement Quality 4.0 should be aware that the impacts in the top 80% are the ones from which they are most likely to benefit.

Based on the data gathered from the chosen papers/articles and their interpretation, the research question posed above was addressed. The following subsections provide examples of the views of different researchers. Each study focused on technologies/elements of Industry 4.0 and various practices or techniques of the quality management field. The different technologies/elements and the different quality management practices covered in publications are indicated in Table 1 and Figure 3, respectively. The perspectives of researchers on the impact that 4IR features have on various quality management practices and methodologies are covered in the next section.

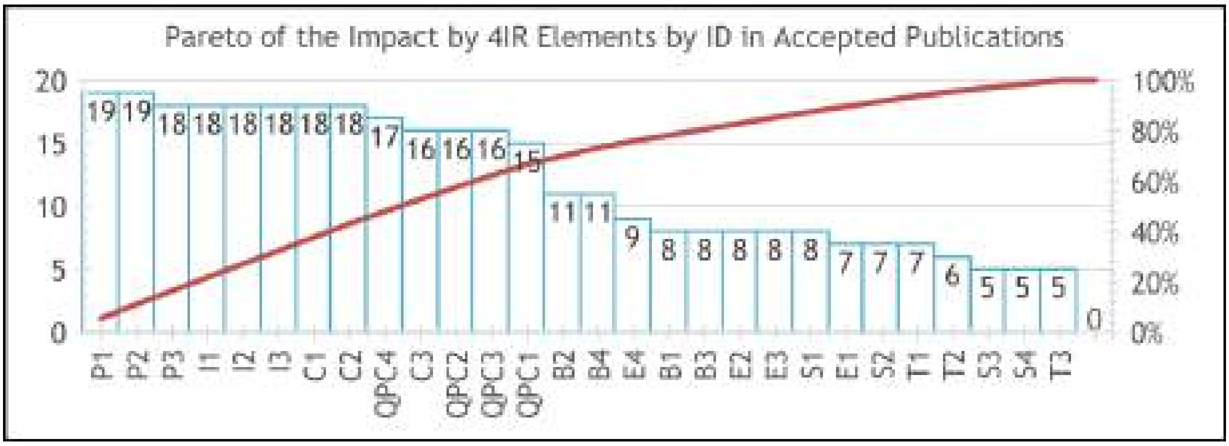


Figure 4: Pareto chart of the impact of 4IR elements by ID in accepted publications

5.1 Benefits associated with Quality 4.0 in traditional QM practices.

- **Evidence-based decision making**

According to Corti et al. [2], Maganga and Taifa [16], and Escobar et al. [21], sensors will make sure that manufacturing systems and processes are transparent, facilitating decision-making and ultimately meeting customer needs. Decision-making based on anything other than high-quality data is reactive, ineffective, and disconnected from reality [21].

Technologies from the Industry 4.0 movement promise to improve quality at every level of the production process, including information needed to plan, maximize, and control. Real-time data transmission and reception increase both the quality and transparency of information.

Prescriptive data analysis algorithms may be utilized to improve the quality of planning, according to Saihi et al. [22]. They further stated that by offering design, performance, and conformance quality measures, these analytics enhance data-informed decision-making.

- **Process management**

The use of big data and analytics can assist in resolving problems related to process efficiency and quality. Companies can move towards proactive, assertive, and intelligent decision-making by evaluating the information they have available. Decision-makers are receiving an increasing amount of data from machines that are embedded with sensors thanks to analytics acting as a new optimizer [2], [21], [22]. Companies should arrange their production processes based on analytics to create smart factories, allowing for better informed and real-time decision-making across the whole value chain [2], [8].

Process monitoring, according to Dias et al. [23], can be carried out by humans or by machine self-correction, allowing for rapid process adjustments. Furthermore, the evidence suggests that increasing automation in the manufacturing process will improve process quality [11], [23].

Shop floors are connected to all the business units and the customers, thanks to the integration and interconnectivity capabilities afforded by Industry 4.0 technologies. breaking down communication boundaries and allowing the process to be redesigned to eliminate faults before the end product is finalized [24], [25], [26].

Cyber-physical systems will create simulations of various production scenarios, using dynamic production variables to determine the optimal scenario before implementation. As a result, the production regime's design and testing will take less time, and the process will be more adaptable. This will result in less downtime on the shop floor [25], [27], [28].

- **Leadership support**

According to Sader et al. [29], big data, integration, and interconnection capabilities enabled by Industry 4.0 help senior management to execute their jobs effectively by improving coordination and collaboration among various levels of management, hence increasing the company's capacity to deliver distinct quality results. Information flow throughout the manufacturing supply chain is significantly improved by Industry 4.0. According to the evidence [28], [29, [30], an improved information flow integrates business processes and makes it possible for ERP systems to improve factory management. Furthermore, the supply of good data to management provides management with information to enable effective decision-making and the provision of the necessary staff support.

- **Business results focus**

Stasiak-Betlejewska et al. [31] claim that automated machines and processes will increase productivity, accuracy, and flexibility through the efficient real-time exchange of information during the manufacturing process. This strategy will make businesses that pay attention to the market’s current needs more competitive [23], [31]. Big data analytics can be used by businesses to gather, analyse and predict future consumer needs based on historical user data [11], [29]. Customer satisfaction is known to be a great catalyst for business growth.

Additionally, according to Stasiak-Betlejewska et al. [31], a business that integrates 4IR technology into its quality management methods can anticipate increased efficiency and cost savings as a result of real-time quality control that is modular, adaptable, and tailored to the user's manufacturing concept, real-time production planning, and overall business integration.

- **Customer Focus**

Industry 4.0 technologies may offer customization capabilities from time to time, according to Sader et al. [28], [29], [30]. Big data analytics, one of the 4IR enablers, will gather information from embedded sensors and use it to forecast trends and future needs, enabling improved product designs, ensuring that customers are satisfied, and preserving the organization's competitive advantage.

Customer satisfaction will be made possible by 3D printing, according to several researchers [30], [32], [33]. They contend that it enables customers to perfectly personalize and alter proposed designs, enabling enterprises to switch from mass to personalized manufacturing. Customers can alter designs mid-production and add personalization because of end-to-end integration, which keeps them informed about the production process and gives them a feedback loop that enables them to share their user experience with producers for future improvements.

According to Zheng et al. [34], the adoption of an Internet of Things platform can assist in identifying critical defect-related data, enabling quicker and greater quality defect avoidance as well as cost savings. As a result, the primary application of the Internet of Things in quality management is the early identification of problems in produced goods [35].

- **Employee Focus**

Sader et al. [29] claim that in a good quality management system (QMS), employees at all organizational levels are actively involved in enhancing the company's abilities to create and deliver value to customers. In this regard, Industry 4.0 will facilitate employee collaboration and communication by offering a choice of employee engagement and human resource management strategies that provide benefits from connectivity and social media [36].

Additionally, 4IR will promote transformation by highlighting individual contributions to the expansion of the company. When a QMS is digitized, digital technology and quality tools, processes, and systems are linked, claim Dias et al. [23] and Ghobakhloo [36], ensuring that employees are cognisant of their daily tasks. This function, which is connected to improving training and learning, boosts productivity, efficiency, and employee engagement.

Furthermore, according to a study by Dalmarco et al. [37], collaborative robotics enable workers to carry out difficult tasks that call for intuitive judgment while handing off laborious or boring tasks to automated systems. Collaborative robotics is therefore viewed as an addition to human activity in circumstances where labor is scarce, there is a lack of production capacity or there is low efficiency and performance in repetitive jobs.

Lastly, researchers believe that process automation and simplification, as well as the improvement to decision-making they provide, can greatly boost the effectiveness of human resources [23], [29], [37]. To customize career development or learning programs to individual employees' behavior, experience, abilities, personality, and learning habits, managers can, for instance, use AI and data analytics to identify significant patterns in information provided by employees.

- **Supplier development**

According to Sader et al. [29], industry 4.0's total integration makes it feasible for stakeholders to communicate effectively with one another. Since they are involved in the production process, suppliers are very sensitive to customer expectations.

Blockchain technology can also support efforts to cultivate suppliers. On the blockchain network, the money used to fund a supplier development program can be tracked [38], [39]. The types of knowledge that are exchanged and the kinds of organizational assistance that providers get can both be tracked using a smart contract. The data collected can be used to evaluate the efficacy of supplier development initiatives.

It is possible to evaluate performance before and after implementing a blockchain training program [40], [41], [42]. Smart contracts can be used by businesses to guarantee that they only do business with suppliers who take part in supplier development programs. Suppliers can be selected using this technique.

Blockchain enables complete supply chain transparency, thus enabling businesses to monitor their business practices. End-to-end openness in supply chains has been touted as the latest answer to the supply chain issue, which is more critical than ever, given concerns about legitimacy [23], [28], [29], [42]

- **Quality planning and quality control**

Collecting and integrating non-production data such as customer experience, customer usage, installation and service, and recycling data into the design stages of new concepts to assure product enhancements and zero errors [11]. This guarantees that planning for any new product also ensures quality.

Process monitoring quality makes certain that errors are found, and the information is saved and made available when needed [11], [23], [37]. Data obtained during traditional quality control and inspections are frequently lost, which makes it more difficult to adapt to the automation process. Traditional statistical process control included drawbacks such as not completing all measurements for a production process on time and, due to the delay in obtaining the measurements, defective products being fully manufactured before the anomaly was detected [1], [2], [4], [11].

According to Chouchene et al. [5], Stojanovic et al. [7], Chiarini [11], and Carvalho et al. [43], the ability to visually identify anomalies is one of the most important manufacturing challenges requiring the use of Industry 4.0-led inspection systems. Manual inspection depends greatly on the working environment, and the operator's perspective and efficiency, all of which are frequently impacted by pressure, weariness, and degree of passion [11], [23]. Additionally, visual control is time-consuming and typically yields unsatisfactory corrective results because it is frequently random. Small faults that are invisible to the naked eye are missed but can be found easily in the 4.0 era.

5.2 Challenges associated with Quality 4.0 in traditional QM practices.

While Quality 4.0 has the potential to improve quality management in various ways, some challenges need to be addressed. Some of these challenges are included in the table below.

Table 3: Challenges of Quality 4.0

QM Practices	Challenges posed on each element by Quality 4.0	Consequences	Publications
Process management	The effective integration of new technologies with existing processes and legacy systems and ensuring that employees are trained to use them seamlessly and effectively.	Integration issues with existing systems and processes could lead to disruption of operations and decreased efficiency.	[1]-[9], [11]-[19], [21]-[26]
Customer focus	Data privacy concerns while collecting customer data and ensuring the accuracy and reliability of the collected data.	Data inaccuracies and errors could compromise product quality, customer satisfaction, and overall business performance.	[1]-[16], [18]-[26]
Evidence-based decision making	Quality 4.0 generates vast amounts of data. Managing and analyzing this data can be a significant challenge and ensuring the accuracy and reliability of the data collected is a challenge.	The decisions made based on unreliable or inaccurate data could result in poor business performance and can also harm the reputation of the company. Moreover, decision-makers might make decisions based on incorrect data, leading to incorrect conclusions, and taking the company in the wrong direction.	[2]-[9], [11]-[15], [17]-[19], [21]-[25]
Business result focus	Ensuring the accuracy and reliability of the data collected, as	Data privacy and security breaches could result in legal and	[4], [7], [9] [13], [15], [16], [18]-

QM Practices	Challenges posed on each element by Quality 4.0	Consequences	Publications
	well as addressing cybersecurity concerns.	reputational damages for the organization.	[20], [25], [26]
Employee engagement	Employee engagement requires significant investment in training and development, and addressing concerns related to job displacement.	Employees may not be comfortable using the new technologies, leading to decreased engagement and productivity. Lack of training and development opportunities for employees may lead to skills gaps and hinder organizational growth and innovation. Job displacement concerns may lead to employee dissatisfaction, low morale, and increased turnover rates.	[10]-[17], [20], [24], [26]
Supplier development	Ensuring that suppliers are comfortable sharing data and ensuring that the data collected is accurate and reliable.	Supplier discomfort with data sharing could hinder collaboration and innovation, leading to missed opportunities for business growth.	[11], [12], [15], [18], [22]-[26]
Top management support	Ensuring that top management is comfortable using these technologies and is well-trained to offer support to the rest of the organization.	Top management's discomfort with the new technologies could lead to resistance to change, resulting in decreased adoption rates and missed opportunities for process improvement and cost savings.	[11]-[14], [16], [17], [20], [24]-[26]

6 CONCLUSION

This systematic literature review concludes that there has been a significant increase in publications on the impact of 4IR technologies on quality management practices in the manufacturing sector. Although Quality 4.0 implementation will improve quality management procedures holistically, they will mostly improve evidence-based decision-making, process management, and customer focus. However, challenges such as data accuracy, cybersecurity, employee training, and integrating technologies into existing processes and systems must be addressed to yield optimum results. The study serves as a guide for researchers and practitioners looking to implement Quality 4.0 in manufacturing.

The consensus in the literature as presented by this systematic literature review encourages organizations, even those in developing countries like South Africa, to transition to Quality 4.0 to improve their manufacturing practices and reduce the impact that poor quality has placed on their products and brand image.

Future research should broaden the scope to encompass the impact on other practices and explore effective ways of addressing challenges related to Quality 4.0 to optimize benefits.

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A CRITICAL REFLECTION ON THE PROMINENT COST OF POOR QUALITY (COPQ) INCIDENTS IN THE SOUTH AFRICAN AUTOMOTIVE INDUSTRY IN THE LAST DECADE

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ABSTRACT

Cost of quality is an aspect of quality management that measures the financial impact of quality on an organization. This paper presents a semi-systematic review of significant CoPQ incidents in the South African automotive industry over the past decade. The purpose is to identify patterns and similarities in these incidents to facilitate learning, prevent their recurrence and maintain competitiveness in the South African economy. Using a cause-and-effect diagram, the review highlights the root causes contributing to CoPQ incidents, such as inadequate quality control, ambiguous supply chain processes, and a lack of customer focus. Based on the findings, the study recommends investing in Quality 4.0 initiatives as a solution. These initiatives can improve real-time quality control, prioritize customer-centric quality management, and provide opportunities for employee development. The study contributes to the current understanding of CoQ and offers recommendations for South African organizations to enhance their quality management practices ensuring global competitiveness.

Keywords: CoPQ in South Africa, Cost of Quality, Manufacturing, Quality 4.0, Quality Control

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1 INTRODUCTION

The South African government's vision of expanding employment opportunities from 10 million in 2010 to 24 million by 2030 highlighted the labour-intensive manufacturing industry as a significant generator of job opportunities [1]. South Africa's manufacturing sector was thus designated as the country's economic backbone [1]-[3], currently contributing 12% of the country's GDP. As the country's leading manufacturing sub-sector, the automotive industry employs over 11000 people and contributes significantly to South Africa's economy [2], [4], [5]. However, the industry faces various challenges, including inconsistent power supply, limited local demand and intense competition from foreign firms [1], [2]. In addition to these challenges, the industry has been grappling with cost of poor quality (CoPQ) incidents that have emerged as another critical factor affecting its performance.

CoQ incidents, such as product recalls and quality failures, not only result in direct costs for manufacturers but also reduce output and tarnish the reputation of companies, causing clients to turn to alternative brands [6], [7]. In recent years, South Africa has experienced several high-profile CoPQ incidents in various industries, including automotive, food and other consumer goods. In the last decade, the South African automotive industry was plagued by three significant CoPQ incidents, as reported by several media outlets [4], [8], [9], [10]. These incidents have raised concerns about quality control and safety standards in South African automotive manufacturing, thus undermining public confidence in locally produced products, resulting in decreased contributions to the country's GDP.

As Figure 1 illustrates, the contribution of the South African automotive industry to GDP has declined significantly from 7% in 2012 to 4.3% in 2022.

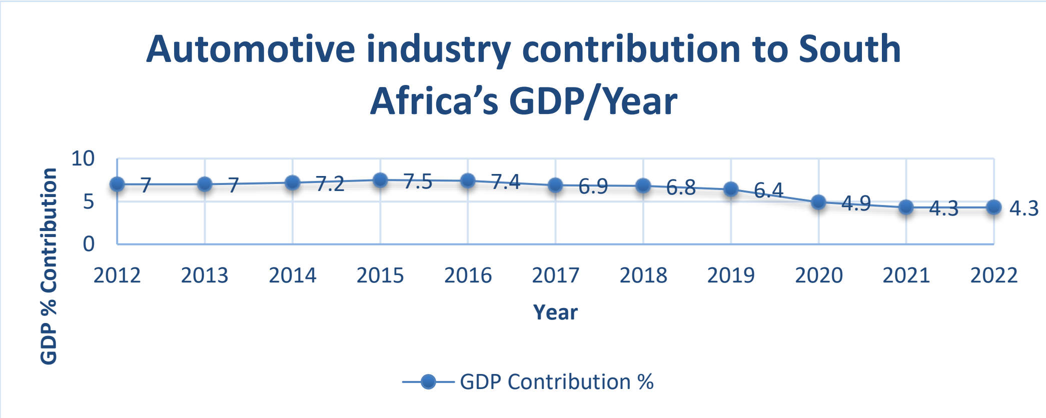

Figure 1: Automotive industry contribution to South Africa's GDP/Year [1], [4], [11]

In light of these challenges, this critical reflection aims to provide valuable insights into some of the prominent CoPQ incidents that have occurred in the past decade, focusing on three leading vehicle manufacturers, that have been widely reported in literature and by respected newspapers, such as Business Day, City Press, Daily Maverick and The New Age. The study systematically identifies trends, repetitions and similarities in these incidents, to promote avoidance and ensure that the industry remains competitive. By examining these incidents, this study seeks to contribute to the body of knowledge on CoPQ incidents in the South African automotive industry, providing a basis for further research and discussion on this critical issue.

2 THEORETICAL BACKGROUND

2.1 Cost of Quality

The concept of Cost of Quality (CoQ) is widely used by organizations as a tool to measure the financial cost incurred due to the production of products or provision of services. Cost of Quality (CoQ) is a subset of quality management (QM) [6]. Quality management includes all the activities related to ensuring that a product or service meets or exceeds customer expectations.

Activities such as quality planning, quality assurance, quality control and continuous improvement form part of traditional QM tasks. CoQ is one of the tools used in quality management to measure the financial costs of producing products or services and to identify ways to reduce those costs [7], [12]. The concept of CoQ was first introduced by Armand V. Feigenbaum in the 1950s and later, in the 1970s, Philip B. Crosby popularized it and introduced the concept of "zero defects”. Another pioneer of CoQ is Genichi Taguchi, who developed the Taguchi method of quality control in the 1980s.

According to Surange et al. [13], the cost of quality refers to the additional expenses incurred in producing a product or service caused by errors, defects and/or poor performance. In essence, every time a task or process is repeated to rectify errors, the cost of quality rises [13], [14], [15]. CoQ encompasses all costs associated with quality, including prevention costs, appraisal costs, and internal and external failure costs, as shown in Figure 2.

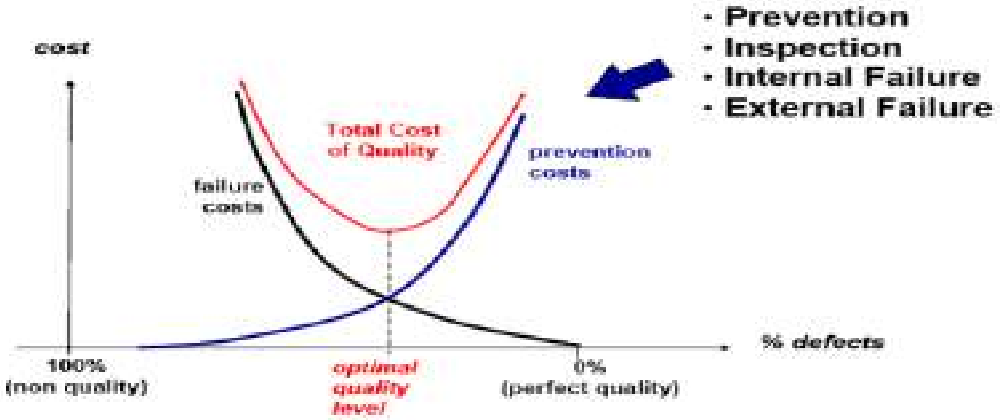

Figure 2: Cost of Quality [7], [13]

According to Makhanya et al. [16], cost of quality is a sum of cost of good quality (CoGQ) and cost of poor quality (CoPQ), as seen on Equation (1). CoGQ comprises all the costs associated with ensuring quality, i.e., prevention and appraisal costs as seen on Equation (2).

$$Cost\ of\ Quality\ = Cost\ of\ Good\ Quality + Cost\ of\ Poor\ Quality \quad \textbf{(1)}$$

$$Cost\ of\ Good\ Quality = Prevention\ Cost + Appraisal\ Costs \quad \textbf{(2)}$$

$$Cost\ of\ Poor\ Quality\ = Internal\ Failure\ Costs + External\ Failure\ Costs \quad \textbf{(3)}$$

Prevention costs refer to the costs associated with preventing defects from occurring, such as training and education, process improvement, and research and development [16]. Appraisal costs are incurred when products and services undergo inspection and testing to ensure compliance with quality standards. On the other hand, CoPQ is a sum of all the costs associated with internal and external failures as seen on Equation (3). Internal failure costs encompass the expenses related to identifying defects before the customer receives the product, while external failure costs encompass the expenses incurred when defects are discovered by the customer after they have received the product [7], [17], [18].

Measuring CoQ can help organizations identify and eliminate the sources of defects and ultimately improve the quality of their product or service [17], [18]. Reducing this cost can lead to increased customer satisfaction, increased market share and reduced costs due to fewer defects, which in turn ensures that the business stays competitive with increased profit margins. CoPQ external failure incidents can have severe consequences for manufacturing organizations, including financial loss, damage to reputation and image, increased costs resulting from rework, repair and warranty claims, and negative impacts on the economy, even in highly developed economies [12]. This paper focuses on external failures as identified by consumers.

3 RESEARCH OBJECTIVES

Despite being a leading manufacturing country in Africa [1], [2], South Africa has had several manufacturing problems over the past decade. It is crucial to reflect upon these errors, as they provide valuable lessons from which we can learn and improve. Therefore, the objective of this study is to systematically examine existing literature to explore the implications, root causes and overall consequences of quality-related incidents to organizations.

4 METHOD

The research question, which outlines the objective of the study and the researchers' goals, is directly related to the methodology because it defines the process employed to answer the question [16]. This study explores poor quality incidents and quality failures in the South African automotive industry to determine if there is a pattern to and any similarities between these incidents. By so doing, the researchers hope to identify lessons that can be learned, thus preventing recurrences. If such lessons can be learned by South African manufacturers, the researchers believe that the competitiveness of the South African economy can be maintained. The researchers employed a semi-systematic review methodology to enable a comprehensive examination of various research traditions and their implications. A semi-systematic literature review follows a structured process to identify and include relevant studies but may not adhere to all the rigorous methodologies of a fully systematic review. Researchers may opt for this kind of a review if the area is not yet widely researched. By synthesizing the findings using a meta-narrative, this study ensures transparency and enables readers to assess the reasonableness of the arguments.

4.1 Time span

This study spans a 10-year period.

4.2 Research terms and databases

The primary search terms utilized in this study were "South African Automotive" AND "Cost of poor Quality" AND "Quality Incidents" AND "Product Recalls". In addition, the study included articles that concentrated on "Product Recalls" and "South African Manufacturing". The research utilized official government sites, reputable media houses, Scopus, Emerald and IEEE Xplore as databases for collecting literature.

4.3 Inclusion and exclusion criteria

The studies included in this research had to meet specific criteria to ensure their reliability and credibility: they had to be published by reliable sources, such as government official reports and reputable databases, and the studies had to cover incidents of poor quality in the South African automotive industry. Studies that did not contain enough information to fulfil the research objectives were omitted.

4.4 Data analysis

Both quantitative and qualitative techniques were used to analyse the text. In this case, the qualitative techniques involved identifying and grouping themes or patterns that emerged. Data from the grouped themes was summarized and synthesized using quantitative methods.

5 FINDINGS AND DISCUSSIONS

As can be seen in Figure 3, the number of publications on quality incidents in the South African automotive industry has increased steadily in recent years. Although customers had been laying complains regarding poor quality experienced in their automobiles, the topic only gained traction recently when manufacturers began recalling faulty vehicles. In 2013 and 2015 there was only one publication each year, but the number of publications increased to a total of 10 in the period, 2017 to 2018.

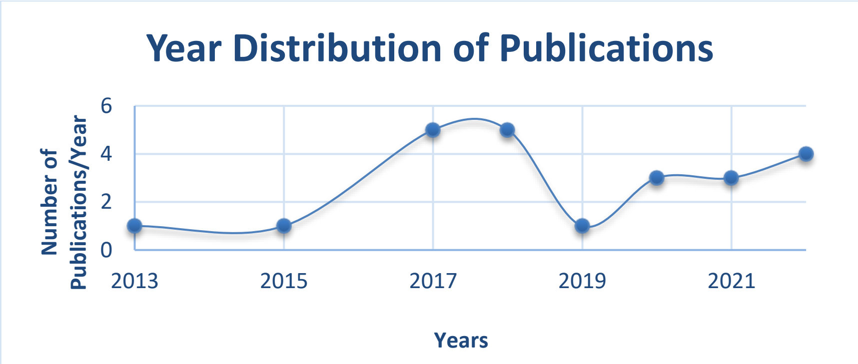

Figure 3: Year-to-year distribution of publications on quality incidents

Although the number of publications dropped in 2019, it picked up again in 2020 and 2021, with three publications in each year, and four publications in 2022. This trend indicates that during this decade, there had been publications covering customer dissatisfaction since 2013, although product recalls only took place later.

Through the semi-systematic literature review, several prominent cost of poor quality (CoPQ) incidents in the South African automotive industry were identified and are presented in Table 1. Each incident had its unique primary cause, with Mercedes-Benz facing brake defects, Toyota dealing with faulty airbag inflators and Ford experiencing vehicle fires.

Table 1: Notable CoPQ incidents in the South African automotive industry

Organization	Model Recalled	CoQ	Year of Recall	Publications
Mercedes-Benz	ML, GL and R-class series	Brake defects	2022	[4], [5], [10], [19]-[24]
Toyota South Africa Motors Recalls	Corolla, RunX, Yaris, Hilux and Fortuner	Faulty airbag inflators	2018	[4], [9], [20], [21], [25]-[28]
Ford Kuga recall	Kuga	Vehicle catching fire	2017	[4], [10], [20], [22]-[24], [27]-[30]

The following section delves into detailed case studies of these incidents, examining their primary causes, possible root causes and the implications they had on the automotive industry in South Africa.

Case 1: Mercedes-Benz Brake Defect Recall [4], [5], [10], [19], [20], [21], [22], [23], [24]

In April 2022, Mercedes-Benz South Africa issued a recall of 13 159 vehicles produced and sold between 2006 and 2019 [10], [24] due to potential brake failure that could result from rusting of the joins of the brake booster housing. The rusting occurred as a result of moisture accumulating in the rubber sleeve that covers the housing, either due to prolonged exposure to water or over time. If not addressed, this defect could cause the brake pedal to disconnect from the system, resulting in compromised braking performance. The National Consumer Commission raised concerns about this issue [22], [23]. The announcement of the recall led to the financial cost of recalling 13,159 vehicles (not published yet), a drop in the share price of more than 4% and reputational damage [10], [22].

Primary cause:

Rusting at the joining points of the brake booster housing

Possible secondary causes:

- **Inadequate quality control**: The first possible secondary cause of the brake defect was inadequate quality control measures during the manufacturing process. The defect was caused by advanced corrosion of the brake booster [10], [22], [24], which indicates that the part may not have been properly treated or coated to prevent corrosion. This suggests that there were gaps in the company's quality control processes, which allowed defective parts to enter the production process.
- **Design flaw**: The Acting National Consumer Commissioner Thezi Mabuza alerted the public that this incident was caused by a flaw in the design of the brake booster [22], [23]. It is possible that the potential for corrosion was not consider sufficiently in the design or the design did not provide sufficient measures to prevent corrosion. This may have caused the brake booster to become more vulnerable to corrosion and ultimate failure.
- **Lack of customer focus**: The manufacturer delayed the recalls since the first complaint in 2006, which demonstrates either a lack of customer focus and/or lack of proper feedback loops from customers, and a lack of accountability, leading to the manufacturer missing the public customer complaints regarding this issue [10], [22].

Case 2: Cost of Quality Incident at Toyota South Africa Motors [4], [9], [20], [21], [25], [26], [27], [28]

In January 2018, Toyota South Africa Motors (TSAM) made an announcement regarding the recall of over 700 000 vehicles due to safety concerns related to their airbags. The purpose of the recall was to replace front airbag inflators manufactured by Takata. These inflators had the potential to burst due to moisture intrusion, thus posing a safety risk. According to Mzolisi Witbooi, the PR Manager for the company, Toyota, along with other car manufacturers around the world, was conducting a recall of vehicles with potentially faulty Takata airbag inflators [9], [25], [26].

This issue had affected almost 100 million vehicles across various brands worldwide. In South Africa, Toyota had identified 730 000 vehicles that were affected by this recall. However, according to an Eyewitness News article in 2018 [9], this was not the first instance of Toyota recalling vehicles due to airbag issues. In 2016, more than five million cars with the same problem were recalled globally. The total cost of this incident was stipulated to be R5 500 000 000 [18]. Before the announcement of the recall, Toyota Motor Corporation's share price was trading at around R877,49 per share on the Tokyo Stock Exchange. Following the announcement of the recall, the share price initially dropped by around 1% to 2% [9], [25], [26], [31].

Primary Cause:

Faulty airbag inflators produced by Takata.

Possible Secondary Causes:

- The secondary causes of the incident were **poor supplier selection** and **inadequate quality control**. TSAM had chosen Takata as a supplier for the airbag inflators without fully evaluating their manufacturing processes, quality control procedures and history. Takata had a history of quality control issues and product recalls [9], [25], [26]. Additionally, TSAM's quality control processes were inadequate, as they did not detect the issue with the airbag inflators during the initial quality checks.

- **Design Flaw:** Another possible secondary cause could have been a design flaw. The airbag inflators were designed to use ammonium nitrate as a propellant, which is a cheaper alternative to other propellants [9], [26]. However, the design was flawed as it did not prevent the potential intrusion of moisture, which caused the inflators to rupture, thus posing a safety risk to drivers and passengers [9].
- **A lack of customer focus**: This could have been a possible cause of this CoQ incident. The company may have been more focused on cost savings and production efficiency than ensuring the safety of its customers. The fact that Takata had a history of quality control issues and product recalls suggests that the company may not have been proactive in identifying and addressing the issue before it became a significant safety concern [9]. The organization also took too long to issue recalls, further putting their customers in danger.

Case 3: Ford Kuga Recall [4], [10], [20], [22], [23], [24], [27], [28], [29], [30]

In January 2017, Ford conducted a recall of 4 556 Kuga 1.6-litre Ecoboost models manufactured between December 2012 and February 2014 for repairs. This recall was triggered by several reports of the company's utility vehicles catching fire. According to Ford SA, there was a potential risk of a B-pillar fire in the event of a frontal collision [32], [33]. This was attributed to the seatbelt pre-tensioner being activated, which could ignite the insulation material surrounding the pre-tensioner. Post investigation, the incidents were linked to a cooling system fault that could cause an oil leak and lead to engine fires. Ford's Kuga recall highlights the importance of maintaining high safety and quality standards during the production process [8], [32], [33].

The National Consumer Commission fined Ford for R35 000 000 for breaching the Consumer Protection Act (protects consumers against unlawful and unfair trade deals) and they also had to pay R227 800 000 to consumers for inconvenience during the recall. The total cost of repairs was not stipulated. At the time of the recall, Ford's share price was trading around R218.18 per share. Following the announcement of the recall, Ford's share price dropped by approximately 4% to R209.09 per share in the days after the news broke. The fires also led to injuries and a fatality [8], [32], [33].

Primary causes:

Defect in the vehicle's cooling system

Possible secondary causes:

- **Design flaw:** One secondary cause of the Kuga recall was a design flaw in the cooling system, which allowed oil to leak and potentially ignite a fire in the engine compartment [8], [12], [32], [33]. The flaw likely originated during the design and engineering phase of the Kuga, where inadequate attention may have been paid to the safety and functionality of the cooling system. To attest to this, Mr A Williams admitted that the cooling system's inability to function in hot climates (South African climate) was due to a design defect.
- **Inadequate testing and quality control:** Another possible cause of the Kuga recall was inadequate testing during the production process. The faulty cooling system should have been identified during testing and addressed before the vehicles were released on the market [32], [33]. Inadequate testing may have been due to insufficient resources, time constraints, or a failure to prioritize safety and quality control.
- **Poor communication**: The delay in the recall of Kuga vehicles by Ford South Africa was partially caused by inadequate communication. Even though the quality control team

identified the faulty cooling system, the information may not have been properly shared with other departments such as marketing or customer service. This may have led to a delay in addressing the issue with the customers that had already bought the vehicle and implementing necessary changes to the product [24], [27], [28].

- **Slow response and lack of customer focus:** Another contributing factor to the delay in the Kuga recall was Ford South Africa's slow response to reports of engine fires. Although reports of Kuga engine fires surfaced in 2015, the recall was not initiated until 2017 [24], [27], [28]. This slow response might have been due to a lack of urgency or inadequate investigation into the issue. It also highlights the absence of efficient customer feedback loops, which could have provided early warnings of the problem. The company's failure to prioritize customer safety is evident. Had Ford prioritized customer safety, they might have discovered the cooling system fault earlier and taken measures to prevent fires from occurring. Instead, it required multiple vehicle fires and a recall before Ford identified the root cause of the problem and took corrective action [12].

The themes discovered throughout the review are listed in Table 2. This is done to identify common threats that South African manufacturing should learn from and solve in order to prevent a recurrence of these significant accidents.

Table 2: Similarities in root causes of the identified CoQ incidents

Possible root causes	Mercedes-Benz brake defect	Toyota South Africa Motors recalls	Ford Kuga recall
Ambiguous supply chain processes		✔	
Design flaw	✔	✔	✔
Inadequate testing and quality control	✔	✔	✔
Poor communication	✔		✔
Inadequate feed-back loops	✔	✔	✔
Slow response and lack of customer focus	✔	✔	✔

As laid out in the table, all three large corporations lacked customer focus because they neglected to carry out adequate testing and quality control, missed a design flaw and delayed recalling the defective vehicles (Mercedes-Benz recalled vehicles that had been manufactured 13 years previously, Toyota South Africa Motors 15 years previously and Ford 5 years previously), putting their valued customers lives at risk. The review also demonstrates that the policies are not stringent enough for manufacturers to fear producing defective products. According to Surange et al. and Makhanya et al. [13], [16], the cost of producing a defect free product is 10 times less than the cost of repairing a product immediately after production before it reaches the customer base, and the cost becomes 100 times more when it is recalled from the customer. This phenomenon is illustrated in Figure 4.

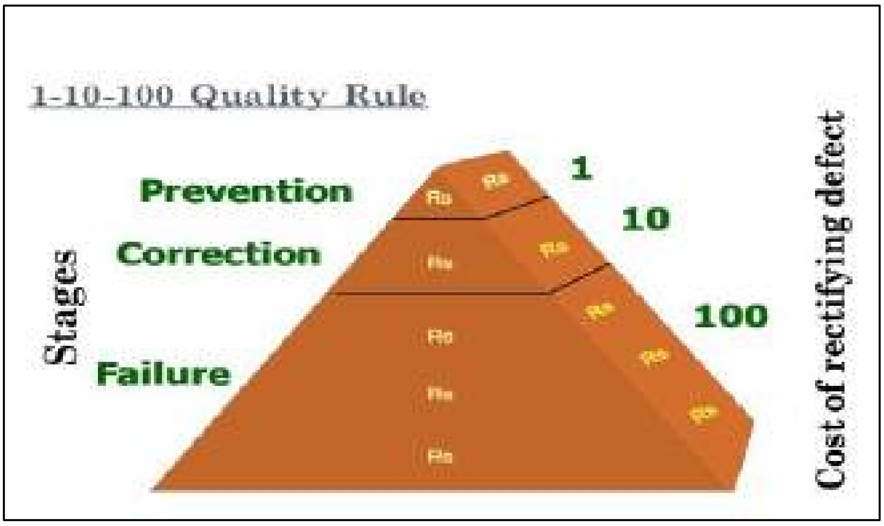

Figure 4: 1-10-100 Rule [13]

The results of the semi-systematic review also indicate that there are similarities in the implications that the three giant automobile manufacturers faced as a result of their respective recalls.

Table 3: Similarities in the implications of identified CoQ incidents

Impact	Mercedes-Benz brake defect [4], [5], [10], [19], [20], [21], [22], [23], [24]	Toyota South Africa Motors recalls [4], [9], [20], [21], [25], [26], [27], [28]	Ford Kuga recall [4], [10], [12], [20], [22], [23], [24], [27], [28], [29], [30]
Financial loss	✔	✔	✔
Market share drop	✔	✔	✔
Reputational damage	✔	✔	✔
Injuries/Fatalities	None reported	None reported	✔

All three experienced reputational damage, which is a significant issue in the automotive industry where consumer trust is essential. According to Mushavhanamadi and Xundu [12], Ford recalls caused customers to avoid other models with no known defects. The recalls also had financial implications, namely the cost of recalling vehicles and the drop in share price. The recalls also resulted in property damage, injuries and a fatality in the case of the Ford Kuga recall.

6 REFLECTIONS & RECOMMENDATIONS

The cause-and-effect diagram, Figure 5, highlights the prominent root causes of the CoPQ incidents in South Africa as identified through the review [8], [9], [10], [12], [21], [22], [23], [24], [25], [26], [32], [33], [34], [35], [36], [37]. This depicts the primary factors the manufacturing sector needs to work on to avoid the incidents from recurring.

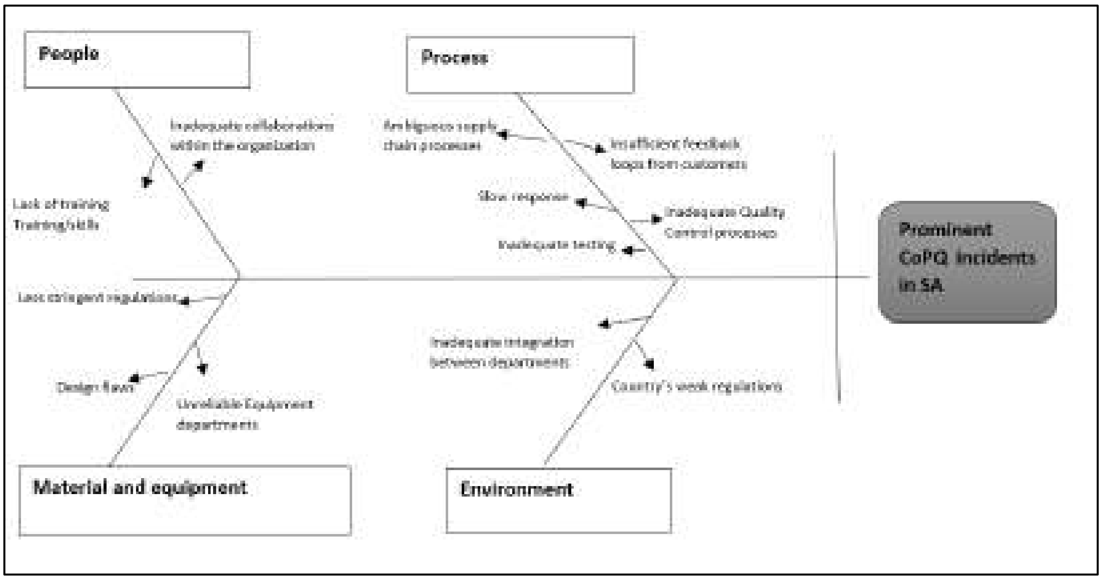

Figure 5: Ishikawa diagram for prominent root causes of CoPQ incidents in SA

To prevent such detrimental incidents in the future and save the future of South African manufacturing, companies should implement a comprehensive quality control program that includes regular testing of raw materials, components, and finished products. Companies should also review their supply chain processes to ensure that all suppliers adhere to strict quality standards and further improve collaboration with suppliers to ensure that all raw materials meet strict quality standards. Additionally, companies should improve their communication with regulators, customers, and other stakeholders to ensure timely and accurate reporting of any defects or issues, ensure transparency and build trust.

Additionally, manufacturers should invest in continuous improvement initiatives to identify and eliminate potential quality issues before they become significant problems. Such improvements include adopting Quality 4.0 into their legacy production processes. Quality 4.0 is a phenomenon of integrating Industry 4.0 technologies into traditional quality management practices [38], [39].

Industry 4.0 technologies like big data analytics, artificial intelligence, augmented reality, virtual reality, 3D printing, the internet of things, blockchain technology, and cyber-physical systems can revolutionize quality management practices by streamlining operations, automating processes, and making informed decisions [38], [39]. These technologies can process and analyse large volumes of data in real time, create intelligent systems that make autonomous decisions, produce intricate shapes and designs more efficiently [40], [41], [42], facilitate communication and data exchange, ensure secure and transparent transaction recording and verification, and enable real-time monitoring and control of physical processes [43].

7 CONCLUSION

This study has identified several prominent incidents that occurred in SA over the last decade. Their causes included insufficient quality control, inadequate training and development, ambiguous supply chain processes and a lack of customer focus. The impact of these incidents was not only financial but also dented the brand reputation and, in one case, caused a death. To prevent such detrimental incidents in the future and save the future of South African manufacturing, this study recommends that companies implement a comprehensive quality control program that includes regular testing of raw materials and finished products, review their supply chain processes to ensure strict quality standards are adhered to, and improve communication with regulators, customers and other stakeholders. Moreover, investing in continuous improvement initiatives, including adopting Quality 4.0 technologies, can significantly improve quality management practices, streamline operations, automate processes and make more informed decisions. By implementing these recommendations, organizations can avoid CoQ incidents and improve their quality control processes, enhance their supply chain management, and create a culture of continuous improvement. The time is now for South African manufacturing to prioritize quality control and create a sustainable future.

Future research should focus on the implementation of Quality 4.0 in manufacturing to reduce cost of quality.

Table 4: Glossary of Terms

Acronym	Full Word	Meaning
CoQ	Cost of Quality	One of the quality management methods used to quantify the costs associated with producing quality goods or services and to find strategies for lowering those costs [6].
CoPQ	Cost of Poor Quality	All the costs incurred by an organization due to poor quality [7], [17], [18]. This may also include hidden costs such as reputational damage and loss in future sales.
CoGQ	Cost of Good Quality	The costs invested in maintaining and improving quality to prevent defects and quality-related issues [17], [18].
Industry 4.0	The fourth Industrial Revolution	A phrase used to characterize the present trend in manufacturing that includes automation, data exchange, and digital technologies, including cloud computing, cyber-physical systems, and the Internet of Things (IoT) [40], [41], [42].
Quality 4.0	Quality Management in the fourth Industrial Revolution	The application of advanced quality management techniques, data analytics, and digital technologies to ensure and enhance product and service quality in the context of Industry 4.0 [38], [39].

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PROGRESSION FROM POSTAL DIGITAL TRANSFORMATION CAUSAL LOOP DIAGRAMS TO STOCK AND FLOWS: A SOUTHERN AFRICAN PERSPECTIVE

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ABSTRACT

Industry 4.0 has revolutionised the way firms manufacture or render services. Firms are deploying digital technologies such as artificial intelligence et al. The postal sector is not unscathed by these sweeping winds of change and has experienced a sharp decline in traditional mail volumes resulting in the tumbling profits placing some designated postal operators on route to extinction. However, trailblazers such as Swiss Post have adopted industry 4.0 disruptive digital technologies and are postal champions from which those trailing behind could learn and aspire to be. This paper explores the construction of stock and flows from the causal loop diagram that defines the dynamic hypothesis in the context of postal digital transformation, and further explores the quantification of aggregate variables and subsequent mathematical expressions. The development of the SD model and quantification of variables provides a novel approach to resolving the challenge faced by Southern Africa Postal Sector.

Keywords: Causal loop diagrams, stock & flow diagrams, SD model

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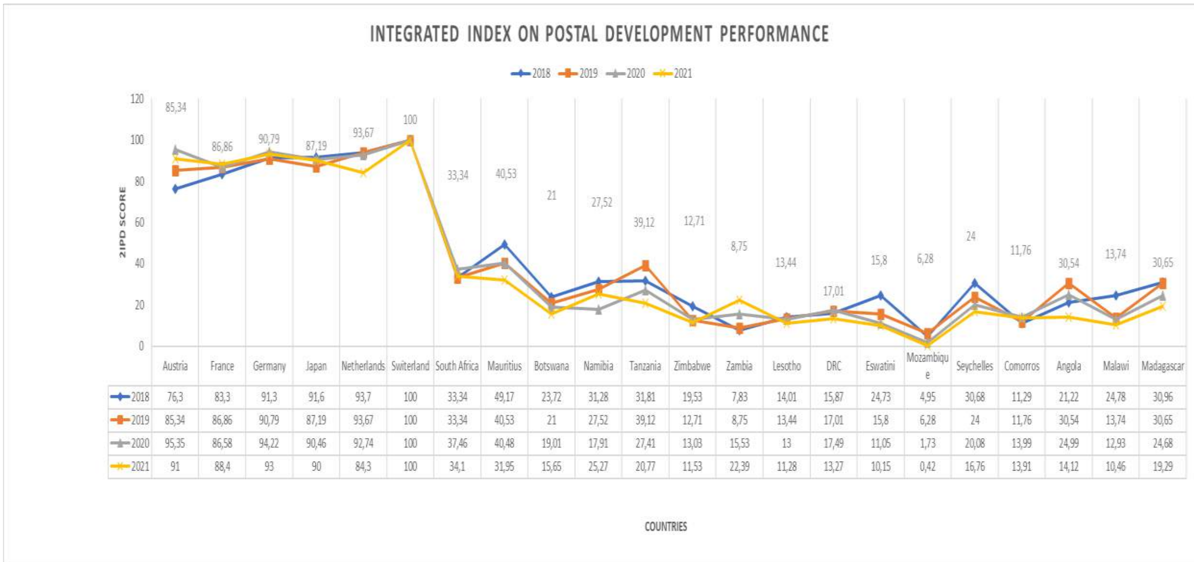
1 INTRODUCTION AND BACKGROUND

The digital age has provoked Postal services across the globe to expand their services well beyond the original service of the Designated Postal Operators (DPOs) which is the distribution of postal mail items. UPU [1] argues that although some DPOs in several countries across the world struggle with financial turmoil, there are DPOs that are effectively competing at an international level, and are financially sustainable. There have been prevalent moves towards digital technologies throughout the developing world, which in turn led to digitalisation across industries including the postal industry. UPU [2] suggests that societal composition is swiftly shifting and the digital age has driven changes in the way society consumes products and services. This shift has led to the progression of the client of the future with exceptional requirements and expectations that the postal sector ought to meet.

However, according to UPU [2], the majority of DPOs are poorly performing on the Integrated Index for Postal Development (2IPD). UPU [2] proposes that the measurement of multiple dynamics of postal development is a complex task, and theorises that to overcome this challenge. According to [3] 2IPD measures the performance of POs in the four vital dimensions of postal development are reliability, reach, relevance and resilience.

Figure 1 paints a picture of the calamity facing the postal sector in Southern Africa compared to the tier 1 countries that perform well on the 2IPD and result in the postal sector in South Africa posting losses in respective countries and leaving the State to bail out the loss making entities, a burden to the taxpayer. Figure 1 illustrates the low scores of Southern Africa as compared to the tier 1 countries led by Switzerland which has consistently scored 100 over 100 points since 2018. Since a picture worth a thousand words, Figure 1 depicts the problem at hand in Southern Africa at a glance.



	Austria	France	Germany	Japan	Netherlands	Switerland	South Africa	Mauritius	Botswana	Namibia	Tanzania	Zimbabwe	Zambia	Lesotho	DRC	Eswatini	Mozambique	Seychelles	Comorros	Angola	Malawi	Madagascar
2018	76,3	83,3	91,3	91,6	93,7	100	33,34	49,17	23,72	31,28	31,81	19,53	7,83	14,01	15,87	24,73	4,95	30,68	11,29	21,22	24,78	30,96
2019	85,34	86,86	90,79	87,19	93,67	100	33,34	40,53	21	27,52	39,12	12,71	8,75	13,44	17,01	15,8	6,28	24	11,76	30,54	13,74	30,65
2020	95,35	86,58	94,22	90,46	92,74	100	37,46	40,48	19,01	17,91	27,41	13,03	15,53	13	17,49	11,05	1,73	20,08	13,99	24,99	12,93	24,68
2021	91	88,4	93	90	84,3	100	34,1	31,95	15,65	25,27	20,77	11,53	22,39	11,28	13,27	10,15	0,42	16,76	13,91	14,12	10,46	19,29

Figure 1: Integrated Index on Postal Development Performance of Southern Africa

2 LITERATURE REVIEW

2.1 System dynamics paradigm

Guller [1] proposes that high-level models are modest models intended at strengthening insights, and analysis of complex phenomena, communication, and decision-making. Fisher [2] argues that system dynamics models have limitless opportunities to act as “flight simulators” that decision-makers may use as a training environment to conduct research and comprehend the complexity of the environments they model. Management of digital transformations and, more specifically, the effects of digital business transformations are becoming progressively complicated in the current business environment where competition and technological revolutions are dynamic and change happens at a faster pace than before [3]. A system dynamic approach offers a holistic view of the postal digital dynamics that are at play in this complex environment and will provide regulators, governments, and posts with a novel tool to manage interventions (policies) that will improve the postal system performance in Southern Africa and lead towards a sustainable future.

2.2 System dynamics principles and fundamentals

Sterman [4] contends that more often, well-intentioned energies to resolve persistent difficulties create unforeseen side effects. Actions taken from decisions taken provoked unforeseen reactions. The result is policy resistance which can be defined as the propensity for interventions to be conquered by the response of the system to the intervention itself. System dynamics is better positioned to counter this blind spot that characterises human mental models that completely miss the mark due to the inability to see the whole.

Yearworth [5] notes that System Dynamics modelling arose from ground-breaking work at MIT in the 1950s by Jay Forrester. Richardson [6] notes Forrester in his ground-breaking article in the Harvard Business Review (Forrester, 1958) put forward an initial statement of the approach that would, in time, become known as system dynamics. Richardson [6] argues that Forrester (1958) fashioned the method on what were then four interesting advances: (a) Progress in computing technology (b) Growth and skill with computer simulation (c) Enhanced comprehension of strategic decision making, and (d) Advances in the comprehension of the role of feedback in complex systems. Richardson [6] notes that Forrester (1958) devised the four fundamentals of industrial dynamics:

- The concept of feedback systems.
- A familiarity with decision-making processes.
- The investigational model approach to complex systems.
- The digital computer simulates a plausible mathematical model.

Maldonado et al. [7] concur with [6] and suggest that system dynamics modelling has been advanced as an approach and technique to (a) Provoke such feedback loops to determine the main growth, balancing, and decay (stagnation) dynamics that drive the behaviour of socio-economic systems, (b) To inspire the system’s dynamic behaviour through the application of differential equations and (c) To examine and design improved policies that will result in enhanced system performance. Maldonado et al. [7] further propose that the modelling process in system dynamics is grounded on iteration between all five stages: (a) Problem articulation (b) Dynamic hypothesis (c) Model formulation (d) Model testing and validation, and (e) Policy analysis and design.

Sterman [8] contends that modelling is a feedback process and not a series of linear steps and that models undergo constantly iterative, persistent questioning, testing, and enhancement. Figure 2 depicts the modelling process; the initial purpose defines the limits and scope of the modelling application, and frames what could be learned from the process of modelling through feedback to streamline a basic comprehension of the problem and the aim of the modelling effort. Iteration can occur from any step to any other step (indicated by the interconnections in the centre of the diagram). In any modelling project, one will iterate through these steps many times.

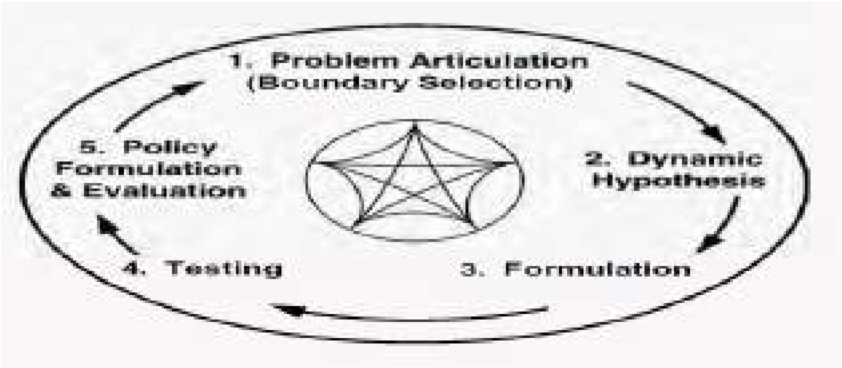


Figure 2: Modelling process

Sterman [8] hypothesises that the model is grounded by mental models and by information gathered from the real world. Stratagems, plans, structures, and decision guidelines in the real world can be considered and tested in the simulated world of the model. The experimentations conducted in the model feedback alter our mental models and lead to the design of novel stratagems, novel plans, novel structures, and novel decision rules. These novel policies are then implemented in the real world, and feedback about their effects leads to new insights in both our formal and mental models as depicted in Figure 2. Forrester [9] and Sterman [8] suggest that modelling is not a lone action that produces answers, but an enduring technique of incessant cycling between the virtual world of the model and the real world of action.

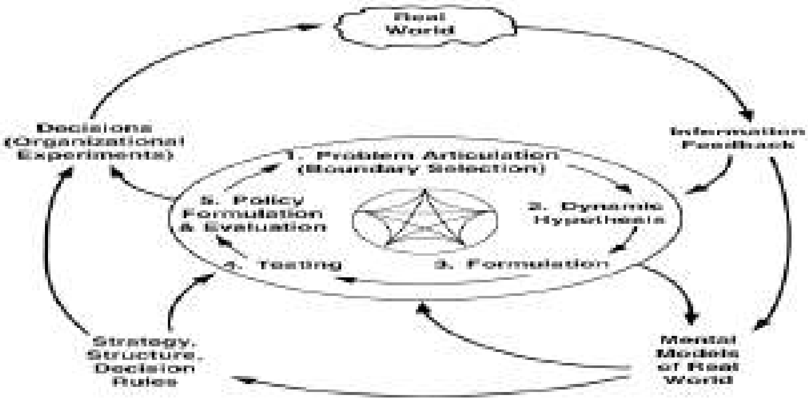


Figure 3: Modelling process embedded in dynamics of a system

2.2.1 Endogeneity and feedback

Richardson [6] suggests that the utmost prominent characteristics of the system dynamics method are indisputably stocks and flows, and feedback loops. These perceptible fundamentals stick out and grasp our attention. But it is important to note that feedback loops are a result of the endogenous point of view [6]. According to Richardson [6], Figure 4 demonstrates the idea. On the left is a depiction of a modest causal system, with causal elements extending outside the system boundary. The dynamics of variables A–E are engendered partially by the interplay among the elements within the system boundary but originate principally from variables P, Q, R, and S outside the boundary. The dynamics of this system are engendered exogenously by forces outside the system boundary.

Richardson [6] on the right is an endogenous view, in which the dynamics of variables A–E are engendered exclusively from the interplay among the variables, inside the system boundary.

Considering an endogenous point of view triggers causal influences to form loops, without loops, all causal influences would point to dynamic forces external to the system boundary. Feedback loops thus enable the endogenous point of view and give it structure [6]. Sterman [8] proposes that system dynamics attempts to discover endogenous explanations for phenomena. The word “endogenous” implies “emerging from within.” An endogenous theory engenders the dynamics of a system through the interplay of the variables denoted in the model.

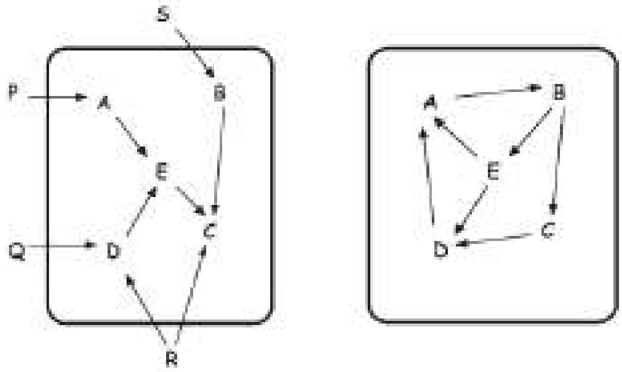


Figure 4: Left: Exogenous view of system structure; causality traces to external influences outside the system boundary. Right: Endogenous view; causality remains within the system boundary; causal loops (feedback)

2.2.2 Causal loop diagrams

Morecroft [10] postulates that a causal loop diagram is a schematic tool for systems thinking researchers, such diagrams illustrate the cause-and-effect relations and feedback processes. Haraldsson [11] suggests that CLDs (Causal Loop Diagrams) pronounce reality through interconnections amongst variables and how they produce a dynamic circular effect. According to Haraldsson et al. [12], CLDs are a means for methodically detecting, examining and communicating feedback loop structures. It is systematic thinking and enables the communication of complex information into a simplified circular loop feedback structure. CLD is a tool that promotes continuous thinking [12].

Sterman [8] proposes that Causal Loop Diagrams (CLDs) are agile and valuable tools for schematising the feedback structure of systems in any realm. Causal diagrams are sketches that illustrate the causal interconnectedness between variables with arrows from a cause to an effect. Figure 4 abridges the explanations of the interconnectedness of polarity. Sterman [8] further notes that a causal diagram entails variables' interconnectedness through arrows representing the causal influences amongst the variable with the significant feedback loops identified in the diagram. Delgado-Maciel et al. [14] suggest that CLD uses diagrams to classify feedback loops. In this diagram, an arrow signifies the causal interconnectedness between some variables.

2.2.3 Stocks and flow diagrams

Iandolo [15] argues that System Dynamics (SD) models can be evaluated through simulation, which is conceivable after the creation of a Stock and Flows Diagram (SFD). An SFD is a quantitative valuation of the system. The Dynamics of the system are evoked in the SFD, and the model construction is arranged through the elaboration of equations that pronounces how the variables are interconnected with others, and how the build-up process is determined by the change in the flows fluctuating the state of the system levels. Ogano [16] proposes that one of the chief confines of CLDs is the failure of CLDs to comprehend the stock-and-flow structure of a system. A stock is the building block of any system. Stocks are the essentials of the system that can be perceived, sensed, calculated, or measured at any given time. A system stock is an accretion of material or information that has built up over time, a reminiscence of the antiquity of fluctuating flows within the system [17]. Ogano [16] further argues that stocks change over time through the actions of a flow. Flows are filling and draining, births and deaths, procurements and sales, growth and decay, payments and withdrawals, triumphs, and disappointments. A stock, then, is the current reminiscence of the antiquity of changing flows within the system.

Sliwa [18] proposes that stocks are essential in producing the dynamics of systems, and suggests that stocks illustrate the state of the system and provide the source for their actions. The evaluation of a problem resolution is principally grounded on the stocks' values. Stocks do not have to be perceptible; stocks can be defined as representing the accretion of information, experience, invention, contagions, impetus, or professed quality of a product. Sliwa [18] further proposes that stocks are important for the following reasons:

- Stocks offer systems with inertia and memory; they accumulate historical events and can vary because of the net value of influx and depletion;
- Stocks are the source of delays;
- Stocks detach rates of flow and create an imbalance in a problem.

2.2.4 A mathematical approach to stock and flows

Sliwa [18] argues that stock-and-flow structures have an exact scientific meaning. Stocks accrue or integrate their flows with the equivalent integral equation, as denoted in Equation 1 below:

$$\text{Stock}(t) = \int (\text{Inflow} - \text{Outflow})\,(dt) + \text{Stock}\,(t\text{-}1) \quad \textbf{(1)}$$

Where (t)=final time, (dt)=time interval, (t-1) = Preceding time moment

Sliwa [18] proposes that the expression Stock (t -1) offers variables with a "recollection" assuring that the stock variable does not overlook its preceding state. Stock variables transform relative to the net flow into it; consequently, the net proportion of change of any stock is its inflow minus its outflow, defining the differential equation:

$$d(\text{Stock})/dt = (\text{Inflow - Outflow})\,(t) \quad \textbf{(2)}$$

Consequently, Sliwa [18] argues; an equivalent stock-and-flow can be effortlessly constructed from any system of integral or differential equations and in addition, a stock-and-flow map of the equivalent integral or differential equation system can be engendered.

3 RESEARCH METHODOLOGY

Kothari [19] suggests that research is a systematic investigation of appropriate information on the topic under consideration. This definition is supported by Leedy and Ormrod [20] who contend that research is a methodical process of amassing, evaluating, and understanding information to grasp a phenomenon under investigation. Pandey and Pandey [21] affirm the notion that research is an essential and compelling instrument in leading humanity to advancement. "Without methodical research, society will progress at a snail-pace" [21].

Melnikovas [22] proposes that one of the approaches to research methodology development is premised on the theoretic idea of the "research onion" advanced by Saunders et al. (2016). Melnikovas [22] further refers to Raithatha (2017) who contends that the research onion offers a comprehensive illustration of the main steps which are to be followed to articulate a robust methodology. The research onion is shown in Figure 5. It defines explicitly the layers from an all-inclusive philosophical outlook to data collection procedures and data analysis tools.

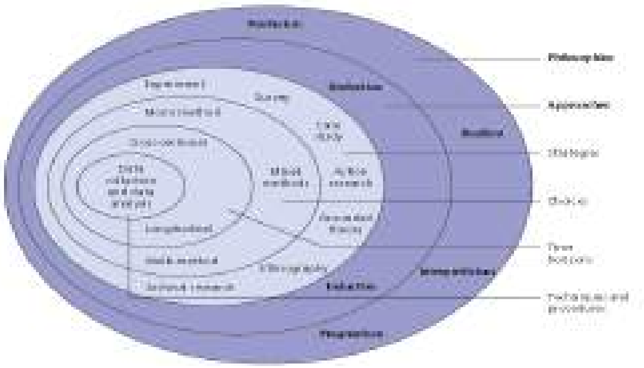


Figure 5: The research onion

This research adopted an interpretivist philosophical worldview and an inductive research approach as the research entailed theory building rather than theory testing in the first phase of the study, followed by adoption of a system dynamic research strategy underpinned by archival research which entailed a critical review of the literature to crystalise insights on dynamics that are at play in the postal digital transformation arena.The factors and concepts (theory) which emerged in the first leg of the study was subjected to a system dynamics research strategy through development of stocks and flows models provided to test the developed theory in a dynamic setting.

4 FINDINGS AND DISCUSSION

4.1 Contextualising the Integrated Index on Postal Development (2IPD) and the emergent dimensions

Mokgohloa et al [23] in their earlier research paper developed ten dimensions that emerged after saturation of data was reached through a meticulous grounded theory technique. The ten dimensions were; (i) Digital culture, (ii) Digital investments, (iii) Operational excellence, (iv) Ecosystem capability, (v) Adoption, (vi) Competitiveness, (vii) Digital capabilities, (viii) Shared vision, (ix) Customer insights, and (x) Diverging interests. The ten dimensions are vital for Designated Postal Operators (DPOs) to improve their performance on the global integrated index for postal development under the auspices of the Universal Postal Union, a United Nations agency for postal services.

The Integrated Index for Postal Development (2IPD) is defined by the UPU [24] as a relative global measure of postal development. 2IPD is a complex index that describes the performance of DPOs in 168 countries. As such, the 2IPD is an exceptional means for examining the performance of the postal sector. The 2IPD according to UPU [25] is grounded on four pillars which are (1) Relevance which appraises the vigour of demand for the full offerings of postal services compared to the finest DPOs in each category of postal activity, (2) Reliability echoes performance in terms of swiftness and certainty of delivery, across all the key segments of physical postal services, (3) Reach implies global connectedness by appraising the extensiveness and deepness of the DPOs international network. Lastly, (4) Resilience shows the degree of the diverseness of revenue streams, along with the aptness to invent and bring about a postal service which serves the broader society.

The Integrated Index on Postal Development (2IPD) is a composite stock that accumulates or depletes over time and integrates three of the seven dimensions which are digital investments, operational excellence, and digital capabilities and can be aggregated under the operations capability maturity stock. The next aggregation comprise of digital culture which incorporates shared vision dimension, competitiveness dimension resulted in financial performance stock emerging. The dimension of adoption translates to the adoption stock. Table 1 illustrates the synthesis and integration of the ten dimensions into composite stocks that emerged that were articulated earlier. Two of the dimensions are exogenous to the system and therefore are outside the boundary of the model, the two are a digital ecosystem and customer insights. Diverging interests are represented by inhibiting factors that will be articulated in the stocks and flow.

Table 1: Emergence of stocks from the seven dimensions

Dimension	Operations Capability Maturity	Digital Culture	Financial Performance
Digital culture		X	
Digital investments	X		
Operational excellence	X		
Adoption			
Competitiveness			X
Digital capabilities	X		
Shared vision		X	

The synthesis depicted in Table 1 resulted in the emergence of the four key stocks that will be utilised to develop the stock and flows. The four stocks are (1) Capability Maturity (CM), (ii) Digital Culture (DC), (iii) Competitiveness (C), and (iv) Adoption (A).

Figure 10 captures the CLD of the four stocks that were articulated in Table 1. Figure 11 characterises the hypothesis and theorises that the adoption of the UPU digital ecosystem by major clients of the postal sector will improve the financial performance of the Postal Sector. The hypothesis further theorises that leadership efforts impact on the potential adopters will improve the adoption rates and will convert potential adopters to adopters

The increase in adopters will diffuse the momentum through formal and informal communication channels which will enhance digital culture which will augment operations capability maturity which will buttress financial performance of the postal sector. Dissent or diverting interests will result in adopters falling off the system and reducing adoption rates and creating a reinforcing loop which must not be allowed to take root.

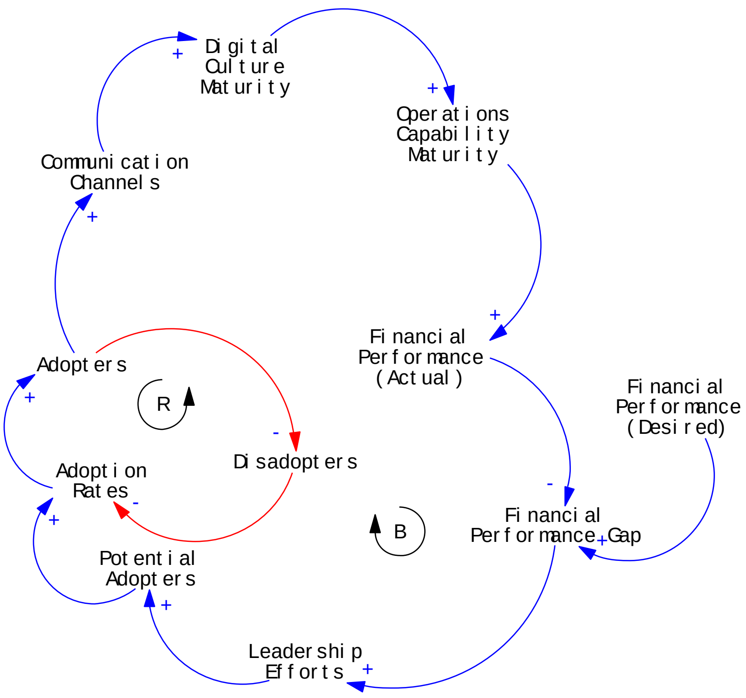


Figure 6: Postal development dynamics CLD as a hypothesis

4.2 Stocks and flows for emergent dimensions including model quantification

The four stocks that emerged and are depicted in Table 2 and Figure 11 are formulated and discussed from 4.1.2.1 to 4.1.2.4. Anylogic PLE software was used to develop the structure of the model and formulate the mathematical expressions that govern the model behaviour to mimic real-life situations. The stocks: capability maturity, digital culture, adoption, and financial performance (competitiveness) are discussed below.

The South African Post Office was selected to test and validate the model and as a result, the data used to quantify the variables were sourced from the South African Post Office and databases of the Universal Postal Union. Figure 12 is the overall model that captures the stock and flows as depicted in Figure 11. Figures 13 to 16 depict the individual stock and flow formulated with the Anylogic PLE software.

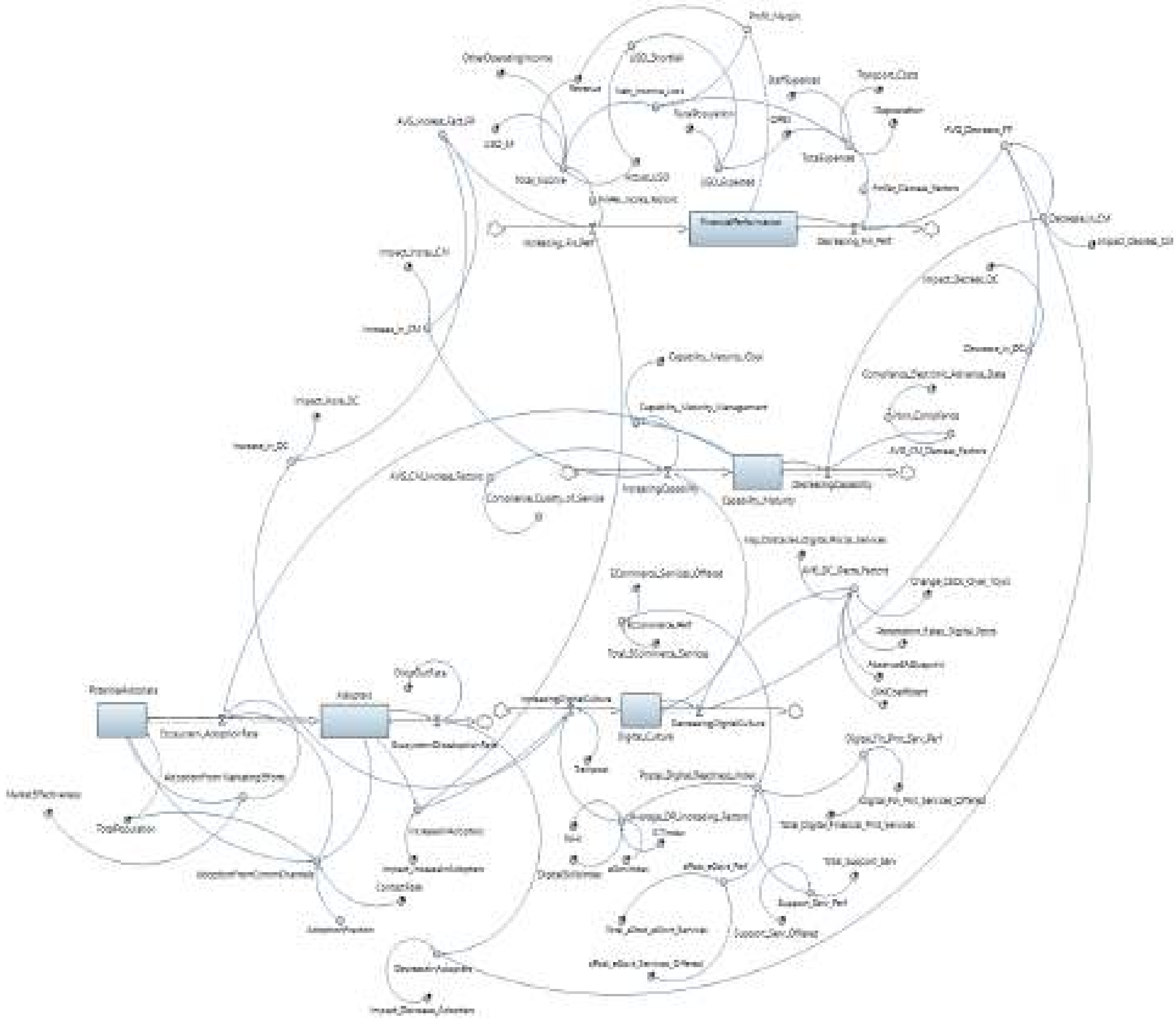


Figure 7: Postal development model with stocks and flows formulated in Anylogic PLE software

4.2.1 Operations Capability Maturity

Figure 8: Operations Capability maturity dynamics formulated in Anylogic

Figure 8 articulates the construction of the goal-seeking structure in Anylogic simulation software as well as the balancing influence loop from diverging interests (Non-compliance to Electronic Advance Data). The discussions on what each of the elements represents are articulated in the preceding chapter. The structure depicted in Figure 8 comprises a single stock which is the operations capability maturity which accumulates capability components over time, based on its flows, increasing capability, and decreasing capability. It is conceptually correct to quality assure that the model is rationally accurate which means that each flow should surge or deplete the capability maturity "stock" with "units" or components over time.

Operations Capability Maturity (CM) is defined as the difference between increasing capability maturity (ICM) and decreasing capability maturity (DCM) which can be described mathematically as in equation 3.

$$d(DC)/dt = ICM - DCM \quad \textbf{(3)}$$

Equation 3 explains that capability maturity over time is the difference between increasing capability maturity and decreasing capability maturity. The capability maturity goal is envisaged to be 0.6 and the current capability based on the 2IPD is 0.33. The gap that exists requires to be managed and as a result, capability maturity management (CMM) emerges as a concept and is defined as the difference between capability maturity goal (CMG) and Capability Maturity (CM) stock resulting in the formulation of the equation:

$$CM\ Goal - CM \quad \textbf{(4)}$$

Equation 4 explains that operations Capability Maturity Management (CMM) is a function of both the operations Capability Maturity Goal (CMG) and the current level of Operations Capability Maturity (CM).

Decomposition of equation 3 yields (i) Increasing capability maturity which is on the left side of the capability maturity stock as depicted in Figure 65 and (ii) Decreasing capability maturity which is on the right side of the capability maturity stock as depicted in Figure 65. Equation 3 represents the two flows that interact to result in the level of capability maturity. Increasing Capability Maturity (ICM) is the sum of Capability Maturity Management (CMM) and average capability management increasing factors (AvgCMIf) which comprise compliance to quality of service (CQoS) multiplied by digital culture (DC) as an increase in digital culture will affect operations capability maturity. The relationship is described mathematically in Equation 5.

$$ICM = (AvgCMIf + CMM) * DC \quad \textbf{(5)}$$

The impact of an increase in capability management (ImpiiCM) is calculated as the total increase impact factor (Tiif) minus the sum of the Impact of an increase in adoption (IiiA) and the Impact of an increase in digital culture (IiiDC). Therefore, the mathematical expression is written as:

$$ImpiiCM = Tiif - (IiiA + IiiDC) \quad \textbf{(6)}$$

Decreasing Capability Maturity (DCM) on the other hand is the difference between capability maturity and a diverging variable in the form of average capability maturity decreasing factors (AvgCMDf) which comprise the overall level of non-compliance to UPU's EAD (Electronic Advance Data) with notation (NCEAD). Therefore, decreasing capability maturity is defined as:

$$DCM = CM - AvgCMIf \quad \textbf{(7)}$$

Warren [189] argues that $X(t+1) = X(t) \mp \Delta X$ is the core theory that lies at the heart of how firms and organisations perform and argues that the rate of loss or gain of a resource (stock) over a period explains the quantity of the stock at any given time, and it does so by depleting or accumulating. It is against this theory articulated by [189] that Equation 4 and other subsequent expressions of other stocks involved in this model are conceptually and mathematically correct.

The variables articulated in equations 1, 2, 3, and 4 were computed to harmonize replication output with representative behaviour patterns and mathematical completeness. For sensible model simulation performance, the baseline values for variables are not articulated in this paper and will form part of a publication on simulation and results. This paper is confined to the development of stock and flows through the formulation of mathematical expressions.

4.2.2 Digital Culture

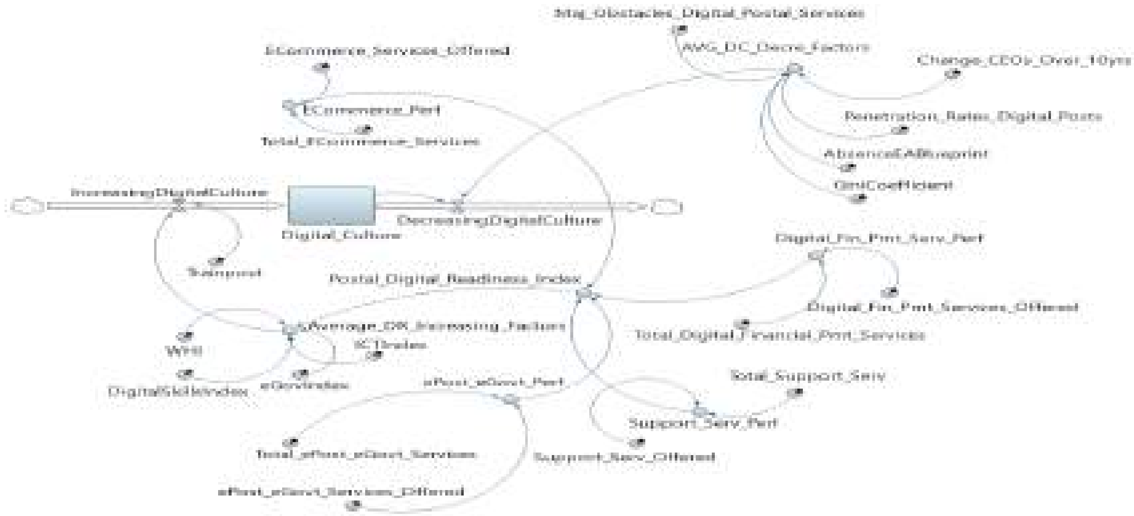


Figure 9: Digital culture dynamics formulated in Anylogic

Figure 9 depicts the construction of the s-shaped growth structure for digital culture in Anylogic as well as the unsought balancing influence from diverging interests. The structure comprises one stock which is digital culture. The digital culture stock has two flows connected to it which are an influx (Increasing digital culture) and a discharge (Decreasing digital culture). The digital culture stock accrues units of digital culture and the two flows move units of digital culture/units of time into and out of the stock.

Digital Culture (DC) is defined as the difference between increasing digital culture and decreasing digital culture which can be described mathematically as in Equation 8.

$$d(DC)/dt = IDC - DDC \quad \textbf{(8)}$$

This construction in the virtual world follows an s-shaped structure in the causal diagram for digital culture, which was derived from the reference mode behaviour pattern for digital culture. Increasing digital culture is the sum of average digital culture factors (Avg_DCIf) and the percentage of staff who attended train-post courses (SATPC) divided by two and multiplied by the increase in adopters (IiA). Average digital culture factors comprise (a) Postal readiness index (PRi) which is a composite of (i) Support Service Performance (SSP), E-commerce performance (ECSP), ePost and e-Government services performance (ePeGSP), and digital financial and payment services performance (DFPSP). (b) Global Index Factors (GIf) that drive a digital culture which is a composite of (i) Word Happiness Index (WHi), (ii) Digital Skills Index (DSi), (iii) e-Government Index (eGi), and (iv) ICT Index (ICTi). Therefore, increasing digital culture (IDC) can be expressed mathematically as:

$$IDC = ((Avg\_DCIf + SATPC)/2) * IiA \quad \textbf{(9)}$$

Where:

$$Avg\_DCIf = (SSP + ECSP + ePeGP + DFPSP + WHi + DSi + eGi + ICTi)/8 \quad \textbf{(10)}$$

Where:

- Support Services Performance (SSP) equals the support services offered (SSO) by the designated postal operator divided by the total support services (TSS) that are available in the ecosystem. Therefore, support services performance is calculated as:

$$SSP = SSO / TSS \quad \textbf{(11)}$$

- E-commerce services performance (ECSP) equals the e-commerce services offered (ECSO) by the designated postal operator divided by total e-commerce services (TECS) that are available in the ecosystem. Therefore, E-commerce services performance is calculated as:

$$ECSP = ECSO / TECS \quad \textbf{(12)}$$

- ePost and e-Government services performance (ePeGSP) equals the ePost and e-Government services offered (ePeGSO) by the designated postal operator divided by the total ePost and e-Government services (TePeGS) that are available in the ecosystem. Therefore, ePost and e-Government services performance (ePeGSP) is calculated as:

$$ePeGSP = ePeGSO / TePeGS \quad \textbf{(13)}$$

Increase in adopters (IiA) = Adopters (A) * Impact of increase in Adopters (ImpiiA) and it can be mathematically expressed as:

$$IiA = A * ImpiiA \quad \textbf{(14)}$$

Decreasing digital culture (DDC) on the other hand is the difference between digital culture and a diverging variable in the form of average digital culture decreasing factors ((AvgDCDf) which comprise the absence of EA blueprint (AEABP), penetration of digital postal services (PRDPS), Gini coefficient (GCOeff) which measures the level of inequality in society, major obstacles to digital postal services (MODPS), and percentage change in Chief Executive Officers over 10 years (CoCEO_10Yrs). O'Reilly III et al. [26] propose that the mainstream studies of organisational culture are grounded on two assumptions: (a) Leaders lead the cause of culture, and (b) Culture is interrelated to ensuing organisational outcomes. O'Reilly III et al. [26], demonstrated through the experimental results constructed on data from respondents in 32 high-technology firms, that the character of the Chief Executive Officer (CEO) influences, to a high degree, organisational culture which is thereafter connected to a comprehensive set of organisational results including an organisation's economic performance.

Therefore, decreasing capability maturity is defined as:

$$DDC = DC - AvgDCDf \quad \textbf{(15)}$$

Where:

$$AvgDCDf = (AEABP + GCOeff + PRDPS + MODPS + CoCEO\_10Yrs)/5 \quad \textbf{(16)}$$

The major obstacle to digital postal services is a composite of factors that hinder fully digital postal services in Africa. These factors are poor investments (PI), lack of digital culture (LDC), lack of expertise (LE), poor integration of merchants (PIM), poor customer adoption (PCA), inadequate training (IT), poor rate of change (PRC), difficulty in finding right external partners (DFREP), custom clearance challenges (CCC), stiff competition (SC), inadequate legal framework (ILF), and limited best practices (LBP). The equation for the major obstacle to digital postal services (MODPS) is:

$$MODPS = AVG\ (PI + LDC + LE + PIM + PCA + IT + PRC + DFREP + CCC + SC + ILF + LBP) \quad \textbf{(17)}$$

4.2.3 Adoption

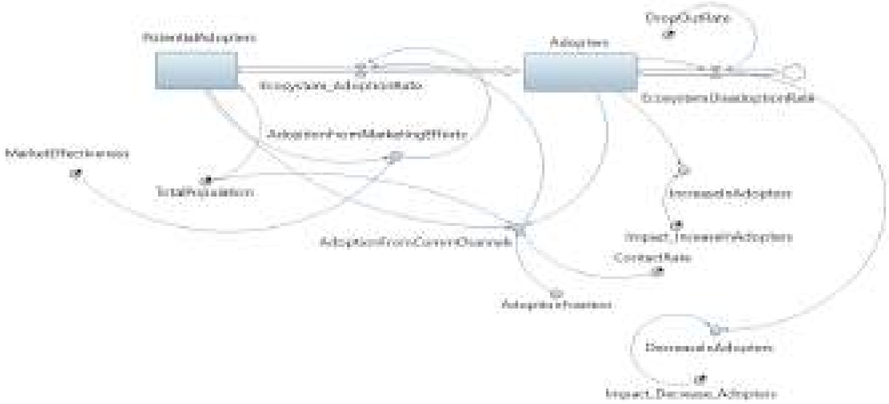


Figure 10: Adoption dynamics formulated in Anylogic

To provide context before the articulation of mathematical expressions, potential adopters are the 174 key customers of the organisation who contribute more than R10 million a month towards revenue at the South African Post Office which is used to validate the postal development system dynamics model. There are currently five key customers who have adopted and had been integrated into the UPU digital ecosystem platform. The UPU digital ecosystem platform is a complex ecosystem offering designated postal operators an opportunity to collaborate and integrate into the postal industry's industry 4.0 platform (ecosystem) which is grounded on the (i) Six industry 4.0 design principles of interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity. (ii) The four Industry 4.0 dimensions of cyber-physical systems, Internet of Things (IoT), Internet of Services (IoS), and smart factories.

The adoption rate is driven by leadership efforts that are in the form of (i) Adoption from marketing efforts which represent leadership efforts to market the digital ecosystem to the 174 key customers, to convince the key customers to adopt the UPU digital ecosystem API (Application Programming Interfaces) and participate in the global postal economy. (ii) Adoption from communication channels which is driven by both formal and informal communication among adopters.

Figure 10 depicts the construction of the s-shaped growth structure for adoption in Anylogic as well as the unsought balancing influence from dis-adoption due to adopters dropping out and ceasing to use the ecosystem. The structure comprises two stocks which are (i) Potential adopters and (ii) Adopters. The digital culture stock has two flows connected to it which are an influx (Increasing digital culture) and a discharge (Decreasing digital culture). The digital culture stock accrues units of digital culture and the two flows move units of digital culture/units of time into and out of the stock.

Adoption from marketing efforts (AME) is calculated by multiplying marketing effectiveness (MI) multiplied by potential adopters (PA). Therefore, the mathematical expression can be written as:

$$AME = MI * PA \quad \textbf{(18)}$$

Adoption from communication channels (ACC) is the product of adopters' stock (A), adoption fraction (AF), and contact rate (CR) multiplied by the quotient of potential adopters' stock (PA) and total population (TP).

$$ACC = A * AF * CR * (PA)/TP \quad \textbf{(19)}$$

The ecosystem adoption rate (ESAR) is calculated by multiplying the sum of Adoption from Marketing Efforts (AME) and Adoption from Communication Channels (ACC) by Capability Maturity (CM) stock because as the capability maturity increases, it will persuade other potential adopters to adopt the UPU API's and integrate to the ecosystem to benefit from the benefits other adopters reap from UPU digital ecosystem.

The mathematical expression for ecosystem adoption rate is written as:

$$ESAR = (AME + ACC) * CM \quad \textbf{(20)}$$

The ecosystem dis-adoption rate (ESDR) represents the number of adopters (A) who discontinue the use of the ecosystem. The calculation of the dis-adoption rate is arrived at by multiplying the dropout rate (DoR) and adopter stock (A). The mathematical expression for ecosystem dis-adoption rate is written as:

$$ESDR = DoR * A \quad \textbf{(21)}$$

The effect of an increase in adopters was articulated in Equation 14 in the preceding paragraphs and further stated below:

$$IiA = A * ImpiiA \quad \textbf{(22)}$$

4.2.4 Financial Performance (Competitiveness)

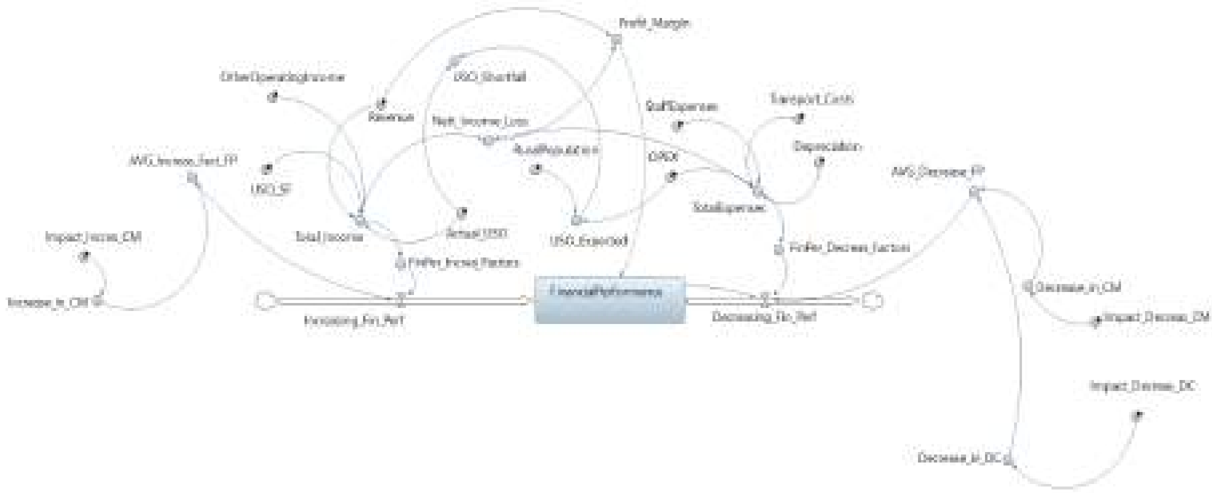


Figure 11: Financial performance (competitiveness) dynamics formulated in Anylogic

Figure 11 depicts the construction of the s-shaped growth structure for financial performance in Anylogic as well as the undesired compensating influence from discontinued use inertia. The structure comprises one stock which is digital culture. The financial performance (competitiveness) stock has two flows connected to it which are an influx (Increasing financial performance) and a discharge (Decreasing financial performance). The financial performance (competitiveness) stock accrues or drains units of financial performance, and the two flows move units of financial performance/units of time into and out of the stock.

Financial Performance (FP) is defined as the difference between Increasing Financial Performance (IFP) and Decreasing Financial Performance (DFP) which can be described mathematically as in Equation 23 below.

$$d(FP)/dt = IFP - DFP \quad \textbf{(23)}$$

Where:

Increasing Financial Performance (IFP) is the average of the sum of an increase in adopters (IiA), financial performance increase factors, and average increase factors for financial performance which can be mathematically expressed as:

$$IFP = AVG\ (FinPer\_Increa\_Factors + AVG\_Increas\_Fact\_FP + IncreaseInAdopters) \quad \textbf{(24)}$$

Where:

Average Increase Factors in Financial Performance (AIFFP) are the average increase in capability management (IiCM), increase in digital culture (IiDC), and increase in adopters (IiA). Therefore, the Financial Performance Increase Factors (FPIF) can be mathematically expressed as:

$$AIFFP = AVG\ (IiCM + IiDC + IiA) \quad \textbf{(25)}$$

An increase in digital culture (IiDC) is expressed as the product of the impact of an increase in digital culture (ImpiiDC) and Increasing Digital Culture (IDC). The mathematical expression that follows is:

$$\textbf{IiDC = ImpiiDC * IDC} \quad \textbf{(26)}$$

The Financial Performance Increase Factors (FPIF) are attributed to total income (TI) which is made up of the sum of revenue (RV), other operating income (OOI), actual universal obligation paid (AUSOPD), and universal service obligation shortfall (USOSF). The mathematical expression that follows is:

$$\mathrm{FPIF} = \mathrm{TI} = \mathrm{RV} + \mathrm{OOI} + \mathrm{AUSOPD} + \mathrm{USOSF} \qquad \textbf{(27)}$$

Decreasing Financial Performance (DFP) is attributed to (i) Financial performance decrease factors (FPDF) which are attributed to total expenses (TE) which are made up of the sum of transport costs (TC), staff expenses (SE), operational expenses (OPEX), and depreciation (DEP). (ii) Average decrease in financial performance (ADFP) which is attributed to the average decrease in capability maturity (DiCM), decrease in digital culture (DiDC) and decrease in adopters (DiA). (iii) Financial performance stock

The mathematical expression that follows is:

$$\mathrm{DFP} = \mathrm{FP} - (\mathrm{ADFP} - \mathrm{FPDF}) \qquad \textbf{(28)}$$

$$\mathrm{FPDF} = \mathrm{TE} = \mathrm{TC} + \mathrm{SE} + \mathrm{OPEX} + \mathrm{DEP} \qquad \textbf{(29)}$$

5 CONCLUSIONS AND RECOMMENDATIONS

This paper articulates the model conceptualisation which is grounded on the research undertaken by Mokgohloa et al. [23] from where ten dimensions (variables) emerged. The dimensions (variables) were further developed into causal loop diagrams or rather “influence diagrams” which unambiguously demonstrate the dynamic feedback relationship between variables within each sub-system in the study by Mokgohloa et al [27]. In that research, both exogenous variables (outside the boundary) and endogenous variables (within the boundary) were identified. The endogenous variables excluding the digital ecosystem, which is exogenous but the subject of the study, were synthesized into causal loop diagrams or “influence” diagrams to describe their interaction in a dynamic setting. The influence diagrams were supplemented by a detailed explanation of the interconnectedness and the loop dynamics for each of the variables presented as causal loop diagrams or CLDs.

This paper further articulates the stocks and flows that emerged from the preceding research by Mokgohloa et al. [27] which dealt with CLDs. The ten dimensions that were discussed in the preceding chapter are further refined and streamlined and described in Table 1. The resultant dimensions are consolidated, and a new causal loop diagram emerges which comprises capability maturity, adoption, digital culture, and financial performance (competitiveness). The emergent CLD has depicted in Figure 6 and grounds the hypothesis in the context of the realities and material conditions that are at play in the postal sector.

The restated hypothesis was presented which theorises that the adoption of the UPU (Universal Postal Union) APIs (Application Programming Interfaces) by key customers of the postal sector will reinforce a robust digital culture. This culture will thereafter strengthen the operations capability maturity of the postal sector and the three stocks will reinforce financial performance (competitiveness) of the postal sector which will ensure the sustainability of the postal sector.

This paper further quantified the variables and developed the mathematical expressions for respective stocks and flows. As a recommendation for future research, the developed stocks and flows should be subjected to model verification and validation tests, and finally policy analysis and design. Sterman [4] proposes that policy design incorporates the development of novel stratagems, structures, and verdict guidelines; and the sturdiness of policies and their responsiveness to unpredictability in the model parameters and structure must be evaluated.

This comprises their performance under an assortment of diverse scenarios, as well as the interplay of diverse policies.

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A FRAMEWORK FOR DEVELOPING SYSTEMS ENGINEERING MANAGEMENT BASED ON A SYSTEMIC VIEW OF THE SOUTH AFRICAN CONSTRUCTION AND DEVELOPMENT INDUSTRY

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ABSTRACT

South Africa has a history of poor performance on large complex construction and development projects, typically Systems of Systems (SoS) integration projects. The most recent failures include the highly publicised Medupi and Kusile projects. A significant component of their failings can be attributed to poor systems engineering and systems engineering management capabilities during the project lifecycle. Most large organisations undertaking complex systems engineering projects in the construction and development sector do not possess internal functional structures that support developing a systems engineering management capability. Literature indicates that the role of complex interface management and project integration is the responsibility of systems engineering management. This research explores the general causes of failures within complex systems engineering projects in the construction and development industry. Outcomes will be used to develop and propose a framework to support the development and performance of systems engineers and systems engineering managers in such environments.

Keywords: systems engineering management, systems thinking, complex projects, development

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1 INTRODUCTION

The Systems Engineering Manager (SEM), which is the final line of progression within the System Engineering (SE) field, directs the design, development, synthesis, and creation of a system based on customer needs, acting as a “chief designer” of the system rather than just being the system analyst [1]. Although research and development in the field of SE have improved our abilities in the interpretation, design, development, implementation, and management of single systems over the past 50 years, we still face significant challenges with the relatively new phenomenon of Systems of Systems Engineering (SoSE), i.e., the integration of multiple complex systems [2].

Carlock and Fenton [3] highlighted that SE handbooks frequently describe the development of individual stand-alone systems, i.e., systems that are identical and deployed similarly at any site location. Developing Systems of Systems (SoS), particularly systems that involve integration with several existing or legacy systems, is a far more significant challenge than developing stand-alone systems. Each system has unique capabilities, constraints, budgets, schedules, and interface requirements that must be considered during development and integrated to work effectively as a synergistic whole. Examples include the integration between different generations of hardware and software or lifecycle stages of systems in the case of brownfield expansions or upgrades. The SoS is generally a heterogeneous system, implying that each system or sub-system of the SoS is generally custom-built or developed to suit specific site conditions of the regions in which they are deployed [3].

Complexity is further exacerbated by the fact that the integrated SoS is a consolidation of independent systems developed by numerous organisations. Although substantial research has been undertaken to address aspects such as risk, uncertainty, schedule urgency, and various other issues in the megaproject environment, the complexity issue has received limited attention. This is surprising given the extreme demand for organisational capabilities required to manage complexity in the megaproject environment. In most instances, poor megaproject performance was attributed to a lack of prior organisational experience and capabilities [4]. This research's System of Interest (SoI) includes complex engineered systems (large-scale plants) as an SoS, such as oil refineries, petrochemical, electric power generation, and mineral processing plants [5]. Procurement of such facilities requires SoSE Management’s capability to manage the integration of independent systems to ensure a successful outcome [6].

Most organisations manage risks associated with acquiring such facilities by transferring the risk to an Engineering Consultant who acts for and on behalf of the owner. Irrespective of how the project is contracted, SEMs with robust Systems Thinking (ST) and SE capabilities are essential to facilitate the system interface integration management necessary to achieve the desired outcomes.

SEM in this environment requires broad-based inter-disciplinary engineering skills at a level considered to be a specialist amongst generalists, capable of managing interfaces and complex integration between teams of domain specialists [7]. Acquiring such knowledge will require meaningful cross-disciplinary exposure and a commitment to remain in the field for a long time. System Engineering Managers (SEMs) must develop such capabilities since the success of a project, from an SEM perspective, is not measured based on quality, cost, and schedule in the short term but also on plant performance over time, i.e., year 1, year 2,…. year 7 or decades [8]. Failure to develop these skills will inevitably result in cost, schedule overruns, and performance implications.

In many instances, performance issues do not show themselves immediately but generally manifest in operational cost escalation over time. This has been a constant challenge for South African organisations, with many megaproject failures impacting the economy in recent years. Prime examples of such failures are the Medupi and Kusile plants at Eskom

[9]. Some of the general causes of poor performance on these projects include the late approval of contracts and design drawings, design errors, poor scope definition resulting in late scope changes, and poor technical management capabilities [10].

A major component of the project's failings can be attributed to poor SEM capabilities during the project lifecycle. A general engineering manager from a functional background or operations support role may not possess the appropriate experience or skillset to perform the role as a technical track lead of large complex SoSE projects. That is the function of an SEM who is considered an expert in managing complex interfaces and integration. Where do such individuals come from, given that they are so challenging to develop? Are we guilty of executing sizeable complex construction and development projects with gaps or inappropriate skills within the project leadership structure/hierarchy? Tertiary institutes and large industries in South Africa need to invest in developing and applying a suitable framework to improve SEM capabilities.

2 METHOD

The nature of the research problem, questions and propositions are aligned with a relativist ontology and a constructionist epistemology, i.e., many truths apply to this topic or questions [11]. However, not all will be relevant to the context of this study. For instance, no single reality or issue impacts the development of SE and SEMs in South Africa. Examples are socio-economic conditions within the country resulting in limited availability of resources to fund projects to support development and encourage staff retention and corruption, which also constrains resource availability. Such issues are not directly within the control of tertiary institutions or industries and have little relevance to a framework for developing system engineers and SEMs. Furthermore, the viewpoints of the individuals regarding barriers to performance will vary based on their perspectives and experiences.

The primary research design is aligned with a qualitative research paradigm to develop theories and foundations to validate or reject the research propositions proposed based on secondary research [12]. Relevant propositions will test the validity of competencies in the proposed framework for developing Systems Engineers and SEMs performing roles in large, complex SoSE project environments. The literature survey combined a structured narrative method and a critical review. The primary focus of the research was highlighting gaps in the development and capabilities of SEM in South Africa. Peer-reviewed journal articles focusing on complex, large-scale construction projects were preferred. The number of citations was also used to measure the quality of the source. Old, outdated material was generally discarded.

The literature review used the draft research questions that informed phrases and keyword searches as sub-section headings. Search questions were designed to explore literature from a broad range of fields, such as SE, ST, Engineering Management, Project Management and Construction Management, to identify relationships with poor performance in SEM. An overview of all research applicable to the search questions and a critical review and analysis is provided. The entire process is depicted in the mind map in Figure 1 below.

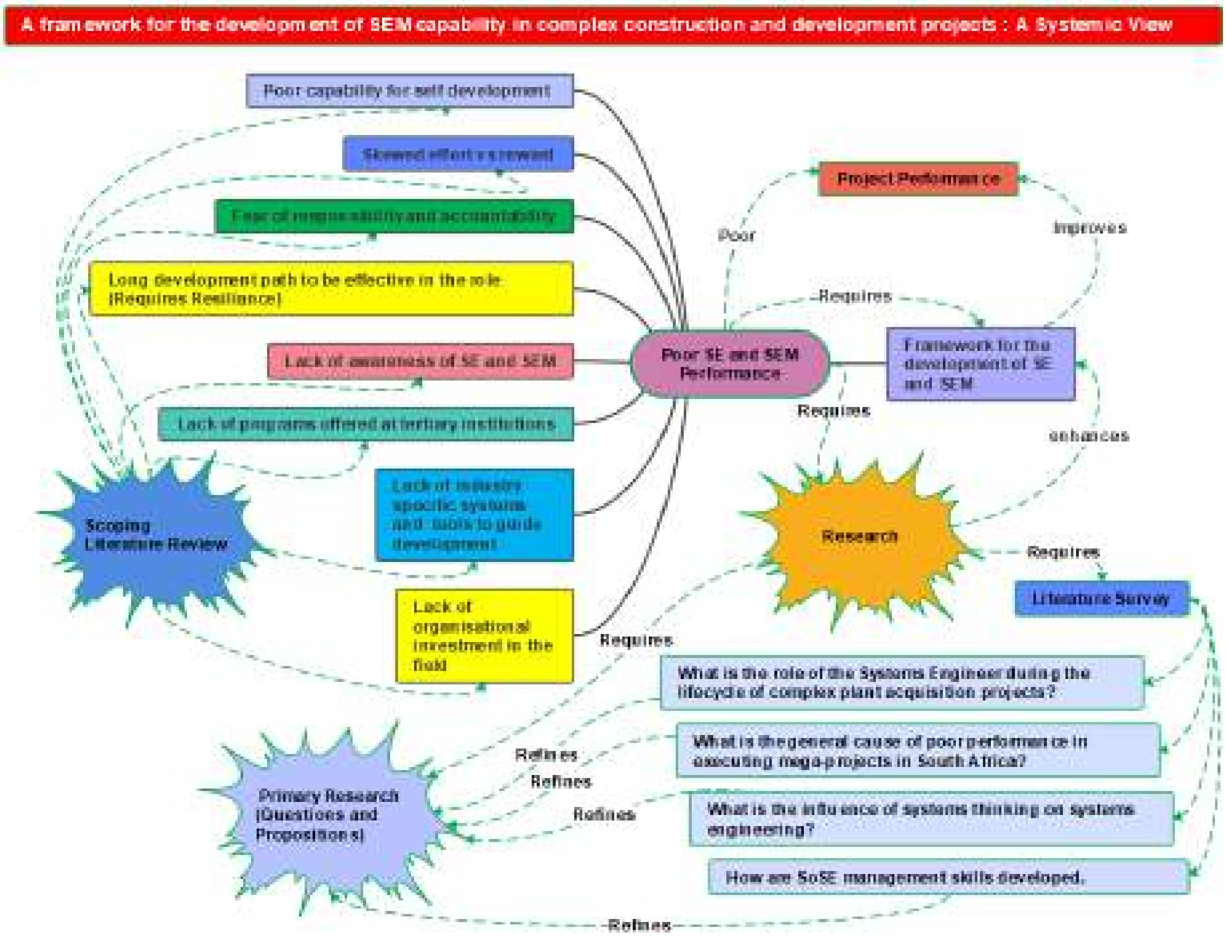

Figure 1: Mind Mapp of Research Method

3 LITERATURE REVIEW

3.1 What is the Influence of Systems Thinking on Systems Engineering?

According to Greene and Papalambros [13], educators and practitioners have acknowledged the value of ST and its positive influence on successfully designing large-scale complex systems. The authors believe it plays a vital role in mitigating several problems resulting from the increasing complexity of large-scale engineered systems [13]. Castelle and Jaradat [14] reinforced this view, citing that the ST paradigm, which supports a holistic approach to evaluating solutions to complex problems, will prevent teams from solving the wrong problems precisely. There is no one-shoe-size-fits-all approach to ST. This implies that a reductionist approach to solving complex engineering problems with a narrow scope field is only beneficial in specific circumstances. Holistic Systems Thinkers must resolve complex multidisciplinary problems requiring a collaborative effort, i.e., ST has a complementary effect on resolving complex SE problems [8, 14].

Frank and Kordova [15] argued that ST is a primary high-order thinking capability that allows individuals to view systems, enhancing success in performing SE tasks. The authors claimed that Systems Engineers must possess skills and experience to apply a “systems view” or display a high system thinking capability to be successful in SE roles. They also raised an interesting view regarding the origins of the ability, i.e., is it natural or developed [15, 16].

Monnat and Gannon [17] used examples of major project failures to highlight how the application of ST in early SE project development processes could have prevented the adverse outcomes. Applying the outward-centric ST in SE enhances the ability to identify external factors such as environmental factors (temperature, wind, rain, sources of resonance), social factors, aesthetics, maintenance, and disposal to ensure that the developed system is technically and commercially successful. Experts the world over expressed the importance and positive influence ST attributes, such as understanding complexity, big-picture thinking (holism), component interfaces and interrelationships, framing a problem (problem structuring), and experiential learning can have on solving problems within complex SE plant acquisition projects [18].

Monnat and Gannon [17] argued that although there is an awareness of the synergistic relationship between ST principals and SE and that applying ST to SE improves engineering outcomes, limited literature is available to guide how to apply ST to SE. Greene and Papalambros [13] indicated that ST in engineering had been understudied due to a limited group of authors contributing to publications in engineering.

Gaps - Several scholars have raised gaps regarding the lack of research in ST associated with SE or frameworks/guidance on how to develop ST within SE. One of the significant challenges is that although scholars universally agree that ST is a critical tool and enabler of performance in the SE field, the application and ST attributes required by Systems Engineers and SEMs are based on the context or area in which it is applied. Little to no literature is associated with developing or applying ST to SE components of complex construction-type projects. Given that some scholars question whether ST can be developed combined with the absence of a framework applicable to this context, it is difficult to screen individuals with the potential to perform effectively in SE, which requires ST capability. Almost no research is available regarding ST and its application and influence on SE over the life cycle of complex plant acquisition projects or SoSE projects.

3.2 What is the Role of the Systems Engineer during the Lifecycle of Complex Plant Acquisition Projects?

According to Chan [19], the Systems Engineer is the individual within the project team who a) evaluates the solution to problems considering a broad range of relevant scenarios, b) delivers a well-balanced technical solution, and c) manages the integration between technical domain resources and specialists within design, safety, reliability, and constructability to develop the solution to complex SE projects.

Zhu and Mostafavi [20] highlighted the dynamic nature of large complex construction projects comprising a variety of sub-systems, such as design, procurement, contract management and administration, safety management and risk management. Each sub-system performs a specific function; for instance, the design team translates Users' requirements into design drawings and specifications for construction. These sub-systems interface and interact with every other sub-system within the system [20]. Changes in any sub-system generally directly affect others, causing the project to deviate with time. A typical example is a design change that affects the design sub-system but also affects construction, procurement, and risk management sub-systems. Changes in procedures may impact construction. Procurement may need to supply alternative materials and equipment. The project risk register may need to be updated once the design error has been eliminated. However, new risks may materialise, such as schedule impact due to changes in material, equipment, or fabrication requirements. The final configuration of the project may differ significantly from its original concept, highlighting the dynamic nature of complex construction projects [20].

Frank and Kasser [21] highlighted three competencies associated with knowledge and experience critical to a Systems Engineer's success. These include a) an expert level of experience in an engineering discipline, for instance, process, electrical or industrial engineering; b) multidisciplinary and interdisciplinary technical knowledge of other engineering domains relevant to the work environment; c) sufficient work experience as a domain engineer and Systems Engineer on several complex SE projects. SE experience in the industry is role-specific; for instance, the Systems Engineer working in marketing requires different skills than a counterpart working as an integration lead in complex project development roles. The Systems Engineer's role depends on his level and experience within the project structure. For instance, an apprentice can execute tasks under the supervision of experienced Systems Engineers. The highest level of performance and rare skill is the ability to analyse a situation, define the problem, develop a solution, and plan the implementation of the solution [21]. Such individuals will typically perform lead roles within the project structure.

Multidisciplinary knowledge does not imply a broad range of awareness or knowing a little about a lot. Although the level of multidisciplinary knowledge required by Systems Engineers need not be at a specialist level, a significantly high level of understanding is required to effectively manage interfaces and integration between specialists from supporting domains [22].

Gaps - Who is the Systems Engineer in large complex plant or SoSE projects in South Africa? Such facilities are generally dominated by mechanical, civil, and structural hardware. Does an electrical or electronic engineering background provide the appropriate experience for performing the SE role in such projects, given that most of the costs flow during the execution phase? A typical example of such a facility is a Petrochemical Plant or Power Plant. The technical team on such projects will generally consist of engineering representation from almost all engineering domains, for instance, civil and structural, process, instruments, and controls, electrical, mechanical, metallurgical and fabrication specialists. Systems in such facilities will typically consist of utility supply systems, feedstock and raw materials handling systems, energy supply systems, control systems, production systems and inventory management systems. Although control rooms, electrical sub-stations and additional electrical and control artefacts can form a significant portion of the overall scope in a new plant when required, the electrical and control scope in a process plant-type facility is generally dwarfed by mechanical, civil, and structural artefacts. An electrical or control engineer's background may not provide the broad exposure required to effectively perform the systems integration role in projects by applying the whole lifecycle approach accustomed to SE.

Zhu and Mostafavi [20] highlighted an example of a late design change that affects the design sub-system but also affects construction, procurement, and risk management sub-systems. Additional examples include delayed equipment orders and technology or material substitution decisions that follow because of schedule risk mitigation. Such changes generally impact an array of interfaces, including metallurgy, the design team (modelling, mechanical and piping, process, controls, civil and structural), fabrication, procurement, construction management, risk management and planning. Identifying the impact of change early is essential for effective change management, a critical skill in a complex, large project environment. Do control and electrical engineers have the necessary experience or exposure to identify and manage all interfaces impacted by such decisions? Computer engineers do not apply to this context, nor does an industrial engineer. The main components of the Electrical, Electronic and Computer Engineering programs offered at the University of Pretoria are indicated in Table 1 to reinforce this view.

The experience of process engineers in applying the whole life cycle approach to design in the context of this study is also questionable. On the other hand, the mechanical engineering degree is offered from a generalist perspective covering electrical, electronics, fluids, thermodynamics, heat and mass transfer, metallurgy, vibrations (dynamics), mechatronics, hydraulics, the strength of materials as well as the design of physical artefacts as core elements [23]. Given that the mechanical and piping role on complex plant development type projects overlaps the broadest range of domains, are high-potential mechanical engineers in a more favourable position to develop into and perform the role of the SE and SEM effectively?

Table 1: Core elements of Electrical, Electronic and Computer Engineering at the University of Pretoria (University of Pretoria, 2023)

ELECTRICAL ENGINEERING	ELECTRONIC ENGINEERING	COMPUTER ENGINEERING
Linear signals and systems	Circuit theory	Circuit theory
Digital systems and microprocessors	Linear signals and systems	Linear signals and systems
Power system components and analysis	Microprocessors	Microprocessors
Energy systems and optimisation	Communication systems	Computer networks
High voltage protection	Electromagnetics	Computer architecture and systems
Electrical machines	DSP programming	Software engineering
Power electronics and electrical drives	Advanced electronics	Intelligent systems
Control systems and automation	Control systems	Network security

Furthermore, as highlighted by scholars, NASA and the Systems Engineering Handbook (INCOSE), the project leadership structures refer to Systems Engineers and SEMs as technical track leads. There is no reference to the general Engineering Manager or Engineering Management role in SE project structures based on international reference material. The NASA Framework in Figure 2 illustrates this view. Since complex plant construction projects, such as a petrochemical plant, are defined as complex SoSE projects, it stands to reason that Systems Engineers and SEMs should lead the technical track leadership structures. Industries need to start applying the correct terminology in the project delivery environment to avoid contaminating such structures with inadequate experience in project leadership roles.

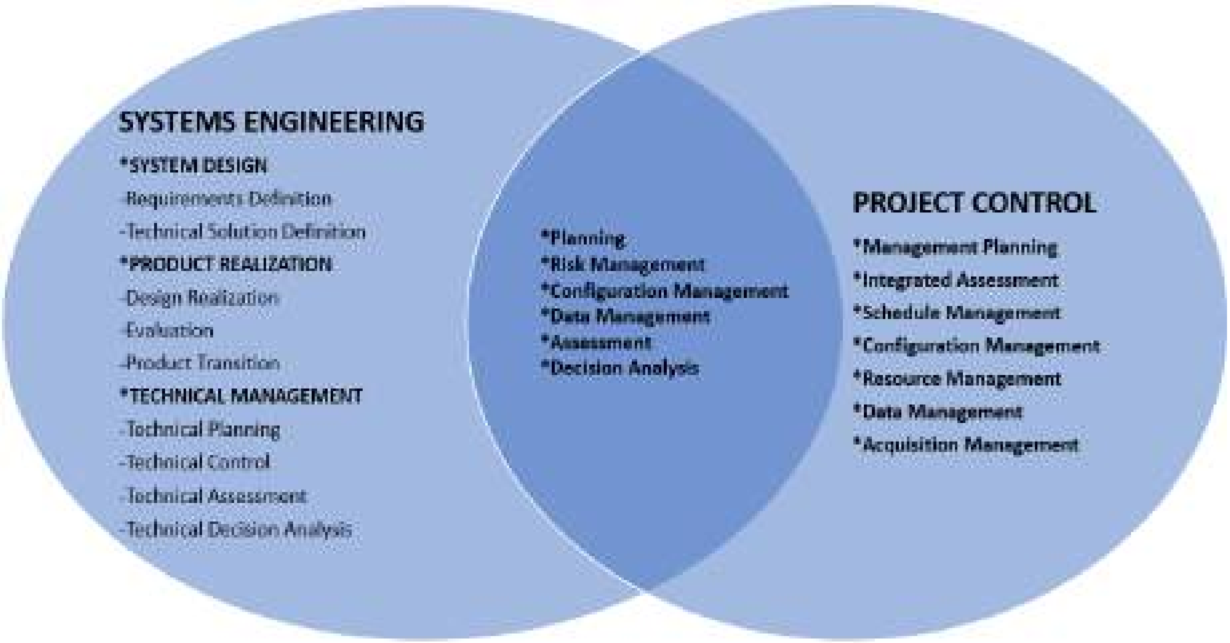

Figure 2: Interface between Systems Engineering and Project Management adapted from NASA [24]

3.3 How are Systems Engineering and Systems Engineering Management Traits and Skills Developed to Improve Systems of Systems Engineering Project Success?

Given the criticality of the SE role, the screening process for the shortlisting of candidates for SE roles should be stringent and reliable to ensure that only applicants who are likely to succeed are accepted. One of the critical traits to enhance success in SE positions is a keen interest and strong will to be a Systems Engineer [25]. Placing the wrong candidates in Systems Engineering positions can be an expensive error, given the cost of development and errors on Systems Engineering projects [21].

Gaps – Frameworks developed by scholars, communities and organisations are currently developed from a general or specific industry perspective. For instance, the NASA framework may contain overlapping content but will certainly not cover all elements or competencies applicable to complex SoS plant-type projects. None of the literature or frameworks provides guidelines on how these skills can be developed or applied as part of a competency development program. An example is the INCOSE framework, which prescribes skills and competencies applicable to SE [26]. Although INCOSE does well to isolate the core competencies applicable to SE, it does not provide a criticality ranking for these skills, which might benefit large industries undertaking large-scale acquisition projects. A criticality ranking will aid in guiding the development of the SE from a risk perspective since a SE possessing 50% of the skills that are less critical to the application context may still represent a high risk to the project.

Also, since SE and SEM competencies are context-dependent, and extant literature suggests that a Systems Engineer and SEM should be an expert in a field and have an overarching knowledge of all other domain engineering fields applicable to his application context, one would feel naturally inclined to question INCOSE's prescribed list of core skills. Why are technical skills not included in the list of core skills? The latest INCOSE framework excludes domain-specific skills since this is industry-specific but introduces other challenges. Since domain-specific skills are critical to Systems Engineers performing roles in complex plant integration projects, industries lacking screening tools or frameworks are often guilty of applying poor selection processes for systems engineering roles [26].

3.4 What is the General Cause of Poor Performance in Executing Megaprojects in South Africa?

According to Tshidavhu and Khatleli [10], surveys with quantity surveyors, engineers and project managers who participated in Megaprojects in South Africa, including Medupi and Kusile, revealed that poor planning and slow decision-making, inaccurate estimation, increased material costs and late contract awards were the primary causes of cost and schedule overruns in Megaprojects. The authors also underlined typical factors resulting in the poor performance of construction projects of varying scales, including design changes, late approval of design drawings, design errors, late scope change (on-site) and poor management capabilities during design and construction [10]. Planning, decision management, procurement and contract management, risk management, concurrent engineering, design integration, and interface management are all roles and responsibilities of systems engineers and SEMs [27]. Failings in these areas, as was the case in both the Medupi and Kusile projects, are indications of poor SE and SEM performance on these projects.

Ika [28] states that applying a one-size-fits-all approach to the execution of projects in Africa is an underlying cause of poor performance. Although several issues were highlighted in various categories associated with the execution of the Medupi project, items of relevance captured under management and organisational problems were poor consideration of water availability (water scarcity), health implications for nearby communities and challenges with local services and capabilities within the project design phase [28]. This indicates a failure to apply the ST paradigm, which supports a holistic approach to evaluating solutions to complex problems during the project's design phase [14].

According to Rafey and Sovacool [29], Medupi, which was Eskom's biggest single investment in 60 years, intended to supply 10% of SA's electricity demand, generates more emissions than 63 of the lowest-emitting countries combined [29]. Kusile and Medupi will be operated at reduced load factors from 2026 [9]. Once again, this indicates failures to apply holistic thinking traits conducive to ST and the life cycle design approach conducive to SE. Reduction in the load factor on account of environmental emission constraints indicates a failure to account for environmental compliance regulations (environmental engineering) during the design phase. This also highlights failings in cross-functional interface management, which is a responsibility of the SEM. Nkambule and Blignaut [30] applied a system dynamics approach to measure and quantify coal-fuel cycle challenges and externality costs over the lifecycle of the Kusile Plant. The model indicated that consideration for external factors over the facility's life cycle resulted in price escalation per unit of electricity produced between 200-400% [30]. This again highlights the benefit of applying the life cycle approach to engineering conducive to SE and the ST paradigm (holistic thinking). ST, SE, and SEM capabilities appear to be gaps within large, complex SoSE project structures.

4 CONCEPTUAL FRAMEWORK

4.1 Introduction

Gaps in the development of ST, SE, and SEM highlighted the importance of awareness of SE and related fields, its link to performance, and a need for an industry-specific framework to guide the development of SEM capabilities within the industry context. As mentioned, competency frameworks exist in a generic form to be customised to their application context. A popular framework is the INCOSE Framework, developed for general industrial applications [26]. Naturally, domain engineering skills (technical competencies) applicable to different industries are excluded from this framework. This intentionally allows industries to include skills directly applicable to their sector. The framework proposed in Table 2 is a customisation of the generic INCOSE framework used as a base to develop an industry-specific framework for system engineering management.

Although the framework was developed for SE, it is also relevant to the field of SEM, which is the most advanced role in the SE career ladder. The approach is to identify critical competencies that can be considered a risk, i.e., competencies that cannot be generically developed. These critical competencies should be used to screen applicants who are most likely to be successful in the SE field applicable to the industry context. This ensures a strong pool of candidates with the capabilities to develop the characteristics required to progress into SEM roles successfully. The 2nd area of interest is the critical competencies required to be successful as an SEM in this sector.

To develop a suitable framework, the research questions were designed to identify the competencies critical to performing SE and SEM roles in the environment relevant to the context of this research. The research questions are listed below:

- What is the impact of SEM on success or performance in large complex SoSE projects?
- Who performs the role of the SEM throughout the lifecycle of large complex SoSE projects in South Africa?
- What are the core competencies required to be effective as an SEM in large complex SoSE infrastructure projects?
- How should the framework be applied to improve SEM performance in large complex SoSE infrastructure projects?

Table 2: Proposed System Engineering and System Engineering Management Competencies

Core Competencies	Professional Competencies	Management Competencies	Technical Competencies	Integrating Competencies	Domain Engineering Competencies
Systems Thinking	Ethics and Professionalism	Planning	Requirements Definition	Project Management	Mechanical Engineering
Lifecycles	Technical Leadership	Monitoring and Control	System Architecting	Finance	Civil Engineering
Capacity Engineering	Negotiation	Decision Management	Design for:	Logistics	Structural Engineering
General Engineering	Team Dynamics	Concurrent Engineering	Integration	Quality	Control Engineering
Critical Thinking	Communication	Business and Enterprise Integration	Interfaces		Electrical Engineering
Systems Modelling and Analysis	Emotional Intelligence	Acquisition and Supply	Verification		Process Engineering
	Coaching and Mentoring	Information Management	Validation		Environmental Engineering
	Facilitation	Configuration Management	Transition		Geotechnical Engineering
		Risk and Opportunity Management	Operation and Support		Metallurgy and Welding

Open-ended search questions based on research questions were designed to allow a rich data pool to be gathered through secondary research. The secondary data was used as a basis to develop the preliminary framework for the industry context, illustrated in Table 2. Research propositions derived from the literature review and aligned with the content of the proposed framework will be tested through primary research. The propositions are outlined in the following sections.

4.2 Effective Screening for Systems Engineering Roles

SE roles in complex SoS construction projects are among the most demanding in the SE field. Progression to the roles of senior Systems Engineer and SEM requires high intelligence, resilience, and strength of character to shoulder the overall responsibility and accountability that comes with such positions. Not every individual can be effective in this role. For instance, domain engineers from projects and maintenance may not be interchangeable. SE errors in the construction industry represent a significant short- and long-term cost risk due to poor plant performance or being beaten to the market by competitors because of schedule delays. This leads to research proposition P1:

P1: Stringent competency screening tools for Systems Engineering roles will assist in improving Systems Engineering and System Engineering Management performance.

4.3 Core Skills of Systems Engineers for Complex Plant Integration Projects

Some skills are more important than others in Systems Engineering roles, considering that very few, if any, individuals will be allowed to acquire all the competencies before performing the role or within his/her career. An example would be interpersonal skills or people skills. An individual scoring high on people skills and low on technical skills will not necessarily be capable of developing the technical skills. This leads to the second proposition:

P2: Some skills are more important than others to enable effective performance in Systems Engineering roles.

4.4 The Long Road to Success

To gain skills to perform at higher levels within the project hierarchy requires patience and a desire to remain in the field for a long time. This is because of the broad range of competencies required to be effective in these roles. It also requires exposure to the right environments to develop the range of knowledge required to be effective at interface management and integration. Although a career in SE may not be ideal for those pursuing instant gratification, organisations need to be wary of talent and implement effective reward strategies to retain System Engineers. Systems Engineers are specialists with context-specific skills requiring a long turnaround time to replace lost capability. In some instances, lost capability cannot be replaced. This leads to the following propositions:

P3: Context specific experience is directly linked to effective performance in SEM roles.

P4: Broad-based technical domain knowledge is directly linked to effective performance in SEM roles.

P5: Individual capability and prior experience impact knowledge adoption rate and performance in SE/SEM roles.

4.5 Framework

The research propositions and framework proposed in this chapter will be tested through primary research and used to develop a suitable framework for the industry context. The conceptual framework of this process is depicted in Figure 3.1 that follows:

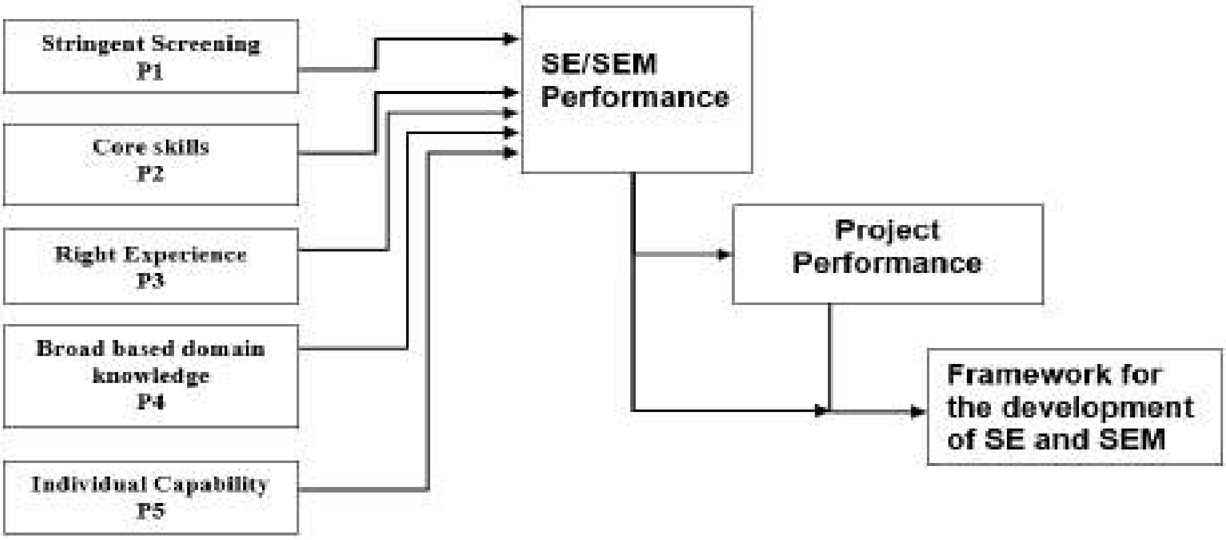

Figure 3: Conceptual Framework for Research

The framework illustrates that the proposed research propositions that positively impact SE/SEM and, ultimately, project performance will be used to test the relevance of the proposed framework. The relevance of the research propositions will be validated based on the data analysis outcomes from primary research, i.e., the primary research is used to validate the outcomes of secondary research. The themes and line of questions used to develop interview questionnaires will be designed to test the relevance of the propositions.

The research propositions proposed are not exhaustive, i.e., research propositions will be modified based on new findings that emerge from inductive research methods. Findings will also be used to update the research questions, where applicable. The final SE/SE management development framework proposed in this research assignment is an outcome of an iterative process.

The Causal Loop Diagram in Figure 4 summarises the literature review to illustrate how an industry-specific framework for developing SE and SEM will benefit the project and organisational performance. The framework will guide the development of competencies necessary to improve SEM, which improves inter-disciplinary, multidisciplinary, and cross-functional interface integration in projects. An improvement in SEM improves the quality of requirements engineering, ensuring that aspects such as geographic and environmental requirements, Legislation, Codes and Standards, Owners' Specifications, Operations, Maintenance requirements, and gaps or project-specific requirements are accurately defined. A key element to improve the chances of success in complex projects is to manage the domino effect of change, from the onset. This starts with a quality framing agreement and design basis, where requirements are formally captured and agreed with the client. This results in higher quality scopes, reducing scope change. Concurrently, this improves project management support quality, risk management and planning, ensuring effective contracting strategies and information management.

Effective contract management and information transfer during design development improve the quality of concurrent engineering, i.e., the interfaces and information flow between teams responsible for developing independently procured systems and the integrated design package (SoS). Typical systems include mechanical, electrical, and electronic equipment and appurtenances. Information delays or late changes within these systems, such as technology changes, have a knock-on effect on the integrated systems, impacting equipment layout, support requirements, system configurations and interface loads.

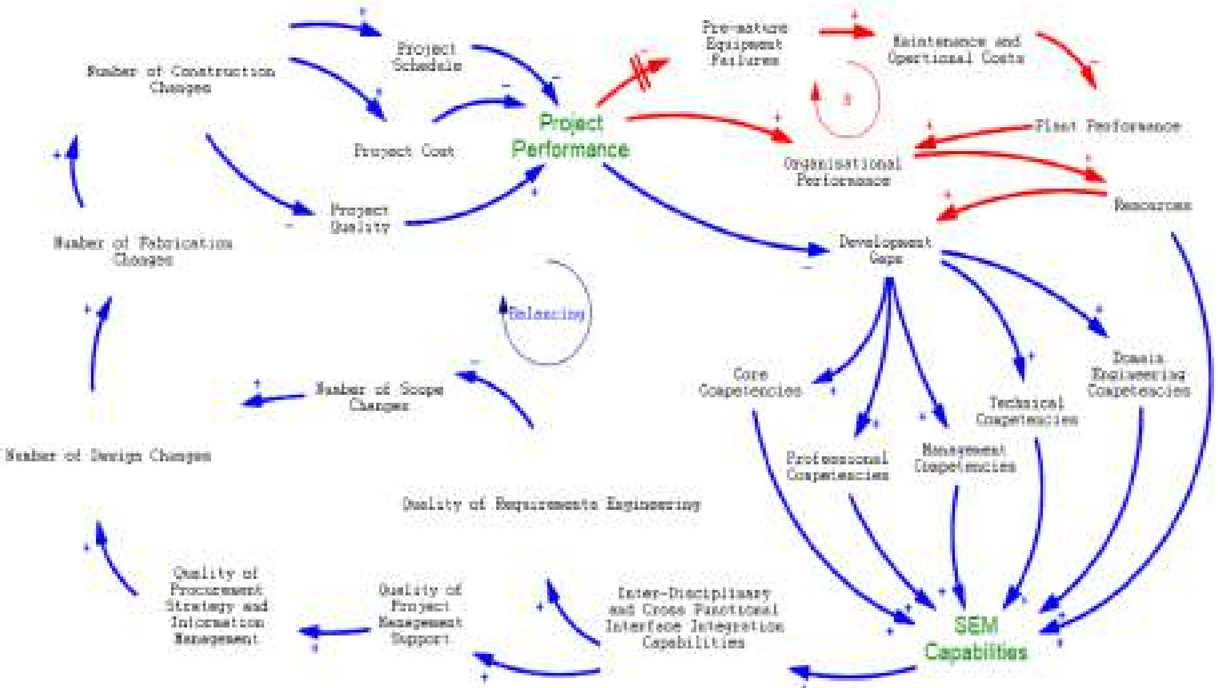

Figure 4: Causal Loop Diagram illustrating the benefits of applying a Development Framework for Systems Engineering Management within the Industry

A change in technology requiring a configuration change will often have a knock-on effect on other technologies due to changes in hydraulic and pneumatic requirements that impact the sizing of pumps, compressors, and blowers within the system. This may impact energy demand due to changes in motor sizing. This domino effect impacts various elements of discipline engineering (inter-disciplinary), other disciplines (multidisciplinary) and functions such as cost control, planning and contract management, to name a few. Ultimately, an improvement in requirements engineering and framing resulting in higher quality scope definition combined with improved planning and risk management improve procurement management and information transfer, improving design quality and schedule.

This reduces the change associated with the fabrication of independent systems and integration of the independent systems into the SoS during construction. Typical fabrication and construction changes include equipment modifications and site clashes resulting in changes in configuration and requalification of quality assurance and quality control procedures. A consequence of effective interface integration during project development resulting from an improvement of SEM is an improvement in the overall project performance (cost, schedule, and quality). This improves organisational performance in the short term through direct project costs and long-term through a higher performance of the facilities (higher reliability, lower maintenance, and operational costs), improving cash flow, thus reducing the payback period.

The organisation will have financial resources to attract and retain a strong talent pool, provide resources, and fund a regular pool of projects to support the continuous development and sustain a high level of systems engineering performance within the organisation. The absence of a practical development framework has the opposite effect, with all loops forming negative reinforcing loops, causing a downward spiral within the organisational performance. This is directly through cost, schedule creep as well as poor quality of the project. The consequential effect is an immediate negative impact on organisational performance and a long-term effect resulting from the poor performance of the facility (regular breakdowns, higher emissions, lower efficiencies resulting in high energy costs and low production rates). Payback time increases, constraining financial resources that can be allocated to talent retention and the development of new talent. A framework is also essential to act as a screening tool to support recruitment by identifying candidates best suited to succeed in systems engineering roles within the hierarchy.

5 CONCLUSION

This research aims to identify the critical components of ST and SE that influence the development of SEM capabilities to effectively lead large complex SoS projects. The research will be extended to Project Management, Engineering Management and Construction Management fields to analyse performance and identify gaps in Systems Engineering Management capabilities. Findings will be used to develop a framework to support the development of SE and SEM within Organizations responsible for the execution of large, complex infrastructure projects. The emphasis is on improving the capabilities of individuals occupying technical leadership roles, such as Project Engineering Manager within the project work breakdown structure. Findings can also be applied by tertiary institutions looking to design or improve courses intended to enhance competency development for the sector.

Testing and validating the framework will be done through structured interviews. The interview sample will include individuals from various sectors, including client organisations within the mining, energy, and petrochemical sectors and individuals from consultancies providing project services to client organisations. A pool of candidates from the Aerospace and Defense industry can also be considered to provide a basis for comparing the SE tools, systems and approaches applied between the industries. Experienced SE and SEM managers will be considered. Inductive and deductive analysis methods will be used to analyse data collected. The approach should manage bias through triangulation of data sources, analysis methods and sites.

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IMPLEMENTING SYSTEM THINKING TO MODEL PAIN MANAGEMENT IN BURN INJURY PATIENTS

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ABSTRACT

Over 1.5 million burn injuries occur in Sub-Saharan Africa each year. Severe burns are one of the most devastating forms of trauma. The management of major burn injuries is complex. Modern burns care has become well-orchestrated with goal-directed actions, including resuscitation, infection control, critical care, wound care, pain management, nutrition support, and psychosocial and physical rehabilitation. Burns pain experience is a complex combination of distress, anxiety, delirium, and situational and emotional factors. Effective pain management is central to optimising outcomes during recovery from burn injuries. Pain management guidelines are published by international bodies regulating burns care. In this paper, systems thinking provides a systemic approach to analysing the complex pain management factors impacting burn injury patients' recovery. This research will implement a conceptual Causal Loop Diagram as an input to a System Dynamics model to simulate the impact of various systemic solutions to pain management.

Keywords: pain, burns care, management, systems thinking

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1 INTRODUCTION

Severe burns are one of the most devastating forms of trauma [1]. Studies in 2018 indicated that 1.6 million people in South Africa annually suffer burn injuries, and as many as 3 200 patients require specialised burn care [2]. Cloake et al. [3] state that in South Africa, burns are a significant and urgent public health problem responsible for issues relating to short-term morbidities such as infection and long-term physical and psychosocial disability. Burn injuries are painful, regardless of size and actual or potential tissue damage [4]. The International Association for the Study of Pain (IASP) defines pain as an unpleasant emotional and sensory experience associated with, or resembling that associated, actual or potential tissue damage [5]. Therefore, burn injury pain is a complex combination of distress, anxiety, delirium, and emotional and situational factors [4].

The effective monitoring, management, and treatment of burn injury pain are essential to optimise patient outcomes [4]. The effective clinical management of burn injury pain is underlined by complex pathophysiological mechanisms contributing to the difficulty in pain management [6]. Poorly managed pain can lead to harmful consequences such as prolonged recovery, chronic pain and post-traumatic stress syndrome (PTSD) [7]. Comprehensive protocols can be helpful in pain management [4].

Burn injury pain management guidelines are published by international bodies regulating burns care. The International Society for Burn Injuries (ISBI) released recommendations for burn pain care in 2018. More recently, the American Burn Association published guidelines on pain [8]. The ISBI Guidelines state that each patient should be evaluated individually. Developing detailed unit-specific protocols will reduce complications associated with using multiple agents, optimise patient outcomes, and likely lead to optimal results [4]. A holistic approach and protocols utilising multimodal pharmacological and adjunctive non-pharmacological treatment can optimise burn pain management. However, many barriers exist to improving protocols, like provider bias and inadequate education [9].

Since pain is a complex problem, systems thinking may provide a perspective, language and a set of tools to understand the influences of the various pain factors on patient outcomes and each other. The concept of systems thinking emerged around 1960 as an alternative to linear thinking to understand the dynamic behaviour of complex systems and develop comprehensive solutions [10]. Bertalanffy [11] presented a general system theory with universal applicability across multiple disciplines. Barry Richmond defined systems thinking as the art and science of understanding the underlying structure of systems to make inferences about their behaviour [12]. Senge [13] also described it as a framework for analysing interrelationships between system elements to see the whole better. Today, systems thinking is applied to various fields and disciplines, such as social sciences, engineering, business and management, computer science and medicine, to solve complex problems that are not solvable using conventional reductionist thinking [12], [14].

This paper applies systems thinking to analyse and model the main factors influencing pain management in burn injury patients. A thematic review of recent burns management literature identified the factors and their relationships. These were captured in a Systemigram before identifying a suitable system archetype that describes the observed behaviour. The archetype was used as a template to construct a Causal Loop Diagram (CLD) to help interpret and understand the system's dynamic behaviour.

2 METHOD

Systems thinking is a transdisciplinary field with various tools to improve understanding of the behaviour and structure of a complex system. A transdisciplinarity research field integrates domains that transcend traditional boundaries of the health, social and natural sciences [10], [15]. Systems thinking views complex problems as systems comprising interconnected tangible or intangible components with functions within the system boundary to fulfil a purpose [16], [17]. The interactions between system components and the environment form a complex whole that cannot be derived from observing the parts in isolation. These interactions cause feedback between the elements themselves and the environment, resulting in an emergence that may surprise observers [18]–[20].

“Wicked and messy” problems are technical and multifaceted, including cultural, political, infrastructural and regulatory concerns. This requires multiple perspectives to see the big picture and make connections between and among seemingly disparate events and processes to intervene with high-leverage changes to address the problem [17]. Complexity science can be used in burns care study processes at the cellular, physical, and societal levels as complex systems at different levels [21]. Systems thinking as an integral part of healthcare organisational practices provide reflective dialogue for deep insight to shift entrenched mental models [22].

Systems thinking focuses on the whole system to study its structures and behaviours to understand the deep roots of complex behaviour [12], [17]. Stakeholder mental models describe a system’s structure that causes behavioural patterns [14]. Modelling the structure helps reduce complexity to understanding at different levels of abstraction. The cause-effect feedback loops explain the system’s behaviour. Identifying the patterns and interrelationships can help solve complex problems [23]. Mental models are the implicit structures of meanings, assumptions, beliefs, ideas, and values within individuals that act as inner rules of causal relationships. Systems thinking provides a language and system of holistic (integrative) thinking about systems to represent the mental models [18], [24]. Different systems thinking tools help understand and deal with the complexities of business, economics, environmental, political, and social systems [14]. [14], [20], [25]. Common and repeat problem-causing structures in many environments, situations, and organisations help identify a system’s causal storyline or theory [26].

Senge [13] and Wolstenholme [27] define System Archetypes as free-standing and formal views about system structures responsible for generic behaviour patterns that may be counterintuitive. They are the typical patterns of behaviour due to generic systemic structures in combinations of feedback loops in complex dynamic systems [20], [28], [29]. The archetype provides a high-level story or "fingerprint" of the overall system feedback structure [27], [30]–[32]. A standard set of 10 to 12 archetypes exists for complex dynamic systems [13]. Eskinasi and Fokkema [33] found that using System Archetypes to develop small models can be more effective than using large high-fidelity models to develop solutions to complex problems.

As seen in Figure 1, a typical System Archetype comprises intended and unintended consequence feedback loops. An action for an intended consequence in one part of the system may lead to an unintended consequence in another or outside the system. A delay before observing the unintended result or the system boundary may obscure unintended consequences from observers. The solution minimises the side effects in the two-loop, closed-loop system by removing the system boundary obscuring the side effects [30]. Systems thinkers use archetypes to diagnose complex problems by detecting problematic trends, understanding the system's holistic behavioural patterns, and identifying where to intervene [34]. Leverage points are points of power where a small change can result in a significant system effect [35], [36]. Therefore, archetypes can diagnostically describe the existing system structures and behaviour to support decision-making for future actions [37]. Despite being theoretically weak, System Archetypes are still valuable for communicating system insights with a compromise between simplicity and completeness [30].

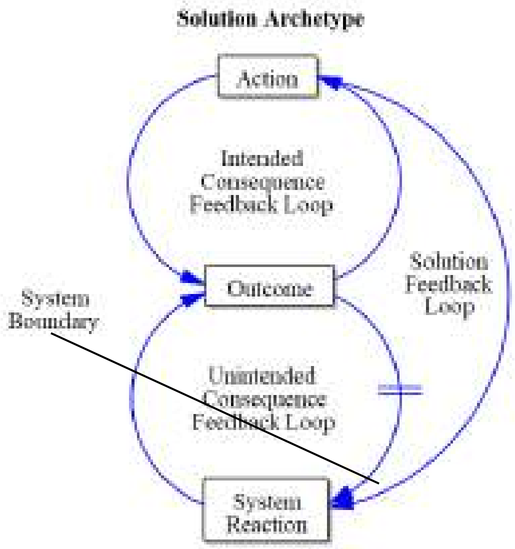

Figure 1: Generic Systems Thinking Archetype

Figure 2 shows a basic systems thinking modelling process that implements System Archetypes [38]. As applied in this paper, the first step is to capture information about the system through a thematic literature survey. Thematic synthesis was used to conduct the literature study [39]. Data were extracted from the available literature regarding burn pain management and analysed. Factors were extracted that influence burns pain management. These factors were combined into themes: pain experience, emotional state, patient satisfaction, patient education, rehabilitation, patient-centred communication, staff knowledge, skill and experience, and dosing.

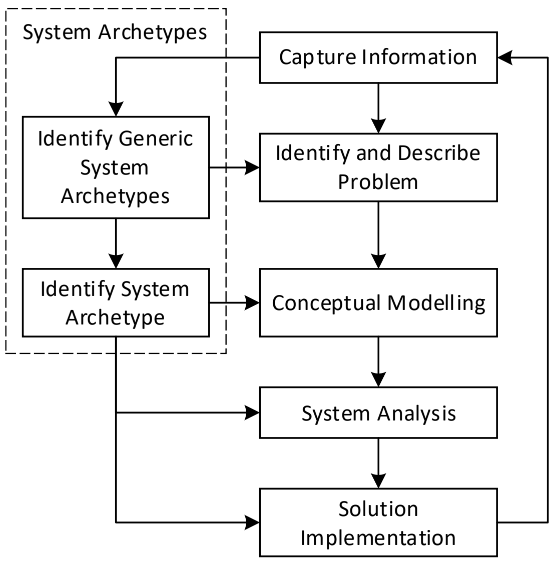

Figure 2: System Thinking Modelling Process using System Archetypes

The retrieved literature is analysed to identify and describe the problem and extract possible issues that cause unwanted or unexpected system behaviour. This paper uses a systemigram as a rich picture to graphically identify the critical variables in the problem situation or system. System Archetypes provide a template or guideline to identify the underlying problematic aspects [30]. Using the identified system archetype, the variables from the systemigram are used to develop a CLD to model the causal relationships and feedback loops. The CLD should include the impact of various interventions with their unintended consequences. The System Archetype helps identify the complex system's variables, interconnectivity, structure, behaviour and possible leverage point(s) to develop a dynamic hypothesis.

3 PAIN

Burn injuries are considered some of the most painful types of injuries. In addition to the pain from the burn injury, its proper treatment is painful and includes wound care, aggressive physiotherapy and surgery. Burns care is multifaceted and changes as healing progresses [8]. The complexity of clinical burn pain management creates a challenging environment in the Burns Care Unit for the multidisciplinary team to manage pain effectively. Pain should be assessed and managed as a collaborative effort, and initiatives that include the Intensive Care Unit interprofessional team can achieve better outcomes [40]. Different themes identified in the literature survey that influence burn pain management are discussed in this section.

3.1 Pain Experience

A burn injury patient's experience of pain is an unpleasant emotional and sensory experience; the experience is complex, and the effects are psychological and physiological [5], [41]. Acute pain occurs immediately after the injury, and the degree of pain is typically related to the depth of penetration of the burn injury into the skin and tissue [6]. The patient's experience of pain is not static. Background, procedural and breakthrough pain exist, and the pain level will vary with care interventions like wound care and rehabilitation [4]. Even when the patient rests, the continuous nociceptive inflammatory process will cause background pain [6].

The patient's pain experience should be assessed during various phases of care and several times daily using pain assessment tools like a patient-self-reported scale. The pain scale should be protocolised and recorded, and staff should ensure consistent language when assessing pain [8]. According to a study by Esfhalan [42], burn patients' pain can be effectively treated and managed with an accurate multidisciplinary pain assessment.

3.2 Emotional State

The burn injury patient's emotional experience and state influence their pain experience and affect pain management. How the patient feels will affect his pain experience. Burn injury pain is a complex combination of anxiety, distress, delirium, and situational and emotional factors [4]. Pain tolerance will be impacted by a patient's mental state [43]. Lang et al. [44] found that anxiety plays a role in the unpleasant emotional response to acute nociception. Post-burn distress must be managed while considering the impact of the emotional factors associated with a burn injury. Neuropathic sensory changes can significantly impact distress, and these changes should be considered and treated as part of burn pain management. Addressing accompanying neuropathic pain can improve burn pain management [4]. Physical damage to the skin of the burn injury patient determines the acute nociceptive response, but it can also contribute to the transition into a chronic pain state [6].

Adverse Childhood Experiences (ACE) play an essential role in the experience of acute pain and the development of chronic pain. Individuals who tend to catastrophise after a burn injury are at risk of acute and chronic PTSD and chronic pain [45]. Burn injury patients with ACE exposure are more at risk for more negative expectations related to pain, greater catastrophising and more significant psychological morbidities [46].

Suffering a burn injury is inherently traumatic, and understanding the patient's trauma history and how it impacts the patient can assist staff in minimising the risk of additional trauma and re-traumatisation [47]. A patient's mental state will impact pain tolerance, anxiety and motivation, and addressing these aspects will facilitate improved treatment [43]. In a study by Duchin et al. [48], multiple patients indicated that their pain experience was more than just physical and reported a greater need for psychological support.

For burn injury patients, the pain may remain an ongoing source of disability long after the recovery period is over [46]. However, long-term psychological issues will be reduced when a burn injury patient’s pain is well-controlled [4]. Burn injury patients’ psycho-affective responses to their background pain include helplessness, anxiety and fatigue [42].

3.3 Patient Satisfaction

It is impossible to eradicate burn injury pain, but when it is safely minimised, patients, families and staff will benefit [4]. Morgan et al. [6] state that given the high incidence of burn injuries and the significant morbidity associated even with minor burns, improved pain management is essential to improve the quality of life of burn injury patients. After healing a burn injury, chronic pain can remain and can have a debilitating effect on the patient’s quality of life. Effective pain management remains a significant challenge.

Stapelberg [49] found that for some patients, the remaining pain memory can be a positive one in which, for example, everyone did their best to help alleviate the pain experienced during dressing changes and after procedures. A study by Keivan et al. [50] demonstrated that religious and spiritual care could help decrease the pain intensity caused by the dressing change and increase the satisfaction of these patients with pain control. The nursing team's continuity in caring for burn injury patients will allow for trusting relationships and bonds to develop. This can improve satisfaction for burn injury patients and staff [43]. The reporting of higher pain scores during hospital admissions can be associated with poorer long-term outcomes and a higher incidence of mental health problems [51].

3.4 Patient Education

Burn injury patients value it when they are included in discussions around their pain management plan [4]. Duchin et al. [48] found that though pain experience can vary, patients are highly interested in improving their understanding of pain and pain-management-related topics. The reported variability in pain experience demonstrated the uniqueness of burn injury pain and its management. Participants highly supported education in pain and a strong desire to understand their pain experiences and care.

Upon admission, severe burn injury survivors often experience pain, anxiety, fear, and uncertainty. Clear, concise information regarding their injury and the treatment plan can reassure the patient and their family. It is essential to communicate the same information consistently throughout the patient’s care [47]. Patients with uncontrolled burn injury pain report it as the worst pain they ever experienced. Studies reported that patients’ satisfaction is closely related to their pain experience and managing that pain [4]. In a study by Duchin et al. [48], patients reported that their pain experience was not just physical and needed pain education, which was most pressing during the inpatient phase of care.

3.5 Rehabilitation

Studies by Dikkema et al. [52] and Lim et al. [53] found that early mobilisation of patients with burn injuries is essential. However, the pain was noted as a barrier to early mobilisation. Patients with uncontrolled burn injury pain have a diminished capacity to participate in rehabilitation [42].

3.6 Nurse-patient Communication

Tetteh et al. [54] found positive results of effective nurse-patient communication to be early detection of a patient’s distress, helping a patient manage pain and improved patient participation in their care. They also found that poor nurse-patient communication results in poorer cooperation during care activities and reduced endurance to pain. Discussions with the patient are essential when setting accurate and individualised goals for an effective pain management plan [4].

3.7 Staff Knowledge, Skill And Experience

Quantitative changes in the patient's pain response to pain management can be observed when pain severity is assessed [44]. The repeated use of pain scoring systems and tools during all phases of burns care enables monitoring the adequacy of pain control. This can ensure optimal pain management. Staff needs to be well-trained to apply pain tools appropriately [4].

A study by Tetteh et al. [54] found that due to the subjective nature of pain, the need for increased communication for a practical assessment and management of pain among patients with burns is highlighted. Therefore, nurses must be well-trained in communication, emphasising patient-centred communication.

Burn centre staff should be trained in burn management [1]. Burn injury patients can receive the best possible acute and long-term care when highly specialised personnel work together in a customised facility with readily available resources [43]. The skill of understanding that burn injuries are inherently traumatic and that the patient's prior trauma and the impact it has on the person can minimise the risk of vicarious traumatisation in staff [47].

3.8 Dosing

The minimum effective dose can be administrated when the measurement of burn pain is accurate. This will facilitate minimising medication-related complications. Under- and overmedication can be avoided when monitoring and adjusting therapy optimises pain control. Practitioners should be aware that all medications have adverse effects and monitor for these effects. Medication choice and route adjustments may be necessary [4].

Despite our increased understanding of the mechanisms involved in the recovery phases, the chronification of burn pain and the effect of pain and suffering on the patient's long-term outcomes, pain management in burn injury patients remains challenging [49].

4 SYSTEMS THINKING MODEL OF PAIN MANAGEMENT

Table 1 presents the systemic analysis of the literature on burns pain management. The matrix cells provide the literature supporting the relationships between the pain management elements. The Systemigram in Figure 3 graphically describes the "story" from the literature study on burns pain management. The nodes in a systemigram are nouns or noun phrases from the themes or factors. Relationships between the factors are represented as arrows, with the verbs and verb phrases from the text description. The principal subject is placed in the top left corner, and the object in the bottom right corner of the Systemigram. A Systemigram helps to identify the system's motivation, management, failure, and remedy. Many people admire a finished Systemigram but fail to appreciate the many failed preceding attempts and failures containing the seeds of eventual success. These defects should not be regarded as problems to be fixed but rather as opportunities to better understand the message of the systemic description. Getting interdependencies correct while adequately portraying the themes can call for a rework of what otherwise looks like the perfect picture [55].

In figure 3, patient-centred communication with a closed-loop feedback structure is essential for patient education. Communication is critical to educating the patients about the protocols and procedures for managing burns pain. Equipping staff with the required knowledge, skills, and experience improves communication and patient education aspects.

Table 1: Pain Management Element Interaction Matrix

Effect / Cause	Pain Experience	Emotional State	Patient Satisfaction	Patient Education	Rehabilitation	Patient-centred communication	Staff Knowledge, Skill & Experience	Dosing
Dosing	[4]		[4]					
Staff Knowledge, Skill & Experience			[1], [4], [43], [47]	[54]		[54]		[4]
Patient-centred communication			[8], [54]	[4], [47]				[54]
Rehabilitation	[4], [7], [52], [53]							
Patient Education						[4], [47]		
Patient Satisfaction		[4]			[51]			
Emotional State	[43], [45]				[42], [43], [46]			
Pain experience			[6], [7], [48]		[7], [43], [52]			[4]

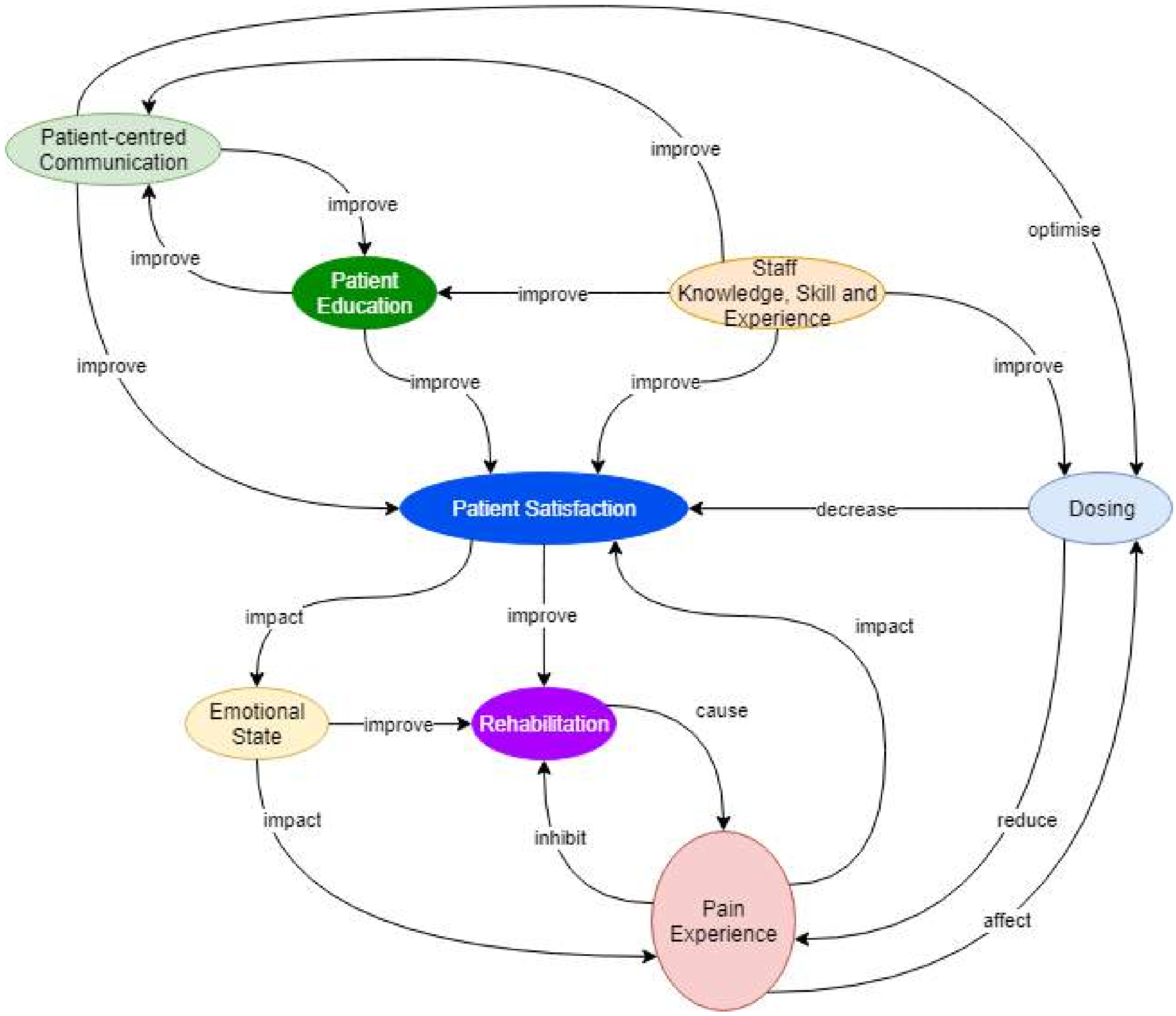

Figure 3: Systemigram for pain management

Patient-centred communication, patient education and staff knowledge, skill and experience factors positively impact patient satisfaction. However, dosing may have some adverse short-term and long-term effects as a method of managing pain with medicine. Improving patient satisfaction also improves the journey of rehabilitation, which in turn may increase the pain patients experience. This increase in pain inhibits the progress of rehabilitation. Another critical element in the system is the emotional state of patients, which can improve rehabilitation and the experience of pain. Even though there seems to be a direct feedback link from the emotional state to patient satisfaction, this is achieved through the improved experience of pain. The negative impact of pain on the emotional state is also realised through patient satisfaction in this Systemigram through the larger feedback loop. The "story" the Systemigram tells can guide the identification of a System Archetype.

The System Archetype chosen for this problem is "Shifting the Burden," which illustrates the tension between implementing a relatively easy solution aimed at the symptoms rather than a fundamental solution that addresses the underlying problematic structures [28]. As seen in Figure 4, implementing long-term solutions demands a deep understanding of the underlying problem and takes time. The symptomatic solution is easier to formulate and solve to produce instant gratification without paying attention to the underlying and fundamental systemic problem. The symptomatic solution reduces the problem symptom and alleviates the need to implement a fundamental solution.

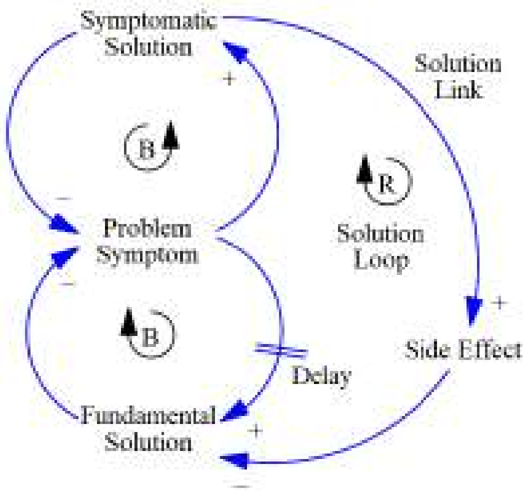

Figure 4: Shifting the Burden

Figure 5 presents the CLD for burns pain management as derived from the systemigram in Figure 3 and based on the "Shifting the Burden" System Archetype from Figure 4. In the context of this paper, the problem symptom is the "Pain Experience" of the burn patient. The symptomatic solution is "Dosing," which is administering medication to control the pain experienced by patients. The fundamental solution is chosen as "Rehabilitation" to enhance the patient's journey to recovery. "Patient Satisfaction" is a side effect as overusing medicine to control pain may have long-term side-effects such as dependency issues.

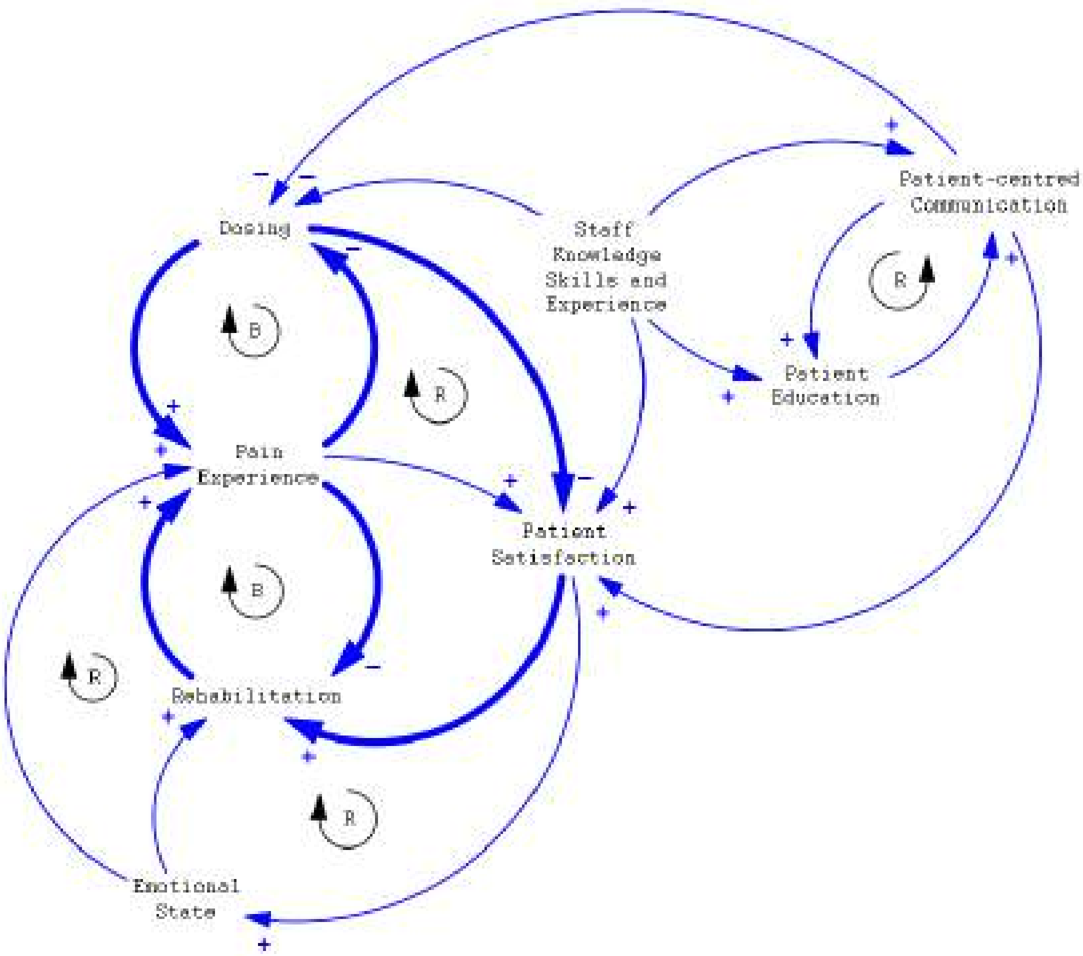

Figure 5: Archetype for Shifting the Burden in Pain Management

Burn injuries are considered some of the most painful types of injuries [8], and managing pain at an acceptable level for these patients is complex. Developing a systems thinking model clarified the relationships between the different and interconnected elements that influence the management of burn injury pain. This model can improve understanding and increase the burn care teams' insight into managing burn injury pain. Improved understanding can lead to improved management and the minimisation of pain. Burn care teams can implement a multimodal approach to pain management utilising this systems thinking model where small interventions can have significant results. It is impossible to eradicate burn injury pain, but when it is safely minimised, patients, families and staff will benefit [4].

5 CONCLUSION

Implementing systems thinking to manage pain experience in burn injury patients involves considering the interconnected elements and dynamics of the system that contribute to their experience of pain. Viewing pain as a system helps understand the interaction of physiological, psychological, and social aspects contributing to pain perception over the burn wound life-cycle of stages, including the acute phase, wound healing, and long-term rehabilitation.

Creating a visual representation or diagram to map the relationships between the different system elements helps identify and interpret the cause-and-effect relationships, dependencies, and interactions. Identifying the feedback loops within the system enables understanding the possible counterintuitive outcomes.

Understanding the dynamic system behaviour may identify leverage points where small interventions can lead to significant changes. These leverage points can be targeted to manage burn injury pain effectively to improve patient experience through targeted medication protocols, enhancing patient education on pain management techniques, or improving communication between healthcare providers and patients.

Recognising the burn pain management system's boundaries must consider the more extensive healthcare system, policies, resources, and cultural factors that impact pain management practices. Engaging all burn pain management stakeholders may encourage collaboration and information sharing to understand the pain experience better and develop comprehensive multimodal pain management strategies.

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MAINTENANCE MODELS – SYSTEMATIC LITERATURE REVIEW 2010-2023

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ABSTRACT

To explore effective maintenance models that have been applied in the industry. Maintenance models were identified from 2010-2023 studies (45) that met inclusion criteria. This was done by applying general Systematic Literature Review and Thematic Analysis Framework. Key relationship between maintenance strategy and company performance have been outlined. Majority of the studies were in the manufacturing and energy sectors. Chinese were the leaders in maintenance model research. Thirty-seven (37%) made use of preventive, prescriptive (13%), maintenance 4.0 (2%) and opportunistic maintenance (7%). Thirty-three (33%) made use of artificial intelligence. Maintenance data analytics based on artificial intelligence promises the maintenance practitioners deeper insights and foresights. Maintenance models in this study lacked success scores hence authors subjectively evaluated the relevant models for power plant setup. Research output in this sector had an upward trend between 2010-2022. These learnings shall be applied in the development of plant maintenance model in the future.

Keywords: Maintenance, Systematic, Model, Techniques, Uptime.

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1 INTRODUCTION

According to EPRI [1] the goal of maintenance is to do the minimum amount of maintenance that guarantees maximum plant reliability. Maintenance function is a sub-system of an industrial organisation, with the function of planning, adjusting, repairing, replacing and modifying the parts of the plant that should be able to perform its specified function over some specified period ([2] and [3]). Maintenance function is therefore one of the discrete building blocks that serve to provide competitive advantage in an organisation. Its management is charged with the responsibility to maintain the plant operational at all times so that the customers' expectations can be exceeded. The top-down relationship between this functional strategy and the organisational goals are depicted in the figure 1 and 2 below.

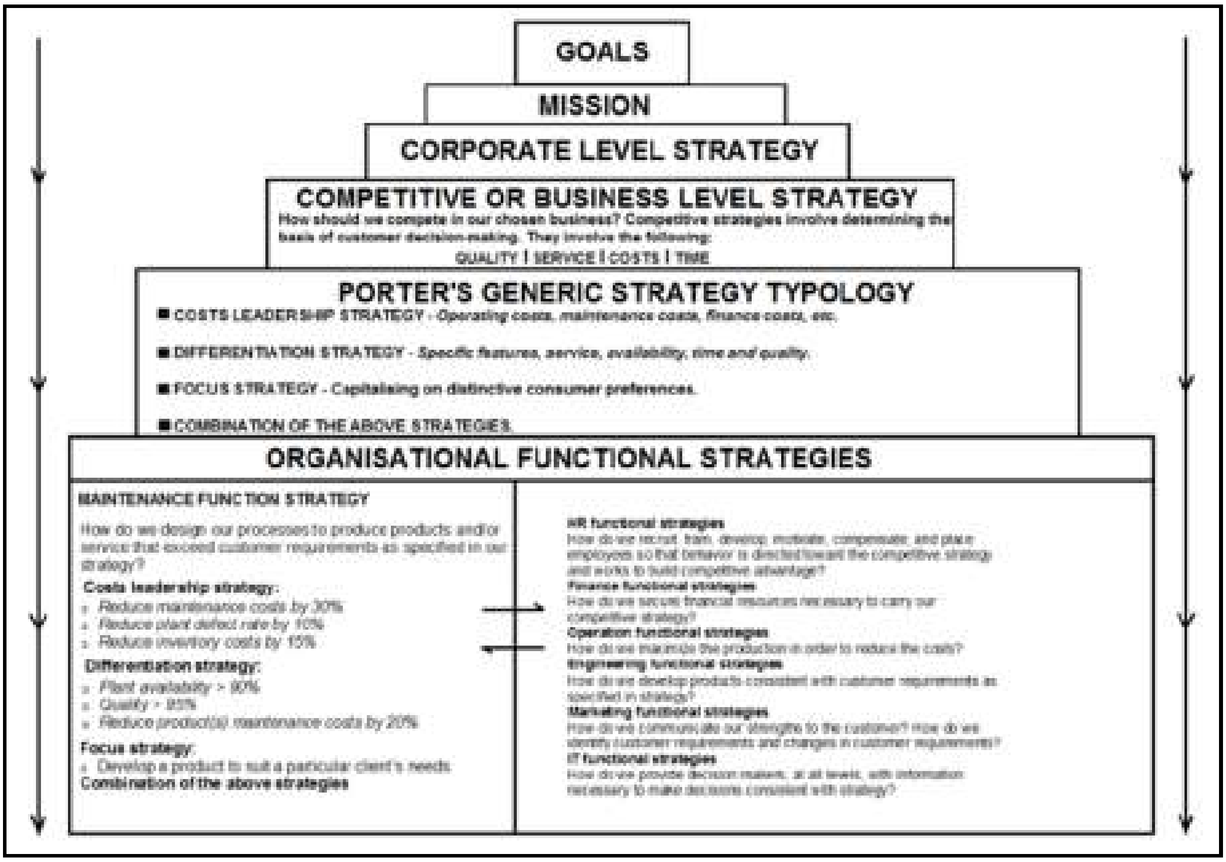

Figure 1: Organizational goals and maintenance functional strategy relationship.

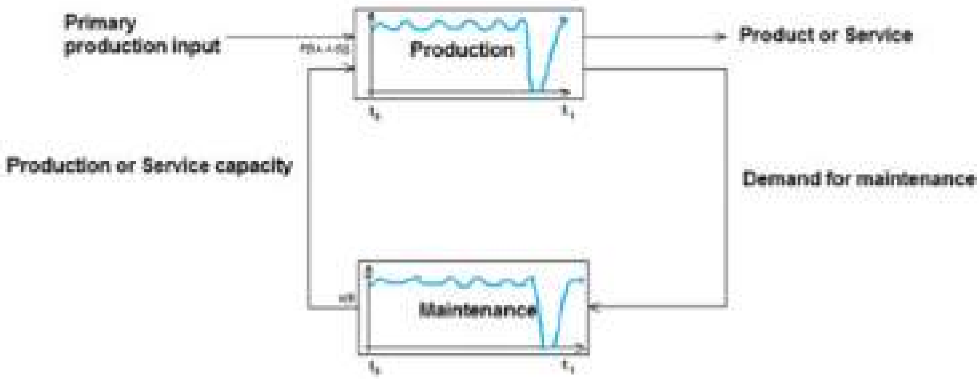

Figure 2: Production-Maintenance relationship. Source: Adapted from Gits [4] and Ben-Daya *et al*. [5].

In this study, systematic literature review (SLR) shall be conducted on the maintenance model studies with the objective to transfer the learnings from the best model to the dust and ash system in a coal-fired power plant in the future.

2 RESEARCH OBJECTIVE

The researcher was tasked to improve the health of the dust and ash plant in a coal-fired power plant and a requirement was identified to explore the other maintenance models in the literature. Maintenance is one of the functions that play a critical role for the best plant uptime (see figure 1). Therefore, the objective of the study is to find attributes that make maintenance model to be successful through systematic literature review by identifying themes that stand-out. The results of this study shall be utilised in building the maintenance model through system dynamics tool in the future.

3 RESEARCH QUESTION

Based on the stated background, systematic research methodology has been adopted to find out the best features that can be adapted in the power plant for an enhanced plant uptime. This study seeks to answer the following question:

- What are the key attributes used in the general maintenance model literature to achieve increased plant uptime?

The study shall characterise the studies by *industry sector, country and continent, maintenance strategies, scientific techniques applied in models, type of publication, impact of the model on plant uptime and research trends*. The results will also be used to conduct benchmarking project within the industry in the future.

4 RESEARCH METHODOLOGY

By using a general internet search in academic websites for pertinent journals, conference papers, theses, and books - systematic literature review (SLR) methodology was applied to find the best attributes in the maintenance models. In order to summarize and evaluate the findings, characterize the attributes of the maintenance models, and emphasize factors that made a model to deliver improved plant uptime, data was then coded and extracted from the included studies. In this work, about 45 maintenance model items were mapped.

A well-defined and repeatable search approach was used during the investigation process, and studies were either included or rejected based on the inclusion criteria.

The benefits and shortfalls of this methodology were known; hence research controls were put in place to remove bias. The ability of this study was to explore several maintenance investigations cases from various socio-cultural contexts and present a holistic view as its main strength. The articles were selected by the author by using key word like “maintenance model”, this could be a source of bias as some of the studies were excluded and others included based on the article contents. In addition to its strength, there were a few limitations to be mindful of. Researchers offered country-specific maintenance sector scenarios, but these were open to their own interpretation and might be subjective [6].

5 SEARCH STRATEGY AND SELECTION PROCEDURE

General internet search through database has been used for assessing and reporting the maintenance modelling research data, to identify special attributes that made a specific model to have a positive impact on plant uptime. The research methodology that was implemented was combination of manual article selection and steps as outlined in figure 1 below. The search google scholar engine made use the following search string: *maintenance model*. Total of 45 articles were identified for the systematic review, the authors made use of probability sampling method where researchers select members of the population at a regular interval to select the final articles to be included in this review, a practical screening was conducted, this was based on the setting of inclusion criteria and flow diagram in figure 3.

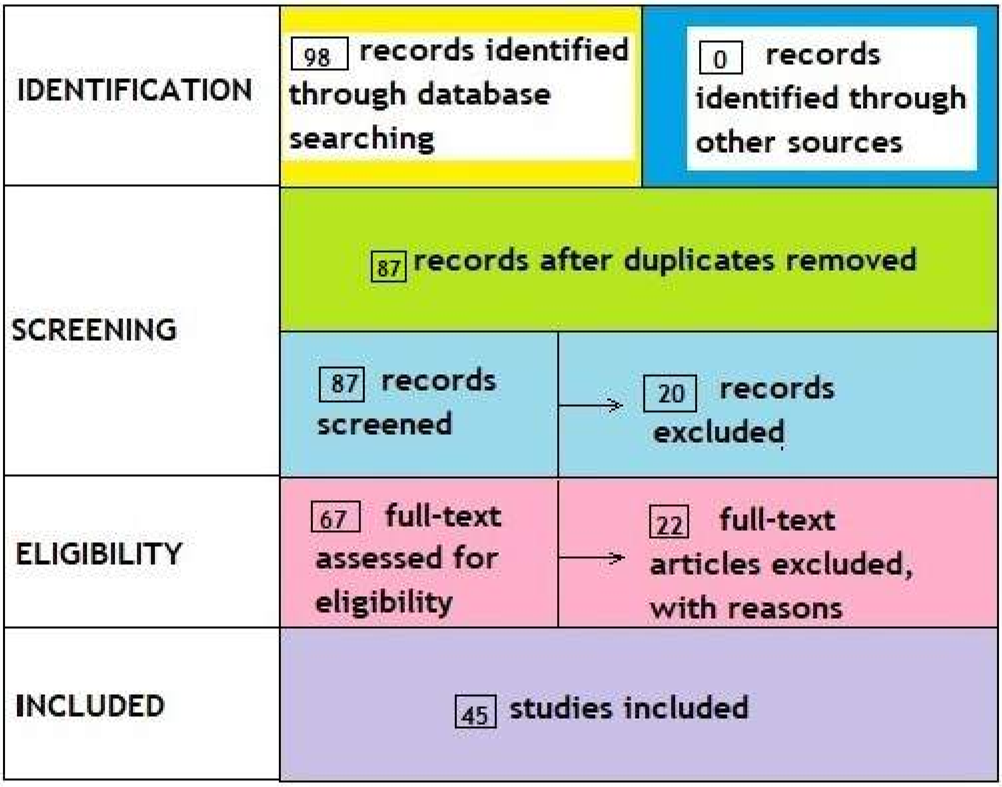

Figure 3: Systematic review flow diagram. Source: Adapted from [7].

6 INCLUSION CRITERIA

The initial search yielded 898 records through general internet search on the 30th April 2023. Sampling was based on: 1st ;10th; 19th ;28th ;37th ;46th ;55th ;64th ;73rd and 82nd web pages as per google scholar search results and each page contained maximum of 10 articles. The 800 records were excluded as a representative sample was obtained. Systematic sampling was provided the author with 98 studies. Figure 3 above provide further details regarding the screening and filtering that was applied as per inclusion/exclusion criteria (Table 1). Only English studies were selected (Table 1). Studies were included if they were published between 2010 and 2023. This included 45 journal articles, books, theses, conference papers and technical reports. This process was followed to assist the peer-reviewers to able to easily establish the replicability of this study for confidence building in the research outcomes [7]. The studies covered maintenance models that could have positive impact on plant uptime project to be conducted in the future.

Table 1: Inclusion criteria

Item	Description
Database searched	Google scholar
Date of search	1st May 2023
Person searching	Sello David Koloane
Database settings	Open to all areas that had researched about maintenance models in the industry

Item	Description
Language	English
Timespan	2010-2023
No. of records obtained	45
Search string	"maintenance model"
Questions	**Review focus**
Population – who?	Maintenance models of the industry in general industry and internationally.
Intervention – what?	Maintenance model that had positive effect on plant uptime. *The objective of these strategy is to eliminate the dust and ash plant unplanned maintenance and increase its uptime*.
Comparator/s – compared to?	Best industry with high uptime locally and internationally.
Outcomes – expected result	Identification of the maintenance model levers that are responsible for high plant uptime.
Setting – where?	In any general industry setup

7 STUDIES SELECTION

The double filtration procedure employed in this inquiry was used to filter the 45 articles that did not meet the inclusion criteria. All of the articles that had complied with the standards were reviewed and coded using qualitative data analysis to identify the relevant themes.

Braun and Clarke [8] posit that '*thematic analysis is a method for identifying, analysing, and reporting patterns (themes) with data*'. The following themes were adopted: *industry sector, country and continent, maintenance strategies, scientific techniques applied in models, type of publication, impact of the model on plant uptime and research trends.* This was the finale of a six-step procedure, as seen in figure 4 below.

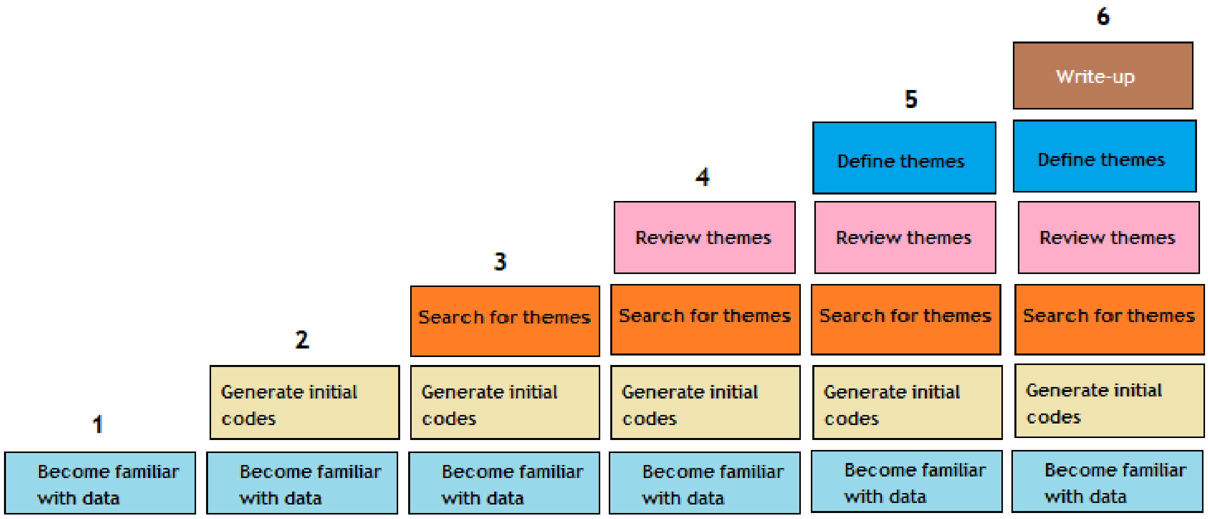

Figure 4: Framework for doing thematic analysis. Source: Adapted from Braun and Clarke [9] and Maguire and Delahunt [10].

The results of the maintenance models thematic analysis have been listed under appendix A ([17]- [59]). This refers to the key attributes used in maintenance systems to achieve excellent plant results in the general engineering industry (RQ). During the application of the research method, it became evident that the studies were not well structured, maintenance systems that were applied to address the plant issues were not the same, for this reason and others, meta-analysis could not be applied as the studies were heterogeneous and did not meet PRISMA guidelines requirements.

8 STUDY CHARACTERISTICS

In an attempt to answer the research question, 45 maintenance articles were initially studied without specific themes of interest. Thereafter, top 6 themes that stood out in the ‘best maintenance model’ were characterised and analysed.

8.1 Industry Sector

The majority of the studies (44%) that were reviewed did not indicate the sector that their maintenance models were based upon (figure 5). This posed a problem for the maintenance practitioners that were seeking for solutions to address their maintenance problems as they did not know if the model was applicable to their respective industry. The industries that were found in the studies include the following (refer to appendix A for details): Energy (16%), Manufacturing (13%), Port (5%), Road network (5%), Transport (4%), Building (4%), Rail (2%), Semiconductor (2%), Aviation (2%), and Defence (2%). These sectors were found to be relevant to the dust and ash system with the coal-fired power plant as the learnings can be adapted. Figure 5 below provide a detailed breakdown of the sectors that were represented in this sample.

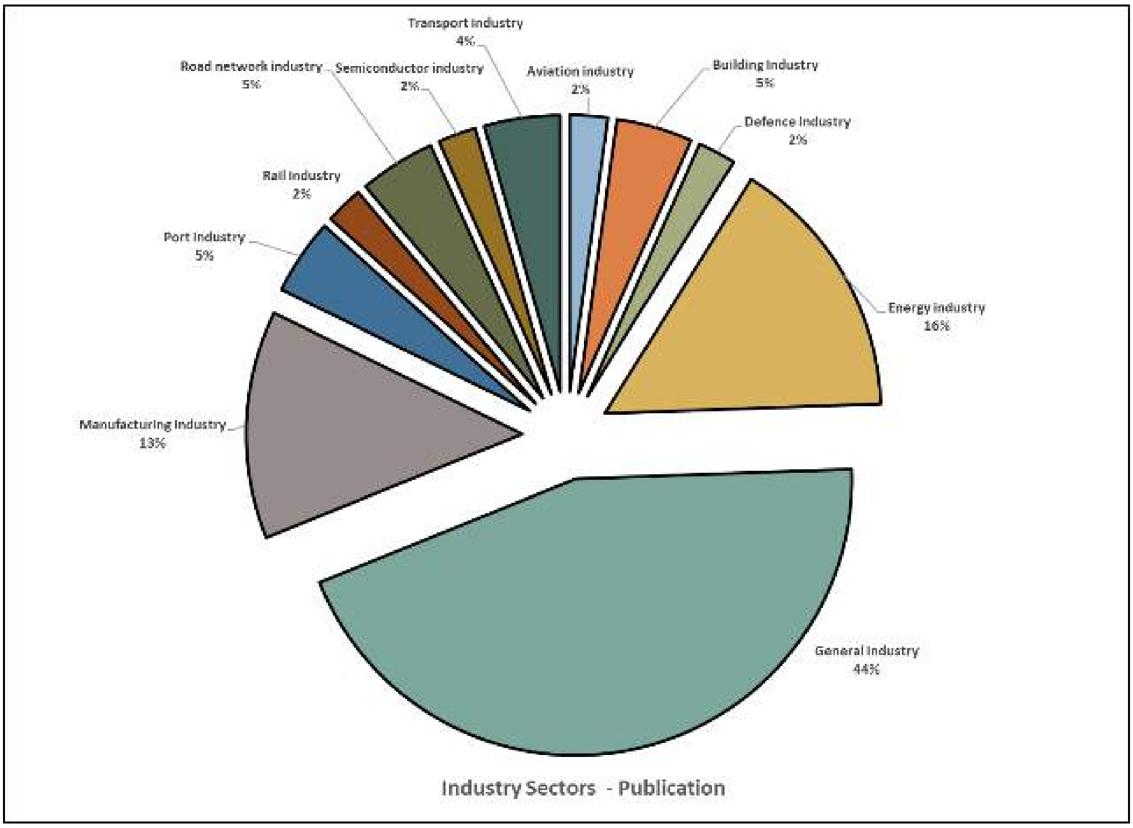

Figure 5: Industry sectors in the studies under review.

8.2 Authorship analysis by Country and Continent

Most of the studies (40%) were based on the research work that was conducted by the Chinese academics. This was followed by the French research studies (7%), the gap between these two nations could perhaps be explained through the population dynamics of these nations. Malaysia had 4% of the studies in the sample. South African researchers contributed 2% of the research work based on this sample and this indicated a need for more local research that can be easily transferred to the industry. Low number of the South African authors in this sample is an indictment as unique South African maintenance problems did not receive the attention of the academia. There is a need to cultivate the academia-industry collaborations so that South African plants maintenance performance can exceed the world class standard if products or services are to continue to be globally competitive. Figure 6 below provide proportions of the countries that were actively seeking solutions for their plant maintenance problems.

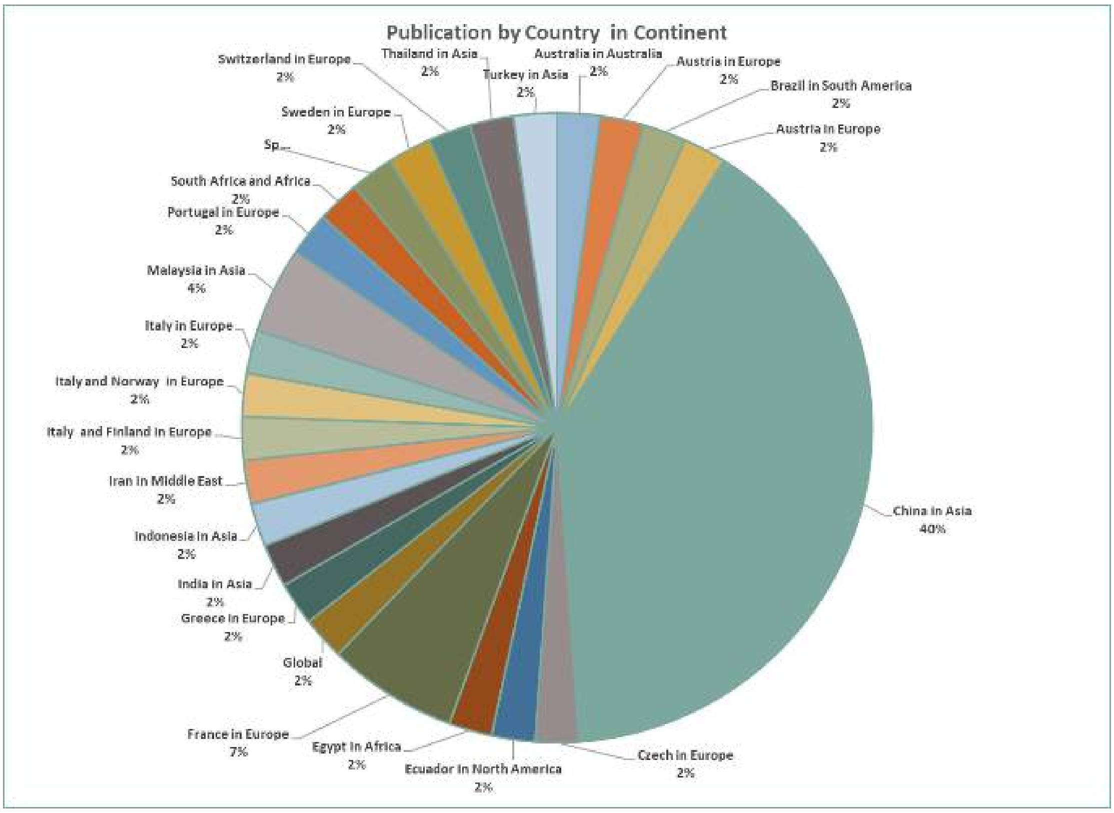

Figure 6: Authorship by country and continent in the studies under review.

8.3 Maintenance Strategies

Najimn, *et al*. [11] defines the maintenance strategy as a decision rule which establishes a sequence of actions to be undertaken with regard to the operation state of the considered system in a plant. According to Nowlan and Heap [12] these include corrective maintenance strategy, preventive maintenance strategy, predictive maintenance strategy and prescriptive maintenance strategy [13]. Figure 1 and 2 has highlighted the dynamic relationship between *Company strategy (CS - x), Maintenance Functional Strategy (MFS - y), Plant Maintenance Strategies (PMS - z) and Company Performance (CP - F)*. Therefore, company performance can be described by the hypothetical model under figure 7.

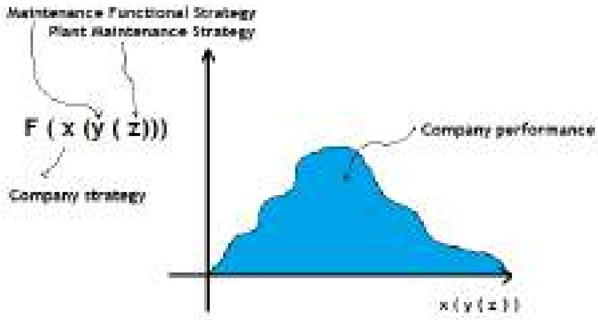

Figure 7: Hypothetical company performance relationship with plant maintenance strategy.

Strategies (z) that were identified in the studies included some of the following: *Age-based and condition-based maintenance, Maintenance 4.0, Opportunistic maintenance, Predictive maintenance, Prescriptive maintenance, Corrective maintenance, Preventive maintenance, Predictive maintenance and Self-maintenance.*

In these studies, most of the articles (37%) had designed their maintenance models to be geared to preventive maintenance for safer and higher performing systems. Prescriptive (5%), Maintenance 4.0 (2%) and opportunistic maintenance (7%) were strategies that were not applied in the dust and ash plant and student will research further on these topics with the objectives to identify possible application in the future. Breakdown of the maintenance strategies that were identified in the studies is shown below under Figure 8.

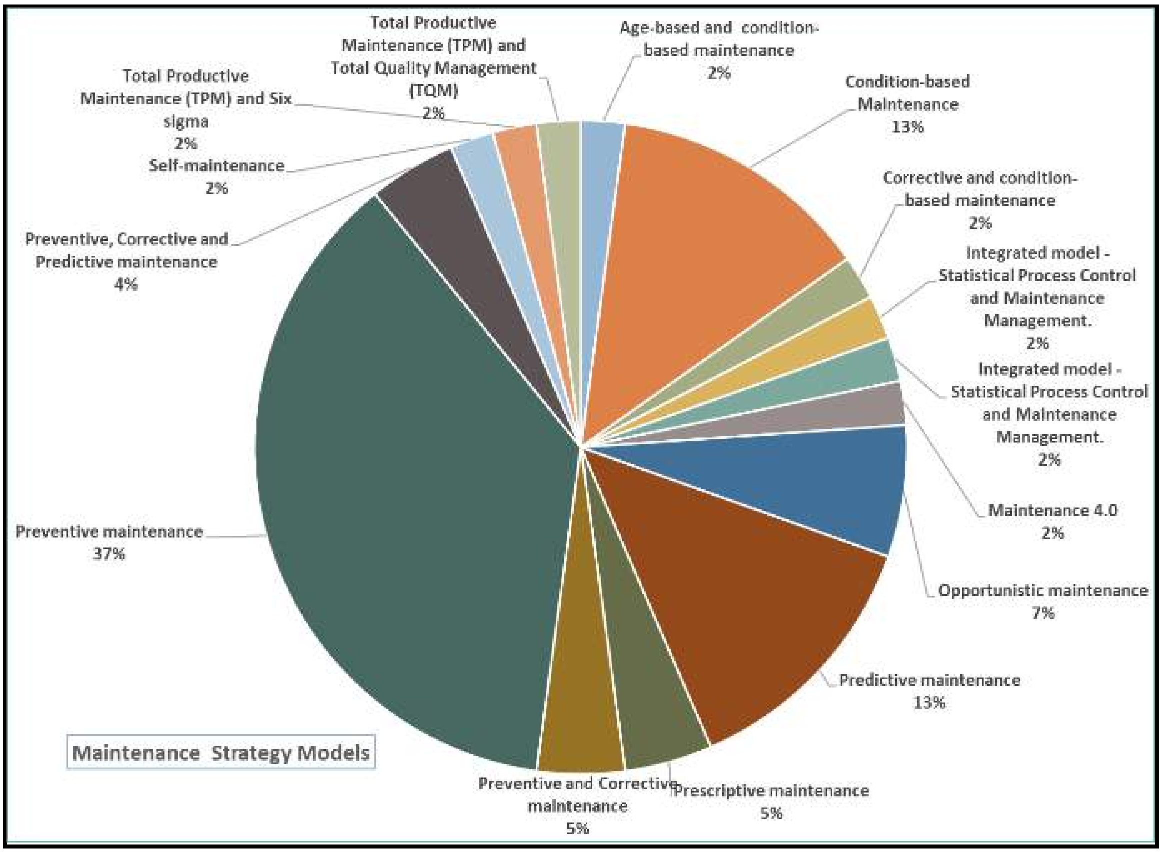

Figure 8: Maintenance strategy adopted in the maintenance models under review.

8.4 Scientific techniques/Theories that were applied in the studies

Table 2 below list the scientific techniques that were identified in the studies. These included the use of *applied advanced mathematics, algorithms, advanced statistics for data analysis and artificial intelligence (AI) for plant maintenance management*. Chief amongst these tools was the application of the artificial intelligence in plant maintenance, Rojek, *et al.* [14] conducted a study on improving maintenance and supervising the machine failures through the application of the artificial intelligence. In this study, they found that "effective use of preventive maintenance requires *large amounts of reliable annotated sensor data* and *well-trained machine-learning algorithms*". These items will have to sourced prior to the implementation of the AI in the power plant. Matlab was the most common software tool used to mimic or simulate the real maintenance model. Table 2 below has comprehensively covered the techniques/theories that were identified from the 45 studies.

Table 2: Scientific theories or technologies or techniques that were applied in the maintenance models under review (Appendix A1-45).

Risk based opportunistic maintenance (RBOM) model. Global optimization algorithm. Monte Carlo simulation. Weibull distribution [A1].	Advanced mathematics and statistics [A8].	Advanced Mathematics. Delay-time-based PM models. Algorithms [A15].	Quasi-Monte Carlo method. Kalman filter. QMC method. DG method to simulate degradation data and maintenance data. Kalman Filter. Non-stationary Wiener process [A22].	Statistical Process Control (SPC). EWMA control chart. Genetic algorithm approach using Matlab software. GA theory - GA is a simulation computer program (It is used as a random search technique for optimization purpose). Regression analysis by the statistical software (SPSS 15.0) [A29].	Constraint Programming (CP) Approach. ILOG CPLEX Optimization Studio Optimiser as a solver engine and using ILOG OPL language. Building condition index (BCI) [A36].
Advanced mathematics. Degradation-Threshold-Shock (DTS) model. Non-homogenous Poisson process (NHPP) [A2].	Advanced mathematics and statistics. Simulation algorithm. Analytical modelling [A9].	Advanced mathematics. Gamma degradation process. Markov process. Global decision rule. Renewal theory. Volterra integral equation [A16].	Total Productive Maintenance (TPM) and Total Quality Management (TQM) [A23]	Deterioration failure described by Gamma process and Random failure described by Poisson process. Renewal process theory. Advanced mathematics [A30].	Markov chains, Kijima model type I, Algorithm - accelerated quantum particle swarm optimisation + Sequential Monte Carlo simulation, Weibull and Gumbell distribution, Reliability model, Metaheuristics approaches [A37].
Time-frequency-domain (i.e., spectrogram) for vibration data used for RUL estimation. Use of neural network. Signal processing, and machine learning methods. Long Short-Term Memory (LSTM) neural network by	Particle swarm optimization (PSO) based integrated approach is used to solve the model [A10].	Advanced mathematics. Monotic, stochastic degradation process. Gamma process. Unscheduled downs follow a Poisson process. Wiener process and Bayesian updating. Markov	Risk-based Maintenance (RBM) and Bayesian Network (BN). Bayes' Theorem. Delphi method. Fuzzy set theory. Dempster-Shafer evidence theory [A24].	Economic-statistical optimization of a Variable-Parameter Shewhart control scheme. Bi-objective optimization problem. Advanced mathematics. Markov chain [A31].	Risk based opportunistic maintenance (RBOM) model. Global optimization algorithm. Monte Carlo simulation. Weibull distribution [A38].

Hochreiter and Schmidhuber [A3].		decision process [A17].			
Markov models. Degradation model. Advanced statistics [A4].	Renewal-reward theorem. Markov chain. Semi-regenerative theory. Advanced mathematics [A11].	None [A18]	Digital twin technique - digital twins integrate digital technology and virtual model simulation technology. Dimension Convolutional Neural Network (1D-CNN). Bidirectional Gated Recurrent Unit (BiGRU) Neural Network [A25].	Markov process. EM algorithm. Multivariate time series model. Advanced mathematics [A32].	Scenario-based genetic algorithm (SBGA) and Particle Swarm Optimization (PSO) algorithm. GAMS software [A39].
Weather Forecasts were integrated to new opportunistic maintenance model [A5].	Gamma degradation process [A12]	None [A19]	Advanced mathematics. Weibull Distribution. Matlab tools [A26].	Intelligent flexible pavement deterioration and maintenance management model. Artificial Neural Network (ANN). Regression analysis [A33].	Self-healing mechanism. Wireless Sensor Network (WSN). NS2 simulator. Effective Fault Detection and Routing (EFDR) [A40].
Deep neural networks (DNN), recurrent neural networks (RNN) and regression random forest (RRF) [A6].	Gaussian degradation process. Semi-regenerative theory. IG degradation process [A13].	Principal Component Analysis (PCA), Statistical Pattern Recognition (SPR) [A20].	Lean Root Cause & Defect Analysis (LRCDA). Root Cause & Failure Analysis (RCFA) technique. Lean Maintenance and Total Productive Maintenance (TPM). Fishbone analysis. Pareto analysis [A27].	Regression model for maintenance planning and prediction. Questionnaire survey, interview and case study. Statistical Package for Social Science (SPSS) software [A34].	Advanced mathematics [A41].
Multivariate Gamma subordinators as degradation model. Artificial intelligence [A7].	Monte Carlo simulation. Opportunistic maintenance model [A14].	Quasi-Monte Carlo method. QMC method. DG method to simulate degradation data and maintenance data. Kalman Filter. Non-stationary Wiener process [A21].	Maintenance 4.0 model. Predictive maintenance based on recent research are Physic, Data-driven, Probabilistic, Stochastic and A.I.-method based. Prescriptive maintenance and analytics. Prognostic maintenance [A28].	Ordinary differential equation (ODE) model. Stochastic process theorem. Newton-Raphson iterative method. Weibull proportional failure model. Euler Method [A35].	Weibull distribution. Rough set theory [A42].
Proposed Model within the Paradigms of SM, CE, and Sustainable Maintenance. Matlab software [A43].	Integrated Autonomous Production Control Mode. Optimization algorithm [A44].	Reliability Block Diagrams to Fault Tree Circuits [A45].	N/A	N/A	N/A

Learnings obtained from this section has been summarised under Table 3 below.

Figure 9 below represents a list of maintenance models that the authors deemed them to be suitable for the dust and ash plant maintenance problems. These models (see table 2 above) were subjected to subjective assessment with reference to the dust and ash plant application by the researchers and the ratings were as follows: score of 1 indicated NOT CONSIDERED, score of 2 indicated CONSIDERED and score of 3 indicated as TO BE TESTED. Below in figure 9 is the results of this evaluation of the maintenance models.

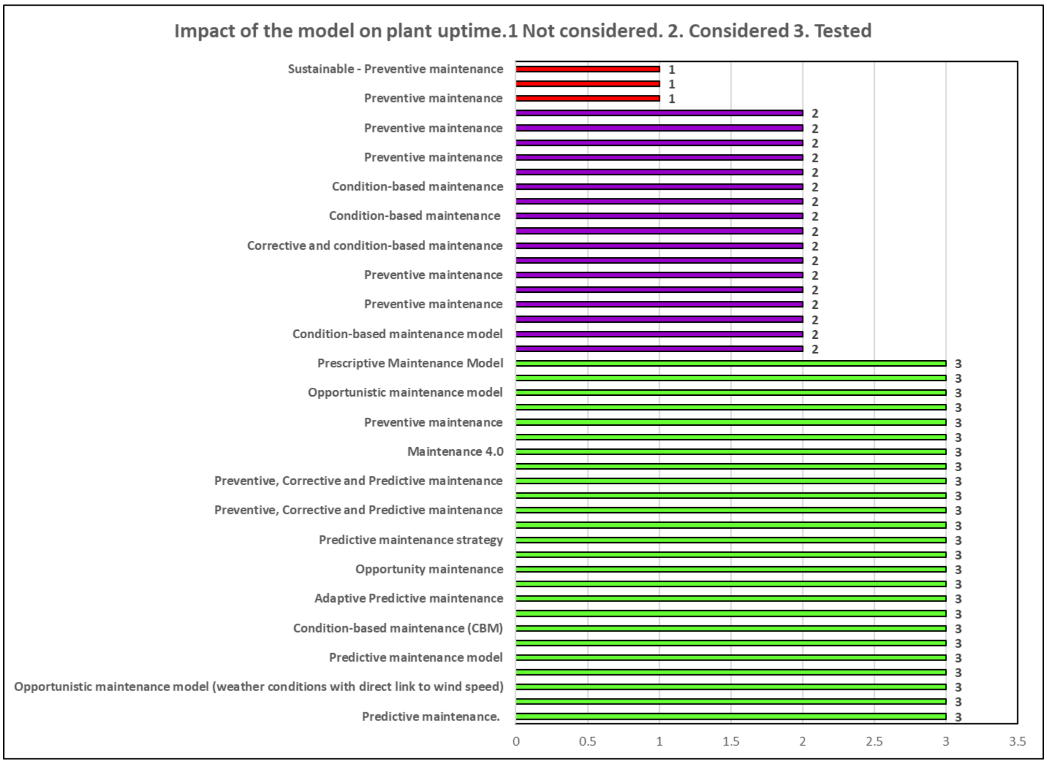

Figure 9: Subjective assessment of the maintenance models' impact on the dust and ash plant uptime by the authors.

- Maintenance strategy models (7%) were subjectively deemed to have no positive impact on plant uptime. This was two preventive models and TPM/six sigma model.
- Maintenance strategy models (35%) were considered to have the potential of positive impact plant uptime.
- Maintenance strategy models (57%) were classed to have positive impact on the plant uptime.

8.5 Type of Publication

Publications in this study was made-up of conference (11%) and journal papers (89%). The leading publication (20%) was the Journal of Reliability Engineering and System Safety. The nature of these papers was that of academia-industry collaboration with the objective to dissect the practical maintenance challenges in the laboratory using academic scalpels through the academic lenses. These joint ventures provide the industry with the benefits of cutting-edge research and highly skilled graduates to solve real maintenance problems [15]. These articles were of high quality, they have been subjected to rigorous peer-review mechanism and published in the internationally recognised academic publication. Figure 10 below depict the type of publications that were used to report the research results of the academia, industry and academia-industry collaboration.

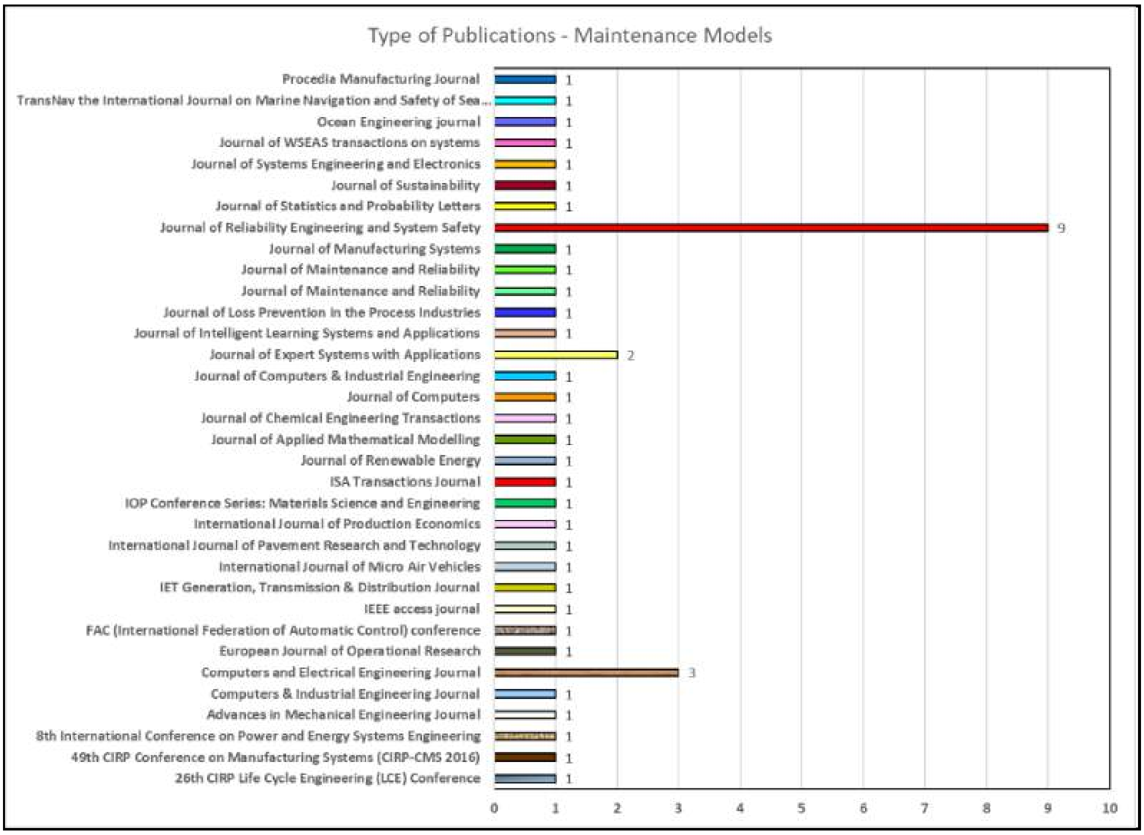

Figure 10: Type of publications in the maintenance model studies under review.

8.6 Number of Maintenance Models Publications per Year

Maintenance models publications (see figure 12 below) indicated an upward trend (2010-2022) and this highlight the importance of the maintenance in the industry in general as more and assets owners realise the relationship between sustainable business profits (figure 1) and the plant health relationship ([4] and [5]).

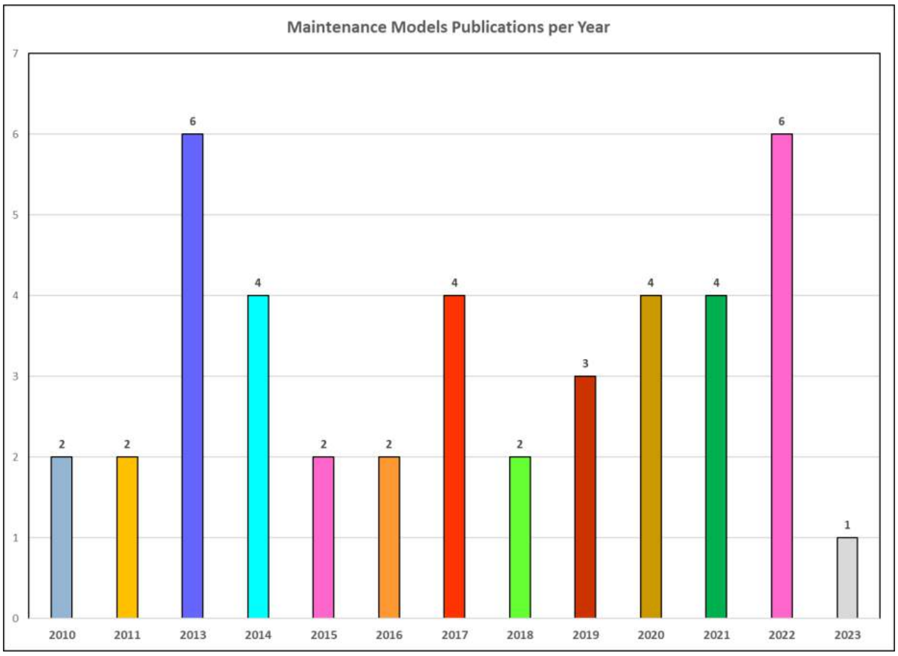

Figure 12: Publication trends in the studies under review.

9 DISCUSSION OF THE RESULTS

Table 3 below provide a summary of the systematic literature review and learnings that are important for the maintenance practitioners.

Table 3: Discussion of results for maintenance models in the studies

Item	**Study findings**	Notes for power plant maintenance practitioners
Maintenance strategy (Section 8.3)	Relationship between maintenance functional strategy, maintenance strategy and company strategy were synthesised based on the general structure of the maintenance functions in the industry and work of Porter [3] on strategy. Gits [4] and Ben-Daya *et al*. [5] work have also demonstrated the value of maintenance in the company. Preventive maintenance was the most common strategy (37%). Maintenance 4.0, Opportunistic maintenance, Prescriptive, Predictive and Self-maintenance strategies formed part of the 21st century innovation and these did not form part of the dust and ash plant maintenance strategy.	Maintenance function is critical for the success of the company. Figure 1 - Maintenance functional strategy model developed by the authors can be used by the maintenance practitioners to justify funding for the maintenance capital projects. This is essential as certain company managers continue to treat maintenance function as a necessary evil. Preventive maintenance remained a vital cornerstone for plant maintenance management. Power plant practitioners to incorporate these innovative strategies in their maintenance management so that plant safety and uptime could be enhanced. Maintenance 4.0 to be prioritised so that plant health can be enhanced. Opportunistic maintenance strategy was found to be applicable to dust and ash plant, but it has to be further researched as literature covering this topic was scarce perhaps due to its nature as it is occurs based on stochastic factors.
Industry sector (8.1)	Significant number of the articles (44%) did not mention the industry sector that their maintenance models were based upon. Energy, Manufacturing, Port, Road network, Transport, Building, Rail, Semiconductor, Aviation and Defence were the industry sectors that studies were based upon. The largest single sector was energy (16%), this was applicable to the power plant and thus it could be easily benchmarked. This confirmed the prevalence of maintenance activities across these sectors.	Researchers must cite the industry sector so that their maintenance models can be easily replicated and validated during the benchmarking exercises. Benchmarking for best maintenance practices should not be confined to energy sector as maintenance models with great attributes were found in the other sectors.
Authorship analysis by country and continent (8.2)	Chinese research output (40%) in these studies was the dominant. This highlights the importance of widening the research net for better learnings through SLR. France ranked second while Malaysia was third.	Future SLR must include other languages for the best maintenance practices. Chinese research done could not be studied and this could adversely affect progress of the dust and ash plant. Translation tools to be sourced so that more research work from the Chinese could be applied to enhance dust and ash plant performance. Chinese industry could be the best place for benchmarking as it represents 40% of the studies.
Scientific techniques that were applied in the studies (8.4)	Maintenance models that were studied in this review applied scientific techniques that included (Table 2 above): *advanced mathematics, advanced statistics, algorithms, neural network and artificial intelligence*. Application of AI will require large amounts of reliable annotated sensor data and well-trained machine-learning algorithms [14].	There is a need to leverage on scientific and technological developments so that plants could be safer, and uptime enhanced. Matlab was the most common software used to study plant maintenance problems hence a need to acquire the skills to use this tool was found to be essential.

Item	Study findings	Notes for power plant maintenance practitioners
	Maintenance strategy models (92%) were considered to have the potential of positive impact plant uptime by the authors. Figure 1 demonstrated the critical value of maintenance within the company. The techniques applied in these studies constituted reliability engineering principles combined with advanced data analytic methods. The following is a list of the probability distributions (Degradation or Failure and Repair) that were identified in the literature: • Normal distribution or Gauss distribution or Bell curve • Lognormal distribution • Beta distribution • Gamma distribution • Uniform distribution • Weibull distribution • Exponential distribution • Binomial distribution • Poisson distribution • Delta distribution, etc. These functions were central to the application of reliability engineering hence any study in this field will require the applicant to be competent in its use.	Company management has to invest in an effective and efficient maintenance strategy if the customer needs have to be continuously exceeded. Extensive application of these mathematical statistics techniques through computing power corroborated the concept of Nowlan and Heap [12] in 1978. Maintenance practitioners have to be competent in the mathematical statistics and maintenance fields (maintenance data analytics) so that insights and foresights can be used to unleash plants' potential. Minimum of about 33% of the articles in this sample were based on the artificial intelligence, this stressed the importance embracing technological development in the 21st century. Quality Data Management standard has to be developed and controls implemented so that its superior day-to-day decision-making can take place when these probability distribution functions are applied.
Type of publication used for maintenance models publication (8.5).	Articles that were reviewed were mostly published through journals (89%). This medium of publication ranked supreme as the quality of the research was subjected to rigorous reviews and their results were reliable.	Maintenance practitioners have to keep themselves abreast with engineering and scientific developments so that plant technical challenges could be tackled based on literature that was subjected to rigorous reviews for safer and plant with higher uptime. Academia-industry collaborations holds the key to unleashing of the industrial world class performance.

10 LIMITATIONS

This research was based on the publications between 2010-2023. It was carried out with English-speaking lenses and entered into the Google database, but it might have missed any other significant research that were published elsewhere (Eg: Chinese that were the leader in maintenance modelling research) or in languages other than English. Due to the multifariousness of the studies included in this review, meta-analysis could not be done as the objectives of the researchers were dissimilar. Examples of studies that were overlooked due to the nature of the inclusion criteria include those that were conducted in Venda, Afrikaans, Damara, Japanese, Chinese and Italian among other languages. The Google database originally gave 898 studies and systematic sampling methodology was applied, thereafter screening and filtering process yielded 45 studies. The characteristics of the 898 studies could have been compromised in the process of filtering and screen. Future research should therefore select sampling methodology that provides better characteristics of the main population and be aware of English-based and one index searches and aim to incorporate studies from regions previously thought to be underrepresented. Due to the possibility of author bias, these study flaws could be contributed to the replication issue [16].

11 CONCLUSION

Majority of the studies (44%) that were reviewed did not indicate the sector that their maintenance models were based upon while 66% of the studies had indicated the industrial sector basis of their maintenance models. This was found to be crucial if benchmarking was to be done.

Chinese academics (40%) were the leaders in this study in terms of output, followed by the French (7%). South African researchers (2%) were not active in this area, and this will make it difficult to benchmark locally as the best were in foreign countries. The remainder of the countries in the studies were on average of 2%. Future research must include translation tools so that more Chinese and other languages could be included in the studies.

Most of the articles (37%) had designed their maintenance models to be geared to preventive maintenance for safer and higher performing systems. Prescriptive (13%), Maintenance 4.0 (2%) and opportunistic maintenance (7%) strategies. Self-maintenance was identified as a new type of maintenance strategy. There is a need to leverage on the technological innovations (Eg: AI, etc.) so that maintenance of the plants can be enhanced, and safety improved. 21st century maintenance practitioner has to be literate in field maintenance data analytics. Maintenance data quality management was essential for a successful maintenance model. This will provide maintenance management with foresights and insights in the competitive world.

Maintenance models that were studied in this review applied advanced mathematics, advanced statistics, algorithms, neural network and artificial intelligence. Matlab was the most common software tool used to simulate the maintenance models. Maintenance strategy models (7%) were subjectively deemed to have no positive impact on plant uptime. Maintenance strategy models (35%) were considered to have the potential of positive impact plant uptime. Maintenance strategy models (57%) were classed to have positive impact on the plant uptime.

Maintenance models publications indicated an upward trend between 2010-2023 indicating the importance of maintenance in the business environment.

12 COMPETING INTERESTS

The authors declare that they did not have competing interests.

13 FUTURE STUDY

- Dust and ash plant maintenance model shall be developed in the future based on these learnings.
- Opportunistic maintenance strategy was found to be applicable to dust and ash plant but literature covering this topic was scarce. Maintenance opportunity in this instance was not weather driven like in the wind energy sector. This area must be thoroughly researched to cover the identified gap in the future.

14 ACKNOWLEDGMENTS

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16 APPENDIX A – MAINTENANCE MODELS IN THE STUDIES UNDER REVIEW (REFERENCE [17] TO [59])

ID	Author(s)	Industry sector	Country and continent	Maintenance strategies	Impact of the model on plant uptime.1 Not considered. 2. Considered 3. Tested	Type of publication
A1	Ame´lie Ponchet, Mitra Fouladirad and Antoine Grall (2010) [17]	General industry	France in Europe	Preventive maintenance	2	Journal of Reliability Engineering and System Safety
A2	Michael Jong Kim, Viliam Makis and Rui Jiang (2010) [18]	General industry	Canada in North America	Condition-based maintenance	2	Journal of Statistics and Probability Letters
A3	Fatemeh Harsej and Sha'ri M. Yusof (2011) [19]	General industry	Malaysia in Asia	Total Productive Maintenance (TPM) and Six sigma	1	Contemporary Engineering Sciences Journal
A4	P. Charongrattanasakul and A. Pongpullponsak (2011) [20]	Manufacturing industry	Thailand in Asia	Integrated model - Statistical Process Control and Maintenance Management.	3	Journal of Expert Systems with Applications
A5	Ankit Gupta, Praveen Kumar and Rajat Rastogi (2011) [21]	Road network industry	India in Asia	Predictive Maintenance	2	International Journal of Pavement Research and Technology
A6	Huynh K.T., Barros A and Berenguer C (2013) [22]	General industry	France in Europe	Condition-based maintenance (CBM)	3	Journal of Chemical Engineering Transactions
A7	Wenzhu Liao and Ying Wang (2013) [23]	General industry	China in Asia	Predictive maintenance strategy	3	Journal of Computers
A8	Elpidio Romano, Teresa Murino, Felice Asta and Piervincenzo Costagliola (2013) [24]	Manufacturing industry	Italy and Finland in Europe	Total Productive Maintenance (TPM) and Total Quality Management (TQM)	3	Journal of WSEAS transactions on systems

ID	Author(s)	Industry sector	Country and continent	Maintenance strategies	Impact of the model on plant uptime.1 Not considered. 2. Considered 3. Tested	Type of publication
A9	Zhijun Cheng, Zheng Yang and Bo Guo (2013) [25]	Defence Industry	China in Asia	Corrective and condition-based maintenance	2	Journal of Systems Engineering and Electronics
A10	Jianlong Ding, Yong Qin, Limin Jia, Shiyou Zhu and, Bo Yu (2013) [26]	Transport industry	China in Asia	Preventive maintenance	2	Journal of Intelligent Learning Systems and Applications
A11	M. Anantharaman (2013) [27]	Shipping Industry	Australia in Australia	Condition-Based Maintenance	2	TransNav the International Journal on Marine Navigation and Safety of Sea Transportation.
A12	Ferreira Cláudia, Canhoto Neves Luís, Campos e Matos José and Sousa Soares José Maria (2014) [28]	Road network industry	Portugal in Europe	Preventive and Corrective maintenance	3	7th international conference on bridge maintenance, safety and management.
A13	Wenbin Wang, Fei Zhao and Rui Peng (2014) [29]	General industry	China in Asia	Preventive maintenance	2	Journal of Reliability Engineering and System Safety
A14	Cheong Peng Au-Yong, Azlan Shah Ali and Faizah Ahmad (2014) [30]	Building Industry	Malaysia in Asia	Condition-based maintenance	2	Journal of Maintenance and Reliability
A15	Jinqiu Hu and Laibin Zhang (2014) [31]	General industry	China in Asia	Opportunistic maintenance model	3	Journal of Expert Systems with Applications
A16	Xuejuan Liu, Wenbin Wang and Rui Peng (2015) [32]	Manufacturing industry	China in Asia	Preventive maintenance	3	Journal of Reliability Engineering and System Safety

ID	Author(s)	Industry sector	Country and continent	Maintenance strategies	Impact of the model on plant uptime.1 Not considered. 2. Considered 3. Tested	Type of publication
A17	Mimi Zhanga, Olivier Gaudoinb and Min Xiea (2015) [33]	General industry	China in Asia AND France in Europe	Preventive maintenance	2	European Journal of Operational Research
A18	Bupe. G. Mwanzaa and Charles Mbohwa (2015) [34]	Manufacturing industry	South Africa and Africa	Preventive maintenance	3	Procedia Manufacturing Journal
A19	Xiaojun Zhou, Changjie Wu, Yanting Li and Leng Xi (2016) [35]	General industry	China in Asia	Preventive maintenance	2	Reliability Engineering and System Safety
A20	Marc Engeler, Daniel Treyer, David Zogg, Konrad Wegener and Andreas Kunz (2016) [36]	General industry	Switzerland in Europe	Preventive maintenance	1	49th CIRP Conference on Manufacturing Systems (CIRP-CMS 2016)
A21	Li Yang, Xiaobing Ma and Yu Zhao (2017) [37]	General industry	China in Asia	Condition-based maintenance model	2	Computers & Industrial Engineering Journal
A22	A. Erguido, A. Crespo Marquez, E. Castellano, J.F. Gomez Fernandez (2017) [38]	Energy industry	Spain in Europe	Opportunistic maintenance model (weather conditions with direct link to wind speed)	3	Journal of Renewable Energy
A23	Qiushi Zhu, Hao Peng , Bas Timmermans and Geert-Jan van Houtum (2017) [39]	Semiconductor industry	China in Asia AND France in Europe	Preventive maintenance	2	International Journal of Production Economics
A24	Chiara Franciosi, Alfredo Lambiase and Salvatore Miranda (2017) [40]	Manufacturing industry	Italy in Europe	Sustainable - Preventive maintenance	1	FAC (International Federation of Automatic Control) conference
A25	Konstantinos A. Tasias and George Nene (2018) [41]	General industry	Greece in Europe	Preventive maintenance	2	Journal of Applied Mathematical Modelling
A26	Walaa Elsayeda Walaa Elsayed, Mohamed Elhosenya, Sahar Sabbehb and Alaa Riad (2018) [42]	General industry	Egypt in Africa	Self-maintenance	3	Computers and Electrical Engineering Journal
A27	Bin Liu, Jing Lin, Liangwei Zhang and Uday Kumar (2019) [43]	Rail industry	Sweden in Europe	Prescriptive maintenance strategies are updated based on the observed/predicted degradation parameters and system state, whereas in conventional time-based maintenance, decisions only rely on historical data without considering updates.	3	IEEE access journal

ID	Author(s)	Industry sector	Country and continent	Maintenance strategies	Impact of the model on plant uptime.1 Not considered. 2. Considered 3. Tested	Type of publication
A28	Qinghe Yuan, Zhenzhen Jin, Shun Jia and Qian Liu (2019) [44]	General industry	China in Asia	Opportunity maintenance	3	Advances in Mechanical Engineering Journal
A29	Leonardo Leoni , Ahmad BahooToroody, Filippo De Carlo and Nicola Paltrinieric (2019) [45]	Energy industry	Italy and Norway in Europe	Preventive, Corrective and Predictive maintenance	3	Journal of Loss Prevention in the Process Industries
A30	Robert Glawara, Fazel Ansaria, Csaba Kardosa, Kurt Matyas and Wilfried Sihna (2019) [46]	General industry	Austria in Europe	Prescriptive Maintenance Model	3	26th CIRP Life Cycle Engineering (LCE) Conference
A31	Danping Lin , Baoping Jin and, Daofang Chang (2020) [47]	Port industry	China in Asia	Preventive and corrective maintenance	3	Journal of Reliability Engineering and System Safety
A32	P. Poór and J. Basl (2020) [48]	General industry	Czech in Europe	Maintenance 4.0	3	IOP Conference Series: Materials Science and Engineering
A33	Manuel S. Alvarez-Alvarado and Dilan Jayaweera (2020) [49]	Energy industry	Ecuador in North America	Preventive maintenance	3	IET Generation, Transmission & Distribution Journal
A34	Yu Zhoua , Gang Koub , Hui Xiaoc , Yi Pengd and Fawaz E. Alsaadie (2020) [50]	Transport industry	China in Asia	Preventive maintenance	2	Reliability Engineering and System Safety Journal
A35	K.T. Huynh (2021) [51]	General industry	France in Europe	Adaptive Predictive maintenance	3	Reliability Engineering and System Safety
A36	Jingjing Wang, Yonghao Miao, Yinggang Yi and Dagang Huang (2021) [52]	General industry	China in Asia	Age-based and condition-based	3	Journal of Computers & Industrial Engineering

ID	Author(s)	Industry sector	Country and continent	Maintenance strategies	Impact of the model on plant uptime.1 Not considered. 2. Considered 3. Tested	Type of publication
A37	Li Chen, Hongsheng Su and Lanlan Huangfu (2021) [53]	Energy industry	China in Asia	Preventive maintenance	2	8th International Conference on Power and Energy Systems Engineering
A38	Shu-Shun Liu and Muhammad Faizal Ardhiansyah Arifin (2021) [54]	Building Industry	Indonesia in Asia	Preventive maintenance	3	Journal of Sustainability
A39	Qiannan Liu, Lin Ma, Naichao Wang, Ankang Chen and Qihang Jiang (2022) [55]	Energy industry	China in Asia	Condition-based maintenance model	2	Reliability Engineering and System Safety Journal
A40	Tiago Zonta, Cristiano Andr´e da Costa, Felipe A. Zeiser, Gabriel de Oliveira Ramos, Rafael Kunst and Rodrigo da Rosa Righi (2022) [56]	General industry	Brazil in South America	Predictive maintenance.	3	Journal of Manufacturing Systems
A41	K.T. Huynh, H.C. Vu , T.D. Nguyen and A.C. Ho (2022) [57]	General industry	Global	Predictive maintenance model	3	Journal Reliability Engineering and System Safety
A42	Zhoukai Wang, Weina Jia, Kening Wang, Yichuan Wang and Qiaozhi Hua (2022) [58]	Energy industry	China in Asia	Preventive maintenance	3	Computers and Electrical Engineering Journal
A43	Jinhe Wang, Xiaohong Zhang and Jianchao Zeng (2022) [59]	Energy industry	China in Asia	Preventive, Corrective and Predictive maintenance	3	Ocean Engineering journal
A44	Hadi Gholizadeh, Maedeh Chaleshigar and Hamed Fazlollahtabar (2022) [60]	Manufacturing industry	Iran in Middle East	Preventive maintenance	2	ISA Transactions Journal

ID	Author(s)	Industry sector	Country and continent	Maintenance strategies	Impact of the model on plant uptime.1 Not considered. 2. Considered 3. Tested	Type of publication
A45	Erkan Caner Ozkat, Oguz Bektas , Michael Juul Nielsen and Anders la Cour-Harbo (2023) [61]	Aviation industry	Turkey in Asia	Predictive maintenance.	3	International Journal of Micro Air Vehicles

PUZZLING TOGETHER LEAN PRACTICES IN THE RECRUITMENT PROCESS: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

"Lean" is commonly known as the practice of improving efficiency and effectiveness by the elimination of waste. In relation to recruitment, waste can be the excess time spent on sourcing, screening and interviewing candidates for a position. Traditionally, recruitment has been reactive and works on filling a vacancy only when the position opens. This approach is feasible for general workers but falls especially short when acquiring talent for higher positions. Talent acquisition is therefore a more strategic alternative to recruitment, where the recruiting team creates talent forecasts and actively searches for talent that will match the current and future needs of the company. This research aims to study strategic means of acquiring talent for organisations, while implementing lean principles within the traditional recruitment process. This method of employment will aid in talent matching while also reducing waste in the process.

Keywords: Recruit, Lean recruitment, Talent acquisition, Strategy

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1 INTRODUCTION

With the fast-evolving world and people requirements, it is important for organisations to have the flexibility to progress and adapt to clients' needs. This means that organisations should strive to be well equipped for the speedily evolving customer, industry, environmental, social and economic needs in their respective endeavours. A crucial contribution to this is the workforce or human capital of an organisation [1]. Human capital refers to the productive capacity of people as income-generating actors in the economy. Human capital includes assets such as education, training, intelligence, skills, health and others that employers value, such as loyalty, integrity and punctuality [1,2]. Human capital is recognised as increasing productivity and therefore profitability [2]. It is the stock of skills and productive knowledge embodied in people. The concept recognises that not all jobs are created equal, but employers can improve the quality of their capital by investing in their employees [2]. Improving the rate of return, on human capital investment lies in enhancing the skills and earning power of individuals and increasing the efficiency of economic decision-making both within and outside the market economy. Therefore, the talent recruited should be well-skilled and equipped for the specific job and, more importantly, should fit into the future needs and vision of the organisation. For this to come to fruition, a more strategic and lean approach to recruitment should be followed.

Lean is a methodology that originated in Japan and which focuses on maximizing customer value while minimizing waste. Lean was introduced through the Toyota Production System (TPS) developed by Toyota in the mid-20th century. TPS was developed to improve the efficiency of the manufacturing process, reduce waste and improve quality [3]. It is based on the two main pillars: "just-in-time" (JIT) production and "jidoka" (autonomation) [4]. While JIT production focuses on producing the right amount of product at the right time, Jidoka has incorporated quality into the production process, allowing employees to stop production when defects are identified. Since its introduction, Lean principles have been applied to various industries outside of manufacturing– industries such as healthcare, finance, and software development [5]. The ultimate goal of Lean is to create a culture of continuous improvement. Therefore, all processes and activities are constantly evaluated, improved, "lean'ed" and modified to add value.

These principles of lean management can also be applied to the recruitment process to improve its efficiency and effectiveness, reduce waste and add value to both the organization and the candidates. According to Benuyenah [6] lean recruitment includes practices that avoid lengthy processes and requirements that add no value to the candidate's experience or employer's goals. The traditional recruitment process comprises the following steps: 1) Identify a vacancy, 2) Sourcing, (typically by advertising a vacancy for a position), 3) Receive and analyse applications, 4) Selection and finally, 5) Hiring. The problem is that these recruitment practices are lengthy, contain a redundancy of steps and duplication of information.

This paper aims to retrieve information on the implementation of a lean recruitment process in which candidates of varying positions are fairly and optimally recruited in a manner that will eliminate any wasteful activities for the hiring department as well as the candidates.

2 LITERATURE REVIEW

Recruitment is the process of identifying a vacancy, finding, evaluating, and hiring talent to fill and occupy an existing vacancy within the company [7]. The process of recruitment follows a specific process that is essential to running a business. The recruitment process is reactive and is initiated once a vacancy arises [7].

Talent acquisition is similar to recruitment as they both seek to obtain talent for companies, but they differ from one another in the sense that talent acquisition is a more strategic approach, and seeks to find long-term candidates for the company [8] as opposed to recruitment that looks at the current needs of the organisation. The goal of talent acquisition is to find candidates with the right skills, qualifications, and cultural fit for the organization to build a strong and high-performing workforce through human capital [8]. When conducting a search for talent, factors that must be considered by the talent acquisition specialists are employer branding, forecasting or future resource planning, diversification of the company's workforce and building a strong candidate relationship for the talent pipeline [9]. To identify long-term candidates the talent acquisition specialists need to have a clear understanding of the company's current status, as well as the possible future development expansion, so that the candidates hired for the position will remain relevant over the dynamic evolution of the company. To summarise, talent acquisition is a process that is continuous, proactive, strategic and forward-looking, unlike recruitment which is short-term and reactive.

A way in which the talent acquisition team may be more strategic in its approach to identifying and reaching the appropriate talent for positions within the company is by categorising and grouping positions in the company that have a similar level of availability in the labour market and allocating equivalent measures to attain the candidates. Candidates may either be a, 1) Simple hire, 2) Difficult mass hire, 3) Specialist hire or 4) Strategic hire [10].

2.1 Simple Hire

This is the case where the traditional recruitment process is most applicable. This group of hires are actively looking for employment and the supply is usually more than the organisation's demand. It is therefore the responsibility of the recruiting agent to select the right candidates from the pool of applicants. This category requires the posting of advertisements, (usually locally) as few skills and qualifications are required. This type of hire need not be too strategic, time consuming or costly [10].

2.2 Difficult Mass Hire

In this category it is ideal to develop talent communities for long-term retention of potentially suitable candidates [10]. Simple forms of active sourcing, for example targeted searches and addressing candidates on platforms such as LinkedIn, may be used to find these candidates. Structural measures to optimize the candidate experience include not only effective selection procedures, but also simple application methods and selection procedures that rely on speed, transparency and evaluation. The daunting task of covering large talent needs requires a comprehensive recruitment system in the sense of talent relationship management. It is not uncommon for carefully curated teams of HR personnel, and target department representatives, to address specific bottleneck departments moderated and managed by so-called talent relationship managers [10].

2.3 Specialist Hire

Specialist candidates are the individuals who are in exceptionally rare fields or have a unique skill. When these candidates are sought for the recruiting agent should merely focus on finding a candidate who can perform the task [10]. Specialist hires are especially challenging since members of this group of candidates are not usually actively looking for jobs. It is the responsibility of the recruitment department to search for, and headhunt such individuals, as applications might fall-short and not reach the candidate. When seeking to hire from this category the hiring department should clearly define the specifications for the position. Furthermore, for this type of talent, more time and resources will be spent 'hunting' for the talent. Once the talent has been identified the offer should be placed as soon as possible. Employee value preposition is key in the 'war for talent' in this category.

2.4 Strategic Hire

This type of hire addresses talent in senior management positions such as CEO's. Whereas all the above cases required a level of talent retention and building a talent community, strategic hire should be dealt with on a case-by-case basis. The organisation should be willing to spend resources and time in acquiring such talent as the search could extend nationally or even internationally. The employee value proposition plays a large role when offering a position to these candidates, but the organisation also seeks to benefit largely from such an employee [10]. Talent in this category should not only have managerial skills but should also have access to relevant markets that will contribute to the growth of the organisation.

2.5 Talent classification matrix

The figure below visually presents the four categories of the type of candidates identified in section 2.4. The horizontal axis represents the level of strategic relevance required by the recruiting department to acquire the talent, where the vertical axis indicates the availability of talent in the labour market for the respective categories. The sizes of the spheres are quantitative measures ranging from high (large spheres) to low (small spheres).

Figure 1 presents the four categories of the type of candidates found in the sections above visually. The horizontal axis represents the level of strategic relevance to the recruiting department to acquire the talent, where the vertical axis indicates the availability of talent in the market for the respective categories. The sizes of the spheres are quantitative measures ranging from high (large sphere) to low (smaller sphere) [10].

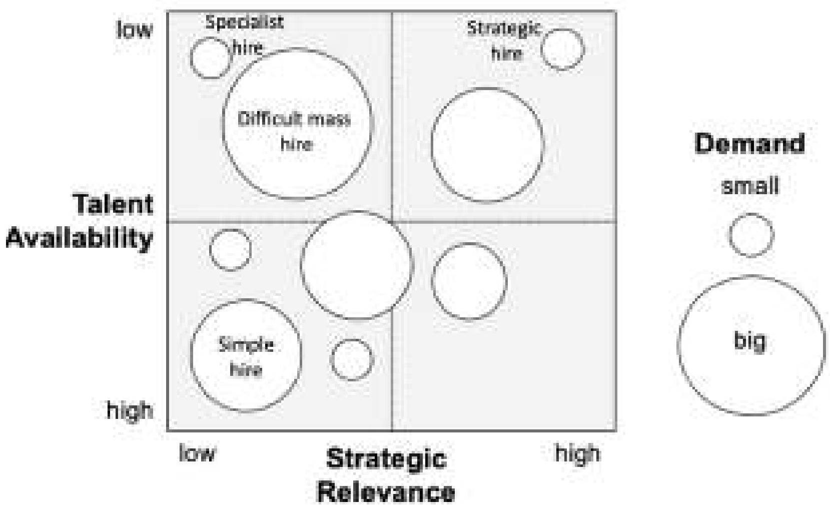

Figure 1: Talent classification matrix

2.6 Conclusion – Literature review

The literature mentioned above indicated that a more strategic approach to talent acquisition could be implemented in organisations, where talent would be categorised and grouped according to theory, availability in the talent market and the amount of effort required by the recruiting department to acquire the talent. The categories for the candidates include, 1) Simple hire, 2) Difficult mass hire, 3) Specialist hire and 4) Strategic hire.

3 RESEARCH DESIGN

A systematic literature review (SLR) was conducted to investigate different lean recruitment strategies in an attempt to modify and eliminate any identified waste in the traditional recruitment process. The research process was separated into three phases, namely, 1) Planning and reviewing, 2) Conducting the review and finally, 3) Documenting the review. The methodology, conducted by Yu Xiao and Maria Watson [11], was adapted as follows:

Planning the review

- Step 1: Develop a research purpose
- Step 2: Develop a research protocol

Conducting the review

- Step 3: Search for and access relevant literature
- Step 4: Selection of studies (based on relevant criteria)
- Step 5: Quality assessment for relevant studies
- Step 6: Data extraction
- Step 7: Analysis and synthesis of findings

Documenting the review

- Step 8: Reporting on findings

The steps above can be visually represented as sub-categories of the mentioned systematic literature review phase.

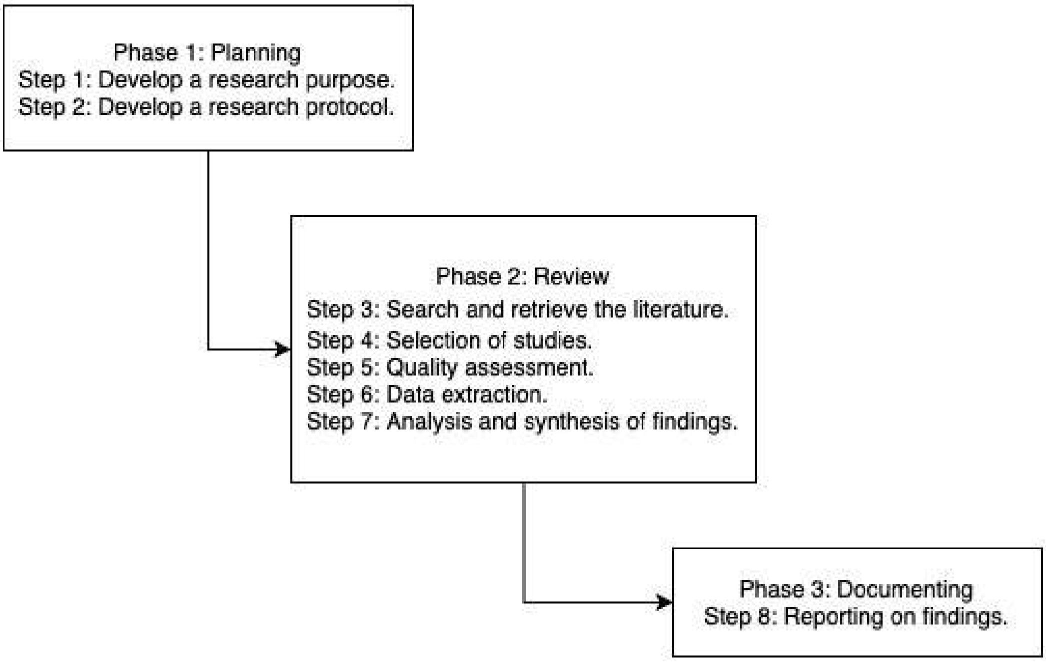

Figure 2: Systematic Literature Review Methodology [11]

3.1 Step 1: Research Purpose

The aim of the systematic literature review is to retrieve available literature on the implementation of lean principles within the traditional recruitment process, in an attempt to eliminate any wasteful steps, while adding value to both the clients (candidates) and the recruiting/HR department of the organization.

3.2 Step 2: Research Protocol

To retrieve the relevant literature, the purpose of the study should be precise and clearly defined. Keywords and inclusion criteria assist in acquiring literature that is specific to the desired study and the exclusion criteria eliminate any misconceptions that were not clearly defined from the keywords and inclusion criteria. The search protocol and the findings are presented in Tabel 1. The steps are presented in the sections which follow.

Table 1:Research protocol

Purpose of study	To investigate the implementation of lean principles in talent recruitment.
Keywords	"lean" AND "recruit" AND "talent acquisition" NOT "health" NOT "weight"
Search databases	• Emerald insight • IEEEXplore • Science direct • Scopus
Inclusion criteria	Literature providing insights into implementing lean practices in traditional recruitment. Literature on identifying wasteful practices within the recruiting departments of organisations.
Exclusion criteria	• Weight loss • Peoples' gifts and specialities
Quality assessment	• Use of language and writing credibility • Studies should be published in English • Repeatable and reputable scientific research methods should have been followed.

4 FINDINGS

The findings from the SLR are presented in this section.

4.1 Step 3: Search and retrieve the literature.

From a literature search of Science Direct, 10 articles were obtained from the keywords. The articles were not relevant to the study, as they did not incorporate lean principles in recruitment, but focused rather on talent management and retention. There were 140 articles retrieved from Emerald Insight-based on an evaluation of the articles' titles and abstracts. Many of the articles were related to the implementation of lean principles throughout the entire organisation but only 4 articles were relevant to recruitment. The IEEEXplorer search database produced 17 articles from the keywords used and one of them addressed the use of lean tools on the optimization of the professional insertion process of newly recruited engineers in a multinational company based in Morocco [12]. Out of a total of 167 articles obtained from the search using the relevant keywords only four of them met the inclusion criteria.

Table 2: Retrieved literature

Database	Retrieved Literature
Science Direct	10
Scopus	0
IEEEXplorer	17
Emerald Insight	140
Total	**167**

4.2 Step 4: Selection of studies based on relevance criteria

After reading the abstracts against the inclusion criteria only four studies were relevant. Several studies focused on talent management and general human resource management tools and strategies. On the other hand , the four retrieved studies provided strategies on acquiring talent as well as lean implementation within the recruitment process of organisations.

4.3 Step 5: Quality assessment for relevant studies

The quality of relevant literature was assessed and analysed by reading the full article or literature. The retrieved literature studies were assessed based on the information the studies provided on talent acquisition strategies and their implementation using lean principles. Quality assessment was based on the use of language, writing credibility and the reputable scientific research methods of the literature. It was concluded that all four retrieved studies were acceptable for inclusion in this chapter.

4.4 Step 6: Data extraction

The literature that was included in the study is summarised in Table 4. The table provides refence to the literature that was found relevant for the study, along with a summary of the content of each article.

Table 5: Summary of included literature

No.	Author	Title	Year	Summary	Reference	Source
1	Gavin W-Wright, William S-Jackson	Talent Rising; people analytics and technology driving talent acquisition strategy.	2018	How companies can leverage world-leading technology to build their own talent acquisition strategies.	[13]	Emerald
2	Pradeep Sashay	Lean Six Sigma tools in the hiring process	2015	How lean principles can be applied to achieve “best-in-class” recruiting capabilities, demonstrating the causal relationship between “value-added” recruiting activities and positive business outcomes.	[14]	Emerald
3	Eric Van Duren, Jim D’Amico and Kurt Knoth	Lean talent acquisition: one team’s journey of improvement	2015	How can lean performance improvement principles help transform an integrated healthcare system’s talent acquisition team to best in class.	[15]	Emerald
4	Vic Benuyenah	Can the concept of “lean management” be applied to academic recruitment?	2021	The implementation of lean processes helps to improve organisational practices; in the case of university recruitment,	[6]	Emerald

No.	Author	Title	Year	Summary	Reference	Source
				however, organisational processes have remained unchanged		

4.5 Step 7: Analysis and synthesis of findings

The key findings from the literature that have been summarised in Table 5 will be provided in this section.

4.5.1 Lean Philosophies in recruitment [6]

V, Benuyenah [6], used the five principles of Lean and weighed them against the recruitment process, which amplified areas of improvement within the recruitment process.

- **Specific value:** Render quality services for the candidate (time, logistics, efforts and communication)
- **Flow:** Creating a system that flows seamlessly without hindrances (bottlenecks) by eliminating unnecessary waiting times for the applicants and recruiter.
- **Pull:** Retrieve only the necessary and relevant information from the applicants and avoid redundancy of information
- **Value stream:** Simplify the process as much as possible and avoid redundancy of processes.
- **Perfection:** Give clear instructions to avoid confusion and 'back-and-forth' communication. Only involve the necessary parties for desired position.

4.5.2 Duplicates and redundancies

The nature of questions on the application form duplicates information already contained in the CV's [6].

4.5.3 Waste in recruitment

Lean recruitment may be achieved by identifying and getting rid of the non-value adding tasks within the recruitment process. The non-value adding activities were categorised into the standard 8 forms of waste was applied within the context of recruitment [14];

Transportation - Recurring communication between HR personnel, candidates, and line Managers. Having multiple phases within the recruitment process that required the candidates or personnel to regularly send information.

Inventory - Piling applications and CV's, due to broad job description.

Motion - Multiple people required to attend interview and sign-off documentation.

Waiting - Long waiting times for compiling short-lists or scheduling interviews. Waiting for sign-off of documentation by relevant parties. Waiting for background checks.

Overprocessing - An extensive review of all applications for compiling short-list

Overproduction - Having a large pool of short-list candidates that need to be interviewed.

Defects - Applications of candidates that do not meet the job requirements or do not qualify for the position.

Skills - Underutilizing current employees for referrals or not integrating them into the interview process according to their expertise.

4.5.4 Case Study

The case study referred to by Van Duren [15], is of a large health care organisation, Spectrum Health that had strong hiring needs since they sat with over 6000 position vacancies annually. Spectrum Health's talent acquisition department partnered with their lean process improvement team in an attempt to strategize their recruitment approach. The changes that came from their collaboration were structural, institutional, and cultural.

- **Structural:** The team realised that using the same recruitment structure for all kinds of hires was no longer appropriate. They developed a model with three swim-lanes that classified the talent as either high, moderate, or low level of intervention required by the talent acquisition team.
- **Cultural:** This is where the team had to introduce and promote the culture of continuous improvement and learning along with change management.

4.6 Conclusions - Findings

The literature highlighted the possible and present wasteful activities that take place in the recruitment departments and how this could lead to longer recruitment processes. These non-value adding tasks could cause frustration on the part of candidates, organisation departments waiting for positions to be filled and the recruiting department. However, the lean philosophies may be used to render services that are seamless and provide value to the candidates.

5 CONCEPT DESIGN FROM LITERATURE FINDINGS

The findings from the literature review and SLR in sections 2 and 3 are summarised in the form of the talent acquisition model presented in Figure 3. The model first categorised the types of hire [10, 15], and then considered tasks that would be most valuable for the candidates within each category.

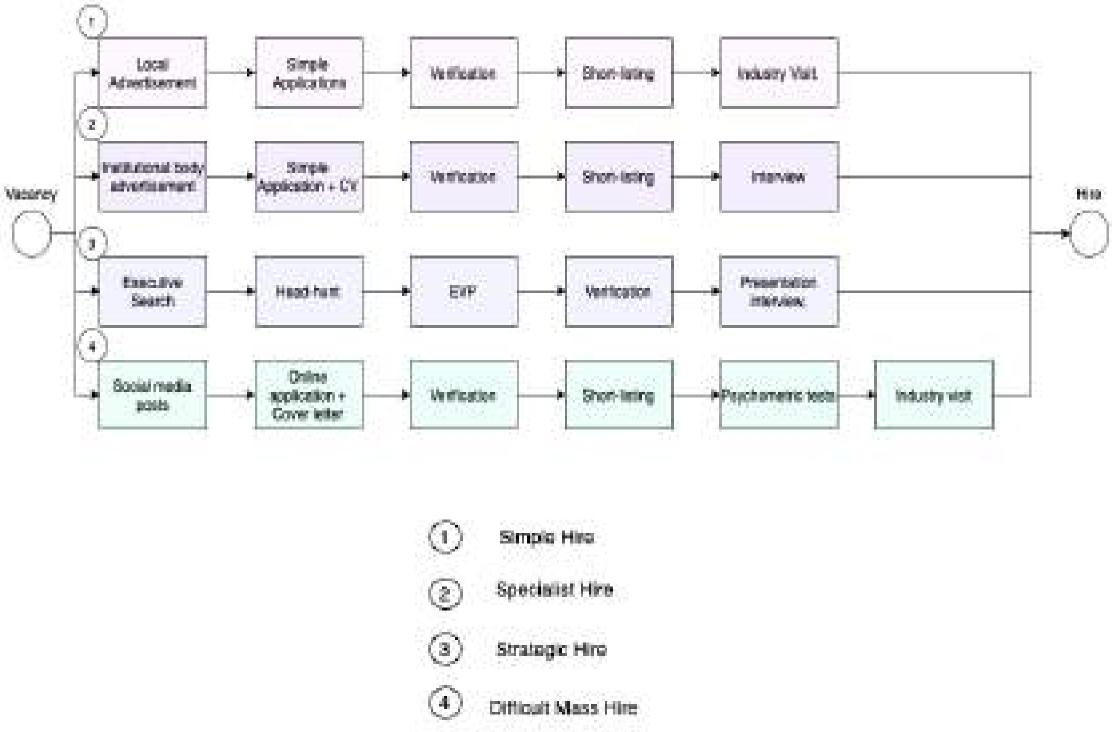

Figure 1: Talent acquisition process

5.1 Simple Hire

For the simple hire candidates, job posts and advertisements should be posted locally. The posts should not be fully digitized but rather advertised on posters near local communal areas such as shopping centres. The online applications should only request basic information from these employees, such as identification information (with proof and certified ID), contact details, and highest level of education. The simple hire candidates do not require to submit CV's as the positions that are listed under this category do not require high levels of education or experience. Candidates will be short-listed, strictly based on their highest level of education and locality, on a 'first-come, first-serve' basis. Finally, interviews are not the best way of verifying these candidates' fitness for the relevant positions, as some might struggle with articulating themselves, in a manner that fairly represents their abilities, due to language barriers or interview pressure. Industry visits with short-listed candidates, where they will be job shadowing for a few days before the final offer is made, would be a more fruitful approach. This differs from the traditional recruitment process which requires a lot of information that is not necessary for these types of candidates.

5.2 Specialist hire

The specialists hire candidates are low in availability in the labour market. As these candidates specialise in a specific domain within their industry they may be easily found within their industry's institutional bodies where they are registered. Vacancies may be advertised on these platforms. Advertisements should give a thorough description of the role and requirements needed for these positions. Online applications should be short and precise, with a focus on the attached CV, where the candidate's experience and expertise will be presented. As this will be a small pool of candidates, short-lists may be compiled faster and the interview panel should comprise the line manager of the department of the vacancy, seniors from the departments that will work closely with the candidate, and a representative from the HR department. This partnership approach will assist the recruiting department in reaching the specialists quicker since the advertisement will be directed to the specialists, as opposed to having a general online post, in the hope that the qualifying candidate is reached.

5.3 Strategic hire

The strategic hire vacancies should not be posted on social networks or locally, but an executive search should be conducted for these candidates. The candidates in this category are not seeking jobs and the talent acquisition team should actively headhunt these candidates from their current positions. The employee value proposition (EVP) plays a big role and attracting these candidates since these candidates are potentially in already existing positions in other organisations. The identified candidate should present his or her work, experience and contributions to a large panel consisting of line managers, employees from different levels, and external experts in the field. An offer should be made shortly after the presentation has taken place. The search for these candidates may be international.

5.4 Difficult mass hire

The difficult mass hire candidates are the candidates actively seeking work and take up a large number of positions in the organisation. These candidates may be reached by placing advertisements on social media platforms such as LinkedIn. The applications should retrieve most of the applicant's information for easier compilation of short-lists. The online applications should be divided into two stages, the first of which will retrieve the basic information of the candidates as well as an overview of their experience in relation to the job requirements. The short-list will be compiled from this first stage of the applications. The second stage will request more details on the candidates for further, and in-depth, evaluation of the candidates. Psychometric tests will evaluate the candidates fit within the organisation, problem-solving skills, and critical thinking abilities. An industry visit will serve to assess the candidates fit within the organisation through job-shadowing, after which an official offer may be placed. This differs from the traditional recruitment process since this approach understands that these candidates have little work experience, but they do have the qualifications for the position. In this case, the cover letter allows the applicants to justify why they are the perfect candidates for the position, as opposed to requesting a CV and short-listing based on experience and qualification alone.

6 CONCLUSION

With Lean being a common tool used by industrial engineers, this paper sheds light on how industrial engineering principles may be applied within the human resources departments. The talent acquisition model in Figure 3 was derived by puzzling together lean tools and strategic talent acquisition from literature. This will assist in targeting talent that is fit for the job through a seamless process that will not just reach the right potential candidates but will also save the HR department time and frustration in the process. Lean recruitment can also be achieved by understanding the different position rankings and categories; 1) Simple hiring, 2)

Difficult Mass hire, 3) Specialist Hire and 4) Strategic hiring within the organisation. Moreover, this will result in value-adding candidates in the organization. Failure to do so will result in organizations either struggling to find applicants that meet the requirements for the position, or on the other hand , will have to work through a long list of applicants and sit through many interviews unnecessarily. This talent acquisition model can assist organizations with their recruitment process, reducing the amount of man hours spent on recruitment. The model is scalable to the size of any organization. The customization and elimination of redundant steps makes this technique unique and will ensure that organizations get talent in an effective and efficient manner as they will be targeting active, passive and not-seeking candidates.

7 LIMITATIONS AND FUTURE STUDY

The talent acquisition model has been developed as a summary based on the principles found in literature on Lean recruitment. The model considered the four types of candidate hires that an organisations recruitment department should consider when attempting to fill a vacancy, and the correct approach to be used for each type. For more accurate results, future studies will not just focus on literature but should also be tested practically. In addition, future studies should focus on incorporating organisational cultural aspects of recruitment as well.

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DETERMINATION OF OPTIMAL DESIGN PARAMETERS FOR AUTOMATED GREENHOUSE FARMING OF TOMATOES IN THE AFRICAN CONTEXT

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ABSTRACT

Tomato plants are uniquely sensitive to extreme weather variation. Consequently, their exposure to the wrong environment may result in deficient fruit growth, disease or pest infestation and ultimately significant yield loss. Farmers require improved farming techniques to consistently meet consumer demand in today's highly competitive agricultural market. Greenhouses have been employed to achieve a conditioned environment for optimal growth. In this era of digitalisation, the operation of greenhouses can be automated to improve operational excellence. The qualitative study outlined in this paper was conducted through a semi-structured interview administered to a South African greenhouse farmer to determine the optimal parameters for farming tomatoes. In addition, a literature study in the global and African context was undertaken to validate the interview findings. The research established the role of manual labour and ideal design parameters for tomato greenhouse farming. The determined parameters were employed to establish a digital framework for automated greenhouse farming.

Keywords: Greenhouse farming, design parameters, digitalisation

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1 INTRODUCTION

Tomato consumption in South Africa (SA), according to a study by the Agriculture, Forestry and Fisheries department, was recorded at over 400 000 tonnes for 2016 with a 4% increase from 2015. Furthermore, a growth of 29% in the South African global export value of tomatoes in 2016 is evidence of the international demand for tomato production and of the necessity for the development of greenhouse production methods [1]. A significant percentage of crop yield is lost annually due to humidity related diseases and random instances of extreme weather variation. Hence, farmers require improved farming techniques to strategically meet the consumer demand in today's highly competitive agricultural market [2]. Fortunately, open-source software and technologies such as moisture and temperature sensors have become widely available and affordable. These sensors in conjunction with microprocessors allow for valuable data collection and processing of greenhouse climate parameters. A Fourth Industrial Revolution (4IR) system-network of these devices can allow for off-site control of the greenhouse to achieve optimal growing conditions in real-time, increased productivity and efficient resource usage [3].

In this paper, the open-source 4IR technologies which facilitate effective monitoring and autonomous control of greenhouse conditions are identified. To facilitate this, firstly the optimal environmental parameters for tomato growing are determined. Secondly, the role of manual labour in the greenhouse farming of tomatoes is defined. The paper is structured as follows: Section 2 presents the literature review which focuses on the growth stages for tomatoes and the role of manual labour in the greenhouse farming of tomatoes. Thereafter, the research method is outlined in Section 3 before the results are presented in section 4. The discussion on the results obtained and the study recommendations are then outlined in sections 5 and 6 respectively.

2 LITERATURE REVIEW

2.1 Introduction

In South Africa, tomatoes are farmed across the entire nation, with the Limpopo province being the most successful with 3 590 Ha of tomato farms as a testament to its ideal-warm climate conditions. The Kwazulu-Natal province followed by the Eastern Cape are also home to large tomato farms. Tomatoes are primarily produced during frost-free climate or otherwise in greenhouse tunnels [1]. Furthermore, South Africa is classified as a 'Semi-arid' region, with the majority of rainfall occurring during summer. The nation sees an average rainfall of approximately 464 mm [4]. As such, these weather conditions are ideal for the survival of the tomato plant. The next section presents the stages of tomato plant growth.

2.2 Tomato plant growth stages

One of the most common tomato types in Southern Africa is the Bush tomato ([5], [6]). This type of tomato plant will produce fruit throughout the growing season which is ideal for commercial farming [7]. The growth stages of the Bush tomato plant according to the Tomato Production Guideline [8] are as follows. The first process is germination. This is the process by which an initial root emerges through the coating of the seed and thereafter progressively through the soil while the seed is buried (planted) in the soil. Optimal temperature and water are critical to the health of the growing root at this stage [9].The second stage is the vegetative growth stage. At this stage, the seed rapidly begins to develop ground roots. The stem that has emerged from the soil becomes thicker and starts to form small branches and leaves. Fertilizer is crucial to supplement the growth of the plant at this stage because the plant will consume significant amounts of Nitrogen and Amino acids that promote cellular development [10]. Thereafter, the third stage is the budding or fruit setting stage. Buds begin to form and petals spread open, during this time pollination will occur and this is best promoted by bees. The pollinated flowers then grow into green tomato fruit as multiple fruit clusters begin to set on the plant [11]. The final stage is red colouring. As the green tomato fruit grows, a gradual change of colour takes place until the fruit is in a shade of red. This is a sign of fruit ripening but is not an isolated indicator of ripeness. Furthermore, the red colouring process is considered the final stage of development before harvesting [11].

Table 1: The growth stages of the tomato plant

Growth Stage	Duration [days]	Accumulated Duration[days]
1. Germination	6 - 8	8
2. Vegetative Growth	14 - 16	24
3. Fruit Set	14 - 21	45
4. Red Colouring	14 - 16	61

Table 1 above specifies the sequence of growth stages and each associated duration. Germination is the shortest yet most critical stage of seed development. Traditional conventional farming methods have limitations and lack reliable efficiency levels to produce enough fruit. Furthermore, the effects that climate change has on agriculture makes traditional farming even more unreliable [12]. Due to the limitations of conventional farming methods, farmers are now exploring Controlled Environmental Agriculture (CEA) like the use of greenhouses. Greenhouse developments have afforded farmers the chance to produce crops at any given time of the year. Greenhouse farmers can therefore farm crops without the limitations and restrictions caused by undesirable climatic conditions and soil landforms. The following sections outline some crucial environmental conditions for growing tomatoes.

2.3 Optimal environmental conditions for growing tomatoes

2.3.1 Air temperature

For optimal tomato plant growth, it is important to note that air temperature corresponds closely with soil temperature. The following ideal air temperature ranges have been identified for each growth stage of the tomato plant according to [8]. From the data in Table 2, a minimum air temperature of 10 degrees Celsius serves as the lower boundary whilst a maximum of 34 degrees Celsius serves as the upper boundary. As shown in Table 2, ideal temperatures for tomato growth generally varies less during the vegetative growth, fruit setting and red colouring stages.

Table 2: Temperature ranges per development stage for optimum tomato production

Growth Stage	Temperature [°C]		
	Minimum	Optimum	Maximum
Germination	11	16 - 29	34
Vegetative Growth	18	21 - 24	32
Fruit Set – Day	18	19 - 24	30
Fruit Set – Night	10	14 - 17	20
Red Colouring	10	20 - 24	30

Furthermore, warm climate conditions that achieve suitable temperatures for tomato growth are ideally accompanied by sun-light/radiation [14].

2.3.2 Soil requirements

Soil composition is critical to the flourishing of the tomato farm, soil acidity in particular should ideally be maintained within a pH range of 5.5 to 6.8 [7]. A high soil acidity is linked to the harmful wilting of plants. Furthermore, fertilisation content for Bush (Determinate) tomato production should contain the following optimal quantities per growth stage:

Table 3: Nutrient requirements *of strong determinate tomatoes* [8]

Growth Stage	Mineral Nutrient					
	N	P	K	Ca	Mg	N:K
Pre-plant	50	50	65	0	0	1:3
Transplant to flowering	45	18	65	10	8	1.4
Flowering to fruiting	55	18	110	70	13	2
Harvesting	70	12	120	55	3	1.7
Total:	220	98	360	135	24	1.6

The values contained in Table 3 above are in units of Kg/ha, the minerals represented are Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca) and Magnesium (Mg). Potassium and Nitrogen are clearly the highest nutrient consumption of the tomato plant, playing a key role in both plant and fruit growth during flowering, fruiting and maturing of the fruit until the time of harvest.

2.3.3 Carbon dioxide levels

Carbon dioxide (CO_2) level in a greenhouse enclosure has been directly linked to crop yield [15]. An experiment was conducted over a period of 300 days by [16]. Results revealed an ideal CO_2 level of approximately 0, 10 % of total volume. It is important to note that CO_2 costs can be reduced by only dispersing CO_2 whilst there is solar radiation and the greenhouse windows are unactuated (closed) [16]. The ideal internal temperature for a tomato greenhouse is an average temperature of 25°C and the ideal CO_2 concentration is an average of 500 ppm which is approximately 0.05% of total volume [15].

2.3.4 Irrigation levels

Irrigation quantities can be represented as a percentage of evapotranspiration (ETc). Evapotranspiration refers to a measure of the evaporation from the soil surface combined with the transpiration of the actual plant. An experiment was conducted for optimum daily irrigation levels for the production of tomatoes, the following three irrigation levels were observed: 50%, 75% and 100% ETc. Each level corresponds to an amount of irrigation water. A 50% ETc is equivalent to 290.65 mm of irrigation water, likewise 75% ETc is 435.97 mm of irrigation water and 100% ETc is equivalent to 581.30 mm of irrigation water [17]. The results obtained indicate a significant relationship between irrigation and fertilization of the soil, hence it is important to maintain ideal soil composition in conjunction with irrigation control. Maximum plant height was achieved under a 75% ETc conditioning, as well as the highest number of healthy fruit and the highest number of total fruit yield [18]. In conclusion, an average irrigation level of 435.97 mm through a dispersion routine of twice a day as discussed above is identified as the optimal irrigation level for the production of tomatoes. However, the study further reveals that composition of the soil has a much greater influence on plant health and growth than irrigation [17].

2.4 The role of labour in greenhouse farming of tomatoes

The production of tomatoes remains a labour intensive process and this implies that a significant expense is attached to manual labour. The soil is initially prepared for plantation, as this involves the removal of unwanted weeds, raking and the laying of fertilizer. Seeds are then dispersed, either by hand or by mechanical device to assist a manual labourer. If seeds are initially planted in containers, they will need to be transplanted [18]. As a tomato plant grows and increases in size, the plant will require support in the form of caging or staking to promote vertical growth that will ultimately maximize fruit yield. Staking is done manually and is a time consuming process, however, the benefits of staking also include reduced risk to disease and a reduced space consumption per plant [7]. Furthermore, the pruning of stems and leaves is a task that is done manually and regularly. This task requires discretion as incorrect pruning techniques may be harmful to the plant [18]. Irrigation and ventilation systems may be manually controlled, in such case, irrigation pipelines and taps will require opening and closing. Similarly, ventilation fans or windows will need to be switched on and off or opened and closed [3]. The most manual labour intensive task, however, is the task of harvesting the fruit produce, similarly to pruning this task requires discretion and is done regularly as many clusters of fruit will begin to ripen at once [7].

2.5 Open-source 4IR technologies for greenhouse automation

It is important to note that greenhouse operations can vary from having minimal technological contribution to being largely autonomous [19]. 'Open-source' technology refers to the characteristic of a software and its associated devices that can be modified freely – by the user - to better suit the specific needs of the user. The programmable codes of such devices are often shared online and can be further developed with ease [20]. In an agricultural context, the device may be a microprocessor that is programmed to receive, process and communicate specific information to a network of actuators and sensors to control a greenhouse environment [3]. In addition to this, these networks can be made wireless and self-sustainable through the use of renewable-energy supply [21].

2.6 Types of greenhouse structures

Several types of greenhouse designs have been developed over time based on attempts to meet the various growth needs of different crops. The two major types of greenhouse structures are referred to as 'Free-standing' and 'Ridge-furrow'. Although the frame structure design may vary, the general materials used for the frame are aluminium, plastic, steel or wood [22]. Furthermore, the frames' truss structures must be strong and durable without being too large in dimension such that it obstructs a significant amount of light transmission into the greenhouse because this will affect the uniformity of crop growth [23]. The materials generally used for the transparent enclosure walls of greenhouse structures are glass, plastic or polyethylene, these are critically selected for their role in heating, insulation and security of crop from theft. Free standing greenhouse types include the arc type, even-span design, Gable-roof design, Uneven-span design, Quonset structure and Lean-to-Greenhouse structure ([22], [23]). On the other hand, Ridge-furrow structures (which are more economical) include types like the Saw-tooth design and the Venlo design [22]. Given these options, the key question remaining is which combination of technologies and materials are suitable for optimal tomato plant growth in an African context? The next section outlines the methodology used in the paper to answer the question.

3 RESEARCH METHODOLOGY

The study followed the qualitative research design, and this was done using a semi-structured interview and secondary research via observational note-taking of four online videos on tomato greenhouse farming as the research methodologies. The observational note-taking through desktop research was conducted as a means of overcoming the limitations posed by the COVID-19 pandemic and South African national lockdown restrictions which were in place when the study was conducted. An initial target population of five farmers with Tomato Greenhouses was set out. These were identified and selected based on their farming experience (at least five years' experience). However, only one farmer agreed to participate in the study. The subject participated in the primary research study by individually responding to the survey instrument via a telephonic interview rather than a face-to-face interaction in consideration of the risks associated with the COVID-19 virus at that time. A qualitative approach was selected because the study aimed to understand the optimal parameters for tomato greenhouse farming for the purposes of identifying optimal 4IR technologies. Qualitative studies make it easy to interpret phenomena and what those interpretations mean in each context. One of the advantages of qualitative research is that it gives access to detailed information about the research topic which is useful in answering how and why questions [24]. This will limit bias and make it easy for scientific generalisation to be made. Figure 1 below summarizes the steps followed in collecting and analysing data for the study.

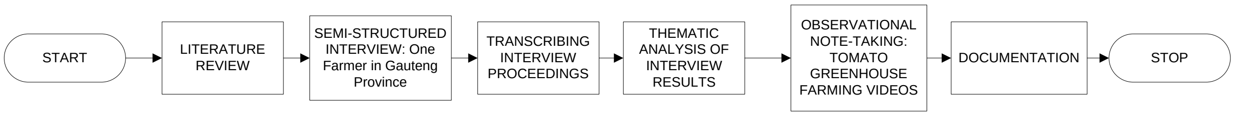

Figure 1: Steps in conducting the research study

Firstly, a systematic literature review was conducted to understand the topic in detail and to aid in developing interview questions that were relevant for the study. Secondly, semi-structured interviews were conducted with an identified farmer from the South African Gauteng Province. One of the disadvantages of semi-structured interviews are that they are time-consuming [25]. To overcome this challenge, the interview was timed to be no longer than forty-five minutes. Another disadvantage is that the information gathered during the interview may be difficult to analyse and generalise [25]. The research instrument used during the semi-structured interview was made up of a total of thirteen questions and four sections consisting of a mixture of dichotomous and open-ended short questions. The interview was intended to obtain a measure of ideal parameters for the optimal growth of a tomato plantation within a greenhouse; the role of manual labour within the operation of a tomato greenhouse facility was also intended to be defined. This was followed by the transcription of vital points that were deducted from the interviews. Lastly, using Nvivo software, the responses were grouped according to categories through the generation of themes and attribute codes. This made it easier to analyse the information. To validate the interview findings, observational note taking of four videos on tomato greenhouse farming available online was conducted. In addition to this, the optimal combination of applicable 4IR technology for an automated tomato greenhouse facility were then derived based on the semi-structured interview responses and four videos analysis.

4 RESULTS

The results section below have been separated into two parts based on the source that the information was obtained from. The results shown in section 4.1 are those obtained through the semi-structured interview (primary research).The results contained in section 4.2 have been extracted through the observation of four online video sources (secondary research). Unfortunately, the response rate to the research instrument was less than desired which may be a consequence of the COVID-19 pandemic. For this reason, four video observations derived from a global context containing information regarding greenhouse farming, which are publicly available online, were utilised to validate the results of the primary research and to better respond to the objectives of this study.

4.1 Semi-structured interview results

The following results have been obtained through an interview conducted by the researcher and a respondent (farmer) in the field of greenhouse tomato farming. The identity of the farmer was kept anonymous to abide by set ethical considerations. However, it can be said that the farmer participating had over ten years of farming experience at a greenhouse facility located in Pretoria – Gauteng, South Africa. Table 4 below outlines the farmers' responses to the semi-structured interview conducted. These results are further analysed and discussed in section 5.

Table 4: Semi-structured interview results

Question	Response
Section 1: Background	
1. Where this greenhouse facility is located [city, province, country]?	Soshanguve - Pretoria, Gauteng, South Africa
2. What is your role/position at this greenhouse facility?	Farmer
3. What is the approximate capacity/size of the green house facility?	Approximately 800 plants in the greenhouse facility
4. What is the approximate capacity/size of a greenhouse workforce?	Two workers per greenhouse
5. What is the approximate annual fruit/vegetable production rate of the greenhouse facility?	Uncertain
6. Which crop/plantation has been attempted to be grown in the greenhouse facility BUT failed?	None, I prepare well and make informed decisions.
Section 2: Environmental Parameters for Tomato Growth	
7. Are tomatoes grown in the greenhouse facility?	Yes
8. If Tomatoes are grown in the facility, what are the success factors of doing so, in your opinion?	Care and maintenance Good fertilization Pest control using chemical sprays
9. Which Environmental Parameters do you believe are most crucial to healthy tomato growth? Please list in order of significance and state ideal quantity range. [Example: Temperature, 23°C - 27°C].	Hot climate, tomatoes must be grown during summer. Fertilization Sufficient Irrigation [Uncertain of parameter values]
Section 3: The Role of Manual Labour	
10. Which greenhouse related tasks are done by manual labour, please list in the table below?	All greenhouse tasks are done manually.
11. Which of the above manual labour tasks do you believe can ideally be replaced by digital/mechanical automation?	Irrigation Spraying of pest control chemicals
Section 4: Greenhouse Automation & Digital Technologies	
12. Is this greenhouse facility automated?	No, no technology. We only use simple mechanical tools.
13. If yes, which greenhouse monitor/control/analyses tasks are automated?	None.

4.2 Video observation results

Table 4 below contains four sections that each outline key observations (from online desktop research) with specific reference to an identified video source. These observations intend to validate the findings of the primary research results in section 4.1 in responding to the research objectives of this study.

Table 5: Secondary research results

	Video source 1	Video source 2	Video source 3	Video source 4
1. Title of video and reference	Amazing Greenhouse Tomatoes Farming - Greenhouse Modern Agriculture Technology [26]	Young farmer making a fortune from Greenhouse tomato farming [27]	Tomatoes Farming: Greenhouse Commercial Nature - Agritech in Future'. [28]	Greenhouse tomato farming [29]
2. Location of Greenhouse	United States of America	Kenya	United States of America	Kenya
3. Greenhouse structure material	Large metal frame structure and enclosed with multiple layers of polyethylene curtain	Gabled-roof design constructed using a wooden frame and enclosed with polyethylene curtain	Ridge-furrow type of greenhouse structure. The frame structure of the greenhouse is metal and the enclosure is made of glass panels.	A wooden structure and a polyethylene curtain
4. Recommended optimal parameters	- *Optimal temperature*: 24°C during the day and 18 °C during the night. - Light intensity: 20 $mol.m^{-2}.d^{-1}$ for maximum productivity	- *Optimal temperature* interval during the day as 16°C to 30°C and 13°C to 18°C at night	- Not mentioned in the video	- The farmer recommends that soil is frequently tested and that the environment is frequently sterilized.
5. Level of farming operations automation	- *Manual operations:* Seedling growing, connection of stalks to the plant stem; transportation; pruning and harvesting. - *Automated operations:* use of hydroponic computerised irrigation and nutrient control system, air temperature sensors, humidity sensors, soil moisture sensors and light intensity sensors.	- *Manual operations:* fertilising, pest control is achieved by inter-planting spring onions in the tomato plantation, seedling growing, connection of stalks to the plant stem; pruning and harvesting. - *Automated operations*: air temperature sensors only.	- *Manual operations:* limited to pruning and harvesting of ripe fruit. - *Automated operations:* This greenhouse utilises a fully automated system of 4IR technology combined with a hydroponic setup and foam slab use. Humidity, temperature, light sensitivity, fertilizer composition and irrigation levels are all monitored and controlled by a single computer system	- *Manual operations*: All operations are done manually. Tomato seeds are sown in smaller containers or in open-field plantations and then transplanted after 18 to 21 days. A drip-line irrigation system is also used in this facility, irrigation is manually controlled and the soil moisture is manually monitored. Furthermore, this farm promotes minimal handling of the tomato fruit for the sake of higher quality produce. - *Automated operations*: None

4.3 Analysis and Discussion

The analysis undertaken in this section is based on the five sets of results contained in section 4.1 and 4.2. This includes the primary research results from the semi-structured interview and the desktop research results of the four video observations intended to validate the primary research. Attribute codes for the optimal greenhouse parameters were generated by Nvivo software.

4.3.1 Ideal parameters for optimal tomato growth

Temperature, light intensity and soil moisture and nutrients levels were identified as the optimal parameters for tomato growth. Firstly, the first three sets of results identify tomatoes as being a warm climate crop. The large greenhouse facility located in the USA of video source one recommends an optimal air temperature of 24˚C during the day and 18˚C at night. In support of this, according to the information from the farmer located in Kenya of video source two, the ideal air temperature range to be maintained within the greenhouse is confirmed as 16˚C to 30˚C during the day and 13˚C to 18˚C at night. These findings correlate with the work by [8], which reveals a more detailed list of ideal temperature ranges as illustrated in Table 2 for each growth stage. The greenhouse farms in both video source three and four do not explicitly state the air temperatures maintained within their facilities. Similarly, the farmer who responded to the semi-structured interview claims that tomatoes are grown during the warm conditions of the summer season of South Africa and that the greenhouse farm is not technologically equipped to monitor exact temperature parameters. Secondly, the farmer in video source one identified the optimal light intensity as 20 $mol.m^{-2}.d^{-1}$. This finding correlates with work by [14] who recommended a light intensity of approximately 100 000 Lux (equivalent to bright sunlight radiation) during the day (08:00 to 16:00) for optimal tomato plant growth. The remaining three video sources and the semi-structured interview respondent have all been unable to specify optimal light intensity. An ideal soil pH range of 5.5 to 6.8 has been revealed through the literature review of Section 2. Thirdly, according to video source one, combining irrigation and nutrient supply via a hydroponic system is the ideal method of irrigation. Video source three is in support of this concept and claims that the irrigation and nutrient content of this hydroponic system can ideally be monitored and controlled by a single computer system. Both farms in video source one and three are located in the USA and are equipped with sophisticated automation technologies. Furthermore, the drained nutrient solution can be recycled through this hydroponic system provided that the nutrient solution is frequently tested and recomposed. In contrast to this, the farmer respondent as well as the farmers in video source two and four, located in South Africa and Kenya respectively, each use soil-based plantations in conjunction with a drip-line irrigation system. This method of irrigation is manually controlled. Optimal irrigation is done twice a day, in the morning and in the evening but soil moisture must be monitored or tested beforehand to confirm moisture requirements according to video source three. Finally, frequent soil testing is also emphasized in the results of video source three for the sake of monitoring soil pH and nutrient composition which both have a significant effect on crop health and crop growth. The farmer explains that Fusarium wilt and Bacterial wilt are consequences of soil with high acidity content. In the comparison of solid soil fertilizer versus hydroponic nutrient solution, we see that solid fertilizer is at a disadvantage; firstly in terms of soil pH control, secondly in terms of effective dispersion composition and lastly in terms of recyclability as described by video source three.

4.3.2 Optimal combination of open-source 4IR technology: Requirements mapping

Based on the analysis in section 4.3.1, the following list of requirements must be satisfied by the final design and therefore all concepts to be generated must adhere to each of these points to be considered for final selection:

1. The 4IR technologies control system must process and respond to environmental conditions in 'real-time'.
2. The 4IR technologies control system must maintain the greenhouse air temperature within the range of 13°C to 18°C during the night (18:00 to 06:00) and within 18°C to 30°C during the day (06:00 – 18:00) for optimal tomato plant growth [8]. In the event that the air temperature exceeds the minimum boundary, an artificial heating system must be activated to manipulate the greenhouse air temperature back to optimal midrange i.e. midrange of 18°C to 30°C is 24°C. Similarly, in the event that the maximum boundary is exceeded, an artificial cooling system must be activated to manipulate the greenhouse air temperature back to optimal midrange.
3. The 4IR technologies control system must maintain a light intensity of approximately 100 000 Lux (equivalent to bright sunlight radiation) during the day (08:00 to 16:00) for optimal tomato plant growth [14]. In the event that the greenhouse light intensity exceeds the minimum boundary of 95 000 Lux, an artificial lighting control system must be activated to return greenhouse light intensity to the optimal value of 100 000 Lux. 4.1.1.4 The 4IR technologies control system must maintain a soil moisture level of 75% ETc or 435.97 mm for a 1 hour duration twice per day (07:00 to 08:00 and 16:00 to 17:00) for optimal tomato growth [17].
4. In the event that the soil moisture level exceeds the minimum boundary of 430 mm during either of the 1 hour periods, the irrigation system must be activated until the soil moisture level is returned to 75% ET_C.

Figure 2: System context diagram

Based on the derived requirements, sensors for air temperature, light intensity and soil moisture monitoring are required for tomato greenhouse farming as shown in Figure 2 above.

4.3.3 Optimal 4IR technology for tomato greenhouse farming

Table 6 below summarises the selected digital design components identified for tomato greenhouse farming.

Table 6: Bill of materials and some 4IR technology for tomato Greenhouse farming

Design component	Description	Image of component (if applicable)
Foundation	Concrete	 **Figure 3: Gable roof design greenhouse [30]**
Frame structure	Aluminium frame: Gable-roof design	
Covering material	Glass panels	
Carbon fertilizer systems		
Heating system	Central boiler with piping rails	
Cooling system	Evaporative cooling - mist dispersion	
Lighting system	Induction lighting	
Temperature sensor	MELEXIS Infrared thermometer – MLX90614 0.02°C accuracy, -40°C to 125°C, 3 to 16V DC	 **Figure 4: MELEXIS Infrared thermometer [31]**
Light intensity sensor	KEYESTUDIO Digital ambient light sensor module – 12C BH1750FVI	 **Figure 5: KEYESTUDIO Digital ambient light sensor module [31]**
Soil moisture sensor	SUNLEPHANT Moisture sensor & pump controller FC-50/170248 with 12V DC relay	 **Figure 6: SUNLEPHANT Moisture sensor & pump controller [31]**
Microcontroller	KEYESTUDIO Arduino Uno R3 develop module board + USB lead	

The gable-roof glasshouse design was conceptualised as the best housing design for the context. This particular structure is an even-span, free standing structure with the more sophisticated material selection and more advanced open-source 4IR electronic components as compared to other structures. The selected light intensity sensor for this context is a digital component rather than an analog one. The infrared temperature sensor provides significantly more precise readings than its competitors but at a significantly higher cost. Each of the above mentioned open-source 4IR technology sensors are compatible with an Arduino microcontroller and can be connected in a wired network to effectively test the functionality and response of a greenhouse model such as the gable-roof glass greenhouse model concept.

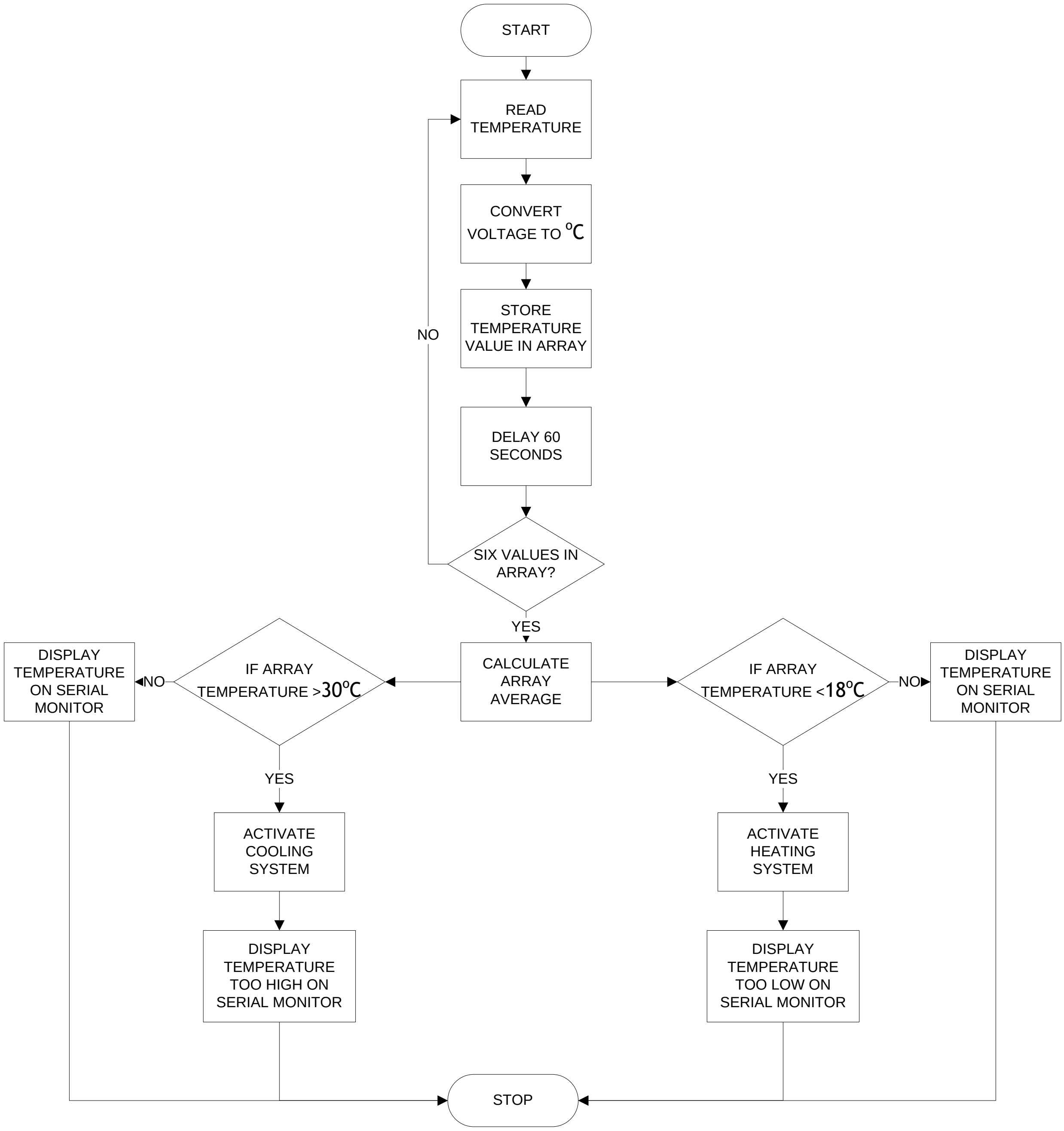

Figure 7: Programming logic for the temperature sensor

A sketch (programming code) was written for each sensor and uploaded into the Arduino microcontroller. The flow diagram in Figure 7 above represents the logical processing of the programmed temperature sensor circuit and its associated Arduino code is illustrated in Figure 8 below.

```
//  Project Title: Greenhouse 4IR Control System
//      Due Date: 05 November 2020
//      Name: Kestell Theron
//      Student Number: 1066917
//      Supervisor: Dr Mncedisi Trinity Dewa
//  The University of the Witwatersrand, School of Mechanical, Industrial & Aeronautical Engineering.

int r1 = 2;                     // Initializing LED indicators for Temperature Sensor circuit (r = red, g = green, y =yellow).
int g1 = 3;
int y1 = 4;

void setup() {
                                            // put your setup code here, to run once:

Serial.begin(9600);
pinMode(r1, OUTPUT);
pinMode(g1, OUTPUT);
pinMode(y1, OUTPUT);
}
void loop() {
                                            // main code here, to run repeatedly:
//--------------------------------------------------------------------------------------------------------------------------------------
//                               Greenhouse Air Temperature Control Code with  LED & Serial Monitor Display criteria
//--------------------------------------------------------------------------------------------------------------------------------------
float temp[6];                              // initialize an array to store 6 temperature sensor readings (with decimal values).
for (int x = 0; x < 6; x++){                // create a count loop to record a reading at every count interval from 0 to 5 (6 readings).
  temp[x] = analogRead(A0)*(100 * (5 / 1023.0));   // storing each sensor reading into the array after converting the analog voltage reading into a degrees celcius temperature value.
  //Serial.println(temp[x]);                // displaying the array of 6 temperature values to the serial monitor(FOR TESTING & VERIFICATION PURPOSES ONLY).
  delay(60000);                             // 60 second delay between readings for system stability
}

float avgTemp = ((temp[0] + temp[1] + temp[2]+ temp[3] + temp[4] + temp[5])/6);  // Calculating the average of the 6 recorded readings in the temperature array for system stability
Serial.println(" ");                                                              // Displaying the Calculated Average temperature in Degrees Celcius on the serial monitor.
Serial.println("Current Air Temperature Average is:");
Serial.print(avgTemp,2);
Serial.println(" Degrees Celcius");
Serial.println(" ");

  if (avgTemp < 18.00){                                       //Setting output criteria for LED & serial monitor display when Temperature is Too Low.
   digitalWrite(y1, HIGH);
   digitalWrite(g1, LOW);
   digitalWrite(r1, LOW);
       Serial.println("  Current Average Air Temperature:  TOO LOW!");
       Serial.println("  Artificial Heating:  ACTIVE! ");
       Serial.println("  Artificial Cooling:  INACTIVE");
       Serial.println(" ");
  }

[illegible]
```

Figure 8: Arduino code for the temperature sensor

5 CONCLUSION

The qualitative study conducted identified optimal environmental parameters for tomato growth in a greenhouse facility. Air temperature, light intensity, irrigation levels, nutrient supply, soil pH and CO_2 levels within a greenhouse facility were identified as the most significant environmental parameters of a greenhouse tomato plantation. An understanding of the role of manual labour in operating a greenhouse facility was also determined. The significance of a farmers' discretion in manually performed tasks such as pruning and harvesting was acknowledged. In addition to this, the limitations of open-source 4IR technologies in performing tasks such as pest, virus and disease detection are revealed. It has been determined that manual labour not only influences greenhouse operational cost but also influences time efficiency and the quality of fruit produce. Furthermore, open-source 4IR technologies applicable to the optimal automation of a greenhouse facility have been identified. In response to the critical research question of this study, the following combination of open-source 4IR technologies will enable optimal automation and control of a tomato production greenhouse facility in a South African context: A greenhouse facility equipped with a hydroponic - foam slab system, air temperature sensors, humidity sensors, moisture sensors, light intensity sensors and CO_2 volume sensors. This network of sensors will provide input to a programmable microprocessor or computer system. The computer system will then process decisions based on sensor input data and activate control switches and actuators to manipulate; a boiler heating-humidity system fuelled by a sustainable energy source (preferably recycled wood), an array of UV-lighting bulbs, a recyclable nutrient-solution and irrigation system and lastly a CO_2 dispersion system. Finally, parameters such as soil pH and pest management will need to be carried out through the good agricultural practices identified in the analysis in Section 4.

6 RECOMMENDATIONS FOR FUTURE RESEARCH

In conducting this research study, the effectiveness of the research instrument and its associated response rate posed limitations on the success of obtaining significant insight into greenhouse farming of the target population of South African greenhouse farmers. In addition, the respondents' opinions and experiences may vary based on their individual expertise and career exposure thus affecting the findings. It is recommended that more focus be given to the target population in future research. Furthermore, it is recommended that research be conducted into the awareness and accessibility of open-source 4IR technologies amongst farmers in lesser economically developed regions such as the continent of Africa. Further work can be conducted to design a tomato greenhouse model facility that employs the open-source 4IR technology network using selected technologies described in section 4 above. This optimal combination of technologies should be simulated and evaluated on its effectiveness in achieving the associated ideal environmental parameters. Furthermore the crop yield, the quality of crop produce and the economical parameters of this facility should be evaluated.

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LEAN-AGRICULTURE: UNEARTHING THE PUZZLE PIECES ACROSS DIFFERENT INDUSTRIES

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ABSTRACT

The lean philosophy has long since moved from manufacturing plants to other operations such as insurance and healthcare. The agriculture industry is no different in terms of production processes, facilities, people, and challenges. However, agriculture provides a different set of challenges due to seasonal variability, bulk production, processing and problems in handling and storage. An opportunity exists to introduce the Lean concepts in more depth in agriculture given the magnitude of waste and losses in this industry. Therefore, the aim of this study is to conduct a rapid literature review in order to retrieve available research on Lean implementation in the agriculture industry to direct future research. The study identified one hundred and two studies highlighting the different applications of Lean-Agri. Given the increase in publication over the years, it is evident that research into Lean-Agri is increasing but more research is needed to further highlight its value and its range of applications.

Keywords: Lean, Agriculture, Rapid Literature review

* Corresponding Author

1 INTRODUCTION

Lean principles were originally developed in manufacturing as a set of tools and techniques that could eliminate waste from the production process. However, Lean techniques later moved from manufacturing plants to other operations, such as insurance, healthcare, government functions, non-profit businesses, and other economic activities, giving rise to Lean X concepts such as Lean accounting and Lean healthcare [1, 2].

The agriculture industry is no different from these industries in terms of production processes, supply chains, facilities and people. Also, its challenges are similar: less-than-desired throughput, facility layout that is not conducive to flow, a need for better project management and business engineering, the need for improved quality management and much-needed assistance with human resource planning and management.

The farmer is essentially a Jack of all trades and master of ALL, required to know various technical disciplines such as mechanics, hydraulics, electrical power, irrigation, structural design and, in recent years, electronics. Over and above these skills, farmers are required to understand how to run a profitable business, including the management of a workforce and resources. Additionally, farmers need an array of knowledge in the chemistry and the science of agriculture itself. They are expected to do all of this to provide for their families and produce for the country while facing unpredictable (natural) circumstances. In this sector, as in other sectors, global competition has resulted in a movement to large-scale production, greater use of standardised technology and more organisational and managerial innovations [2]. The management tools used in the agricultural sector are specialisation, formalisation and standardisation, all of which link to the trend towards fewer and larger farms [2].

Outside the farm, the Agricultural supply chains are complex systems that face the challenge of maintaining the freshness of agricultural products during staging, handling, packaging, and storage [3], while at the same time facing the challenges of integrating the agricultural supply chain into mainstream retail and distribution channels.

Fortunately, Lean is increasingly used in some parts of the agricultural sector [2]. However, differences exist in how Lean is used in the agricultural sector compared to how it is used in the manufacturing sector. It is not clear how Lean principles and tools adapt to farm operations or how farmers interpret Lean Thinking [2]. The challenge remains that Lean in agriculture provides a different set of challenges due to seasonal variability, bulk production, processing and problems in handling and storage [1]

An opportunity exists to introduce the Lean concepts in more depth in agriculture given the magnitude of waste and losses in this industry. However, before introducing Lean principles in more depth to a wider variety of agri-industries, it is important to understand in which of these agri-industries these principles have already been implemented. This will assist with a starting point to have the biggest impact.

The aim of this study is to conduct a rapid literature review, to identify available research on where Lean implementation has occurred in the agriculture industry. Future research can then focus on a further in-depth literature review to determine the details of each of the implementation processes.

The rapid review method that was followed is described in Section 2. The findings are presented in Section 3. Proof of validity is provided in Section 4, after which the conclusion and future research are presented in Sections 5 and 6, respectively.

2 METHOD

The rapid literature review process was used as guidance for this initial study before a more systematic review is conducted in future [4]. The methodology was selected for the rapid search and appraisal of existing research on Lean applications in the agriculture industry. By using elements of a full systematic review, a rapid review provides a rigorous method for assessing existing literature while reducing the overall scope of the review process by allowing concessions such as focusing on the research question, limiting search strategies and/or performing less sophisticated analysis [5].

This study utilised a rapid review strategy using the SALSA framework [5]:

1. Search - A systematic search of databases;
2. Appraise - Selection of relevant studies using inclusion and exclusion criteria and grouping by agri-industry;
3. Synthesis - Extraction of relevant data from literature sources; and
4. Analyse - An analysis of the literature found.

2.1 Search – Systematic search of electronic databases

The aim of the literature review was to investigate whether Lean principles are applied in the agricultural industry. The search was limited to journal articles, conference proceedings, books and book chapters and literature written in English. Since this was a rapid review, only one electronic database (Scopus) was searched using keyword search strings with Boolean logic. When publishing research related to Lean principles, different terminologies (Lean manufacturing, Lean philosophy, Lean Management, Lean production) are used, as Lean is polyonymous. In a similar vein, different terminologies are used in agriculture. Instead of running the risk of unintentionally excluding valuable literature, five different search strings were used. These search strings, as well as the numbers of studies retrieved from each search, are presented in the search protocol in

.

2.2 Appraise - Selection of relevant studies

Inclusion and exclusion criteria were developed to remove irrelevant articles from further analysis (Table 1). Studies that focussed on Lean implementation in agriculture were included while studies that referred to biological sciences, weight loss, Lean Six Sigma, lean meat, lean agricultural season, lean agricultural yield or lean agricultural periods were excluded.

2.3 Synthesis – Extraction of relevant data

The relevant data was extracted from the selected studies. The list of selected literature is presented in the appendix, categorised by agriculture industry.

2.4 Analyse – Analysis of literature found

The literature sources that were extracted were analysed in terms of 1) the type of agriculture industry in which the Lean principles were implemented, 2) the names of authors and 3) the date of publication. It was also noted if the study was based on the larger agri-supply chain or at the point of production, namely on farms. The findings are discussed in Section 3.

3 FINDINGS

Findings from the five different search strings (indicated in Table 1), combined with the inclusion and exclusion criteria, resulted in an initial 119 studies. These studies were combined and duplicate studies were removed, after which 102 studies remained.

3.1 Lean Management in Agriculture

Different, but complementary, results were found in the five different search strings, as explained in the following sections.

Table 1: Search protocol

Objective of study	To investigate whether Lean principles are applied in the agricultural industry.				
Search strategy	The search was limited to: • Journal articles, conference proceedings, books and book chapters, • Literature written in English.				
Databases	Scopus				
Inclusion criteria	Research regarding Lean implementations in agricultural industries				
Exclusion criteria	Biological Sciences Weight loss Lean Six Sigma studies Reference to “Lean” meat in the context of farming Reference to "lean agricultural season", "lean agricultural yield" or "lean agricultural periods"				
Quality assessment criteria	Repeatable and reputable scientific research methods should have been followed.				
Keywords	1	2	3	4	5
	"Lean agri*"	Lean AND agri	Lean philosophy OR Lean manufacturing OR Lean principles OR Lean implementation OR Lean production OR Lean management AND agriculture	Lean philosophy OR Lean manufacturing OR Lean principles OR Lean implementation OR Lean production Within the subject area: “Agricultural and Biological Sciences”	“Lean farm”
Results found	13	40	60	94	2
Inclusion and exclusion criteria applied	6	30	39	42	2
Duplicates removed	102				

3.1.1 Research protocol 1 - Lean Agri

When the phrase “Lean Agri*" was searched on Scopus, 13 results were found. Papers with the phrases "lean agricultural season", "lean agricultural yield" or "lean agricultural periods" were excluded since this referred to specific deficits in seasons (dry spells), profits and periods. After considering this, only six papers [1, 3, 6-9] remained that truly referred to the application of Lean principles in the agricultural industry.

3.1.2 Research protocol 2 – Lean AND agri

After search protocol 2 (Lean AND agri) was followed, 40 results were found. However, seven results were not agri-related since they referred to management practices or lean drilling techniques or lean seasons. Another 4 studies were removed since they referred to lean meat. The remaining 30 studies were considered further and are presented in the appendix.

3.1.3 Research protocol 3 – Lean XX AND agriculture

After searching, 60 studies were found. Of these results, 19 were not related to the study since they referred to electricity, government, agri machines/implements, and the automotive industry. One study was excluded since it referred to plant genetics and another study was excluded since Lean was only mentioned in future research. Overall, the remaining 39 studies met the inclusion criteria and are captured in the appendix.

3.1.4 Research protocol 4 – Lean in agri

After following the search protocol, 94 conference proceedings, journal articles and books/book chapters were found. Of these findings, 33 were not agri-related, since they referred to other industries such as healthcare, construction, aeronautical, marine, software development, research facility, green engineering, automotive, restaurants, and agile manufacturing. Another 6 studies were excluded since they referred to Six Sigma in combination with Lean. One study was excluded since it referred to human weight loss and six studies were excluded that referred to animal/plant genetics to grow lean plants or lean meats. Three studies were excluded because Lean was not the focus of the study, it was only part of a bigger study. Another three studies were excluded since Lean was only referred to in future research. Ultimately, 42 studies remained.

3.1.5 Research protocol 5 – Lean farm

The search protocol delivered two papers, which were both relevant to the study and are therefore presented in the appendix.

3.2 Lean applied to different agri-industries

Of the 102 studies, four studies focussed on Lean management in agriculture. Of the remaining 98 agricultural studies that incorporated Lean principles, the majority came from the food and beverage industry (41 studies) and the timber industry (14 studies), as indicated in Table 2 and Figure 1. The detailed citations per industry are presented in the appendix.

After the food and beverage industry and the timber industry, the next highest numbers were from the crops industry and mixed farms (8 studies each), the red meat industry (5 studies), textile, dairy and fruit industry (4 studies each) and the fertilizer industry (3 studies). Single Lean studies were found in the poultry, coffee, floriculture, horticulture, pesticides, vertical farming and equestrian industries. These have been grouped as “other”.

Table 2: Number of research studies per agri-industry

Agri industry	Nr of research studies
Food and Beverages	41
Timber	14
Crops	8
Mixed farms	8
Red meat	5
Textile	4

Agri industry	Nr of research studies
Dairy	4
Fruit	4
Fertiliser	3
Other	7
Total:	98

It is evident that Lean principles are being applied to a variety of agricultural industries. However, in the overall context of lean implementation, these are not a lot of studies.

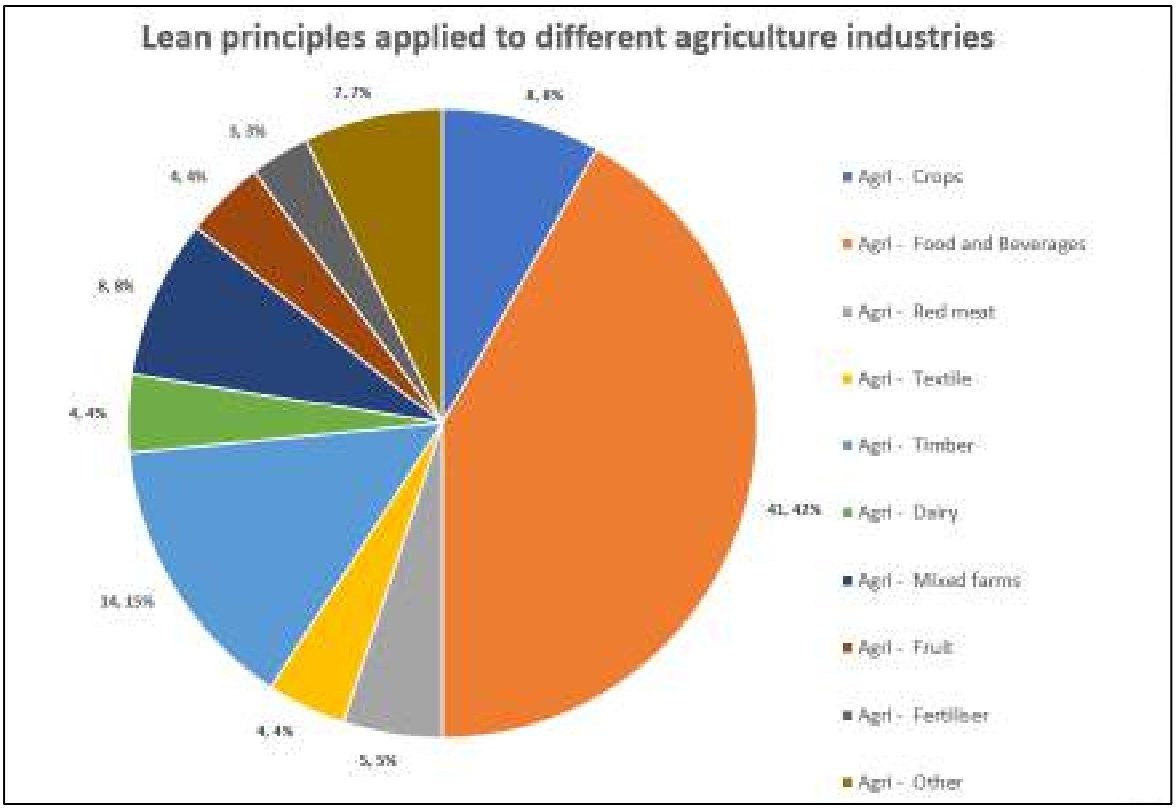

Figure 1: Lean principles applied to different agricultural industries

3.3 Authors

It emerged that there are a few prominent authors writing on the topic of Lean research in agriculture. Table 3 indicates the breakdown of the number of studies per first author, for the authors that published more than one study on the topic (as first author).

Table 3: Number of studies (if more than one) per first author

Authors	Nr of studies (As first author)
Caicedo Solano, N. E.	4
Melin, M. and H. Barth	3
Chen, H.	2
Dora, M.	2
Muñoz-Villamizar, A.	2
Pearce, D.	2

Authors	Nr of studies (As first author)
Taylor, D. H.	2
Zokaei, K.	2

Caicedo Solano, N. E. has four studies published [10-13] on using Lean principles for developing an operational model for minimising cost in agricultural systems. Sowing, cropping, and harvesting are usually treated independently. Waste and the sustainability of operations are generally not integrated into operational planning methodologies for agricultural production bBut Caicedo Solano [11] points out the need to have a clear and precise methodology to minimize waste in agricultural production systems to ensure sustainability. In this study, Lean manufacturing principles are used to identify agricultural operations and the variables that represent waste, build mathematical models, define constraints and illustrate the cost of waste, as well as its minimization through an objective function. In his 2022 study [10], he presents a mixed integer nonlinear programming problem model to solve the planning of agricultural production systems in the stages of sowing, crop maintenance and harvesting.

Melin, M. published two Lean studies done in Sweden. The purpose of the first study [2] was to develop a framework for Lean implementation in the agricultural sector, from an operational and strategic perspective. The study was conducted with a group of Swedish farmers. The aim of the second study [14] was to increase the understanding of Lean implementation in which value stream mapping (VSM) is used to create an action plan at a small dairy and cattle farm in southwest Sweden. Melin [15] also published a third paper (as the second author) to propose a Lean Implementation Framework that small and mid-size farms can use to increase production and profit and yet support environmental sustainability.

Chen, H., ***et al*****.** published 2 studies [16, 17] on Lean supply chains in the agri-food industry. The first paper aimed to support food supply chain decisions to achieve lean performance (that is to reduce/eliminate non-value-adding activities, or "waste" in Lean terms) [16]. The second study aimed to explore an approach to integrating knowledge mobilisation within agri-food supply chains to enhance the collaboration of all value chain actors and achieve a holistic reduction of waste [17].

Muñoz-Villamizar, A. also focussed on the agri-food industry in three studies [18-20]. The first study [19] analysed the gaps and trends, and suggested approaches and methodologies that should be addressed by future studies for implementing Lean and Green management in the agri-food sector. According to Muñoz-Villamizar[18], environmental efficiency should not be treated independently of production efficiency. Therefore, the second study integrated existing methodologies and approaches from Lean thinking, Industry 4.0 and mathematical optimization, and presented a toolkit for integrating, measuring, controlling and improving production and environmental performance in companies. The third study [20] presented a multi-case study in the agri-food industry in which water consumption in company activities is monitored, allowing them to improve their industrial processes based on Lean and Green practices, leading to a zero-waste strategy for this critical resource.

Pearce, D. has been involved in 4 studies in different countries to apply Lean principles in the food industry [21], horticulture [8, 22] and the dairy industry [23]. For the food industry, a systematic review (of 24 studies) was used to show the potential of Value Stream Mapping (VSM), not only to identify and reduce food losses and wastes but also to establish links with nutrient retention in supply chains. The horticulture study [22] determined the factors that drive sustainable performance through the application of Lean methods in the primary production segment of the supply chain for apples and pears. The South African study on horticulture [8] investigated the relationship between patterns of Lean practice implementation, farm size and sustainable performance among fruit horticultural primary producers in South Africa. Lastly, the dairy value chain was investigated in Uganda and used

Value Stream Mapping (VSM) analysis to identify hotspots and analyse the magnitude of both food and nutritional losses in the food value chain.

In 2014, **Dora** [24] stated that a very limited number of studies have focused on the implementation of Lean manufacturing practices within small and medium-sized enterprises (SMEs) operating in the food sector. The study then analysed the status of Lean manufacturing practices and their benefits and barriers among European food processing SMEs. Dora warned that Lean in agriculture provides a different set of challenges due to seasonal variability, bulk production, processing and problems in handling and storage. The study identified and categorised Lean waste and created a Lean implementation readiness index based on the operations management literature. Dora was also a co-author with Pearce, D. on the two horticulture studies [8, 22] as well as the systematic review of the food industry [21] and the value chain study of the dairy industry [25]. Preceding the dairy study of 2019 [23]. Dora also took part in the 2018 study [25] during which a survey was conducted among 246 supply chain actors about their general understanding of nutrition-sensitive agriculture while linking it with food and nutrient loss or waste reduction strategies.

Taylor, D.H. published two studies on applying lean in the agri-food industry. The first study [26] develop an innovative methodology to apply Lean value chain improvement techniques to a complete supply chain for a food product from farm to consumer. The second study [9] showed how value chain analysis techniques have highlighted opportunities for strategic change in a UK agri-food supply chain and presented an initial model of an integrated supply chain based on the application of lean principles.

Zokaei, K. investigated Lean implementation in the red meat industry[27, 28] and the agri-food industry [29]. The first red-meat study [27] highlighted the benefits of Lean production in one specific manufacturing area, the “cutting room”, where meat is split down from a carcass into retail cuts of meat. The second red meat study [28] continued to highlight the benefits of Lean production techniques in different stages of the red meat value chain and reported 2- 3% potential cost savings at each stage of the chain. The agri-food reference by Zokaei [29] is a book chapter in Delivering Performance in Food Supply Chains. The chapter reports on the findings from a major research project (33 extended supply chains) into the UK agri-food industry over a period of four years and across four primary food sectors (cereals, red meat, horticulture and dairy).

3.4 Lean farms

From the above search results, Lean Agri is applied mostly in production/manufacturing type environments like the food and beverage industry and the timber industry.

Agri-industries that are more farm-based are on the lower half of the results, such as crop production, mixed farms, the red meat industry, dairy and fruit industries.

Already in 2015 Dora [1] pointed out that there had been little literature and understanding of Lean in the context of agriculture and specifically farming. It appears that this was the first study that pointed towards lean farming (as opposed to Lean Agri in general).

During the literature search, only six studies [30], [1], [7], [15], [31], [32] referred to implementing Lean specifically on farms (not agri-processing industries). And when searching the term “Lean farm”, only two studies were found [30] [33].

3.5 Publication years

Without limiting the search to any period, the search results are spread between 2004 and 2023 (Figure 2). Since 2004 there has been a steady increase in the number of publications, with the highest number of publications (18) being in 2020. The publications of 2021 focussed on food and beverage (3 studies), mixed farming (3 studies), lean agri management (2 studies), timber (1 study), crops (2 studies), textile (1 study), dairy (1 study), fertilizer (1 study), fruit (1 study) and three “other” studies.

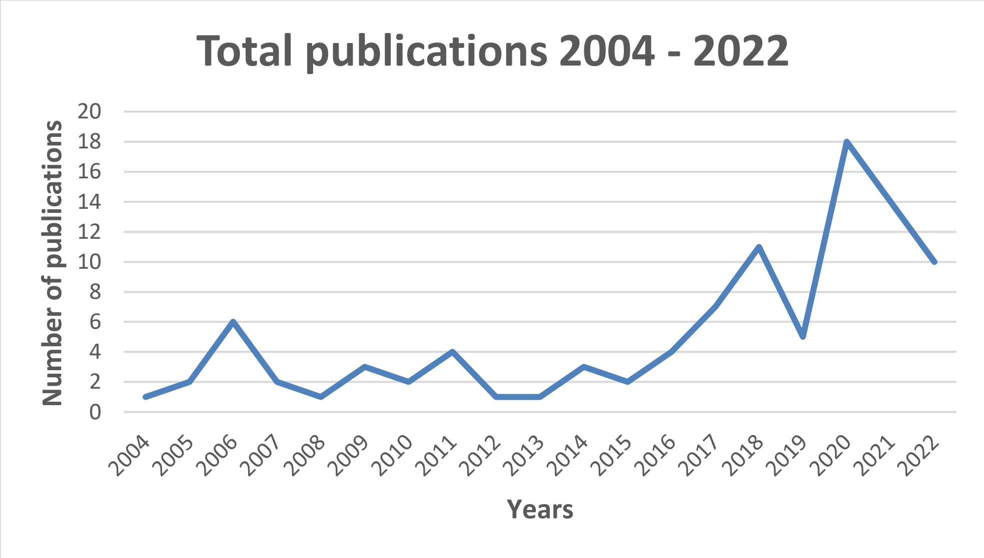

Figure 2: Total publications for the search period

The industries that have more than one citation per year are highlighted in Table 5. There seems to have been an increase in publications over the years, specifically in the food and beverage industry, crops, timber and mixed farming.

3.6 Title of studies

Given the titles of each of the 102 studies (presented in the appendix), a word cloud (Figure 3) of the 100 most used words was generated to illustrate the most pronounced themes of ideas captured by authors.

From Figure 3 the most used words (except for “lean”) are: value, agri-food, food, management, supply, development, production and sustainable. This is indicative of the change and focus that Lean agriculture offers the community by adding value. Support is provided to management and supply chains to increase production. Moreover, lesser-used phrases like "reduction”, “modelling”, “improving”, “integrating”, “adoption”, “strategy” and “design" also indicate the offering of lean-focused principles in agriculture by highlighting the benefits.

Table 4: Search results per agri-industry per year

	Crops	Food and Beverages	Red meat	Textile	Timber	Dairy	Mixed farms	Fruit	Fertiliser	Other	Total
2004					1						**1**
2005		1	1								**2**
2006		1	2		2					1	**6**
2007	1		1								**2**
2008					1						**1**
2009		1			1				1		**3**
2010		1			1						**2**
2011		2			1	1					**4**
2012		1									**1**

	Crops	Food and Beverages	Red meat	Textile	Timber	Dairy	Mixed farms	Fruit	Fertiliser	Other	Total
2013		1									**1**
2014		2							1		**3**
2015							1				**2**
2016		1		1	1		1				**4**
2017		6				1					**7**
2018		1		1	2	1	2			3	**11**
2019	1	4									**5**
2020	2	3		1	1	1	3	1	1	3	**18**
2021	1	7	1	1	2			2			**14**
2022	1	7					1	1			**10**
2023	2	2			1						**5**
Total	**8**	**41**	**5**	**4**	**14**	**4**	**8**	**4**	**3**	**7**	**102**

3.7 Keywords of studies

When looking at the details of the 102 studies, it was clear that there was a trend in the keywords used by authors. Thus, an analysis was conducted on the total number of occurrences of each keyword of the studies. Figure 4 depicts a clustered bar graph indicating the total count of keywords.

As indicated in Figure 4, the most common keywords (except for "lean") are "food", "manufacturing", "production", "supply chain", and "sustainability". This corresponds to the earlier discussions which identified the focus of the majority of the studies. It is evident that the studies emphasise the improvements and integrations that the lean philosophy has to offer the agricultural industry.

Figure 3: Word Cloud of literature titles

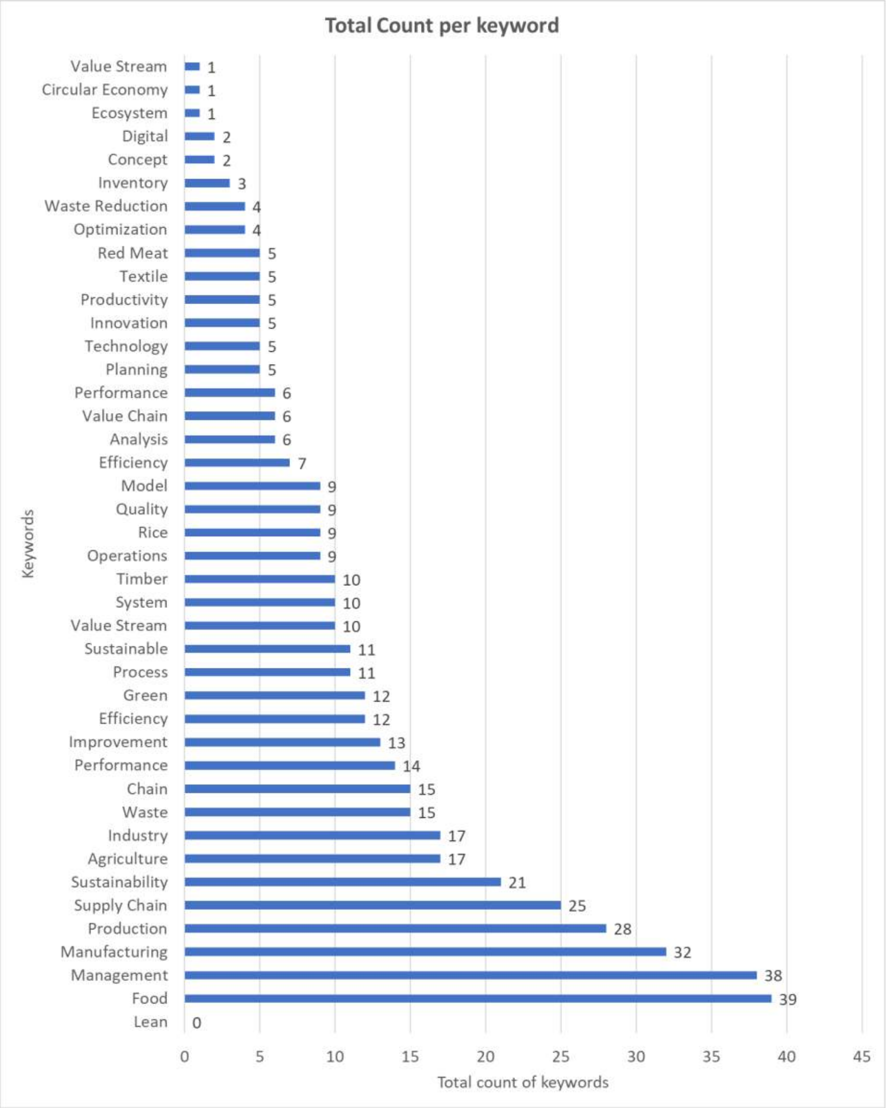

Figure 4: Clustered bar graph indicating the total count per keyword

4 VALIDATION

To ensure that the rapid literature review is valuable to users, a transparent complete, and accurate account of why the review was done, what was done, and what was found, was presented in the study [34].

Furthermore, an adapted version of the PRISMA checklist [34] is used for validating the review conducted in this study (

Table 5). As can be seen from the checklist in

Table 5, this study adequately addressed the data gathering and data analysis phases of the research and the results and discussion of the various aspects of the study were adequately presented.

Table 5: PRISMA checklist for validation

Section and Topic	Checklist item	Section where the item is reported
INTRODUCTION		
Rationale	Describe the rationale for the review in the context of existing knowledge.	1.
Objectives	Provide an explicit statement of the objective(s) or question(s) the review addresses.	2.1.
METHODS		
Eligibility criteria	Specify the inclusion and exclusion criteria for the review and how studies were grouped for the syntheses.	2.1.
Information sources	Specify all databases, registers, websites, organisations, reference lists and other sources searched or consulted to identify studies. Specify the date when each source was last searched or consulted.	3.
Search strategy	Present the full search strategies for all databases including any filters and limits used.	2.1.
Data collection and selection process	Specify the methods used to decide whether a study met the inclusion criteria of the review.	2.1
Synthesis methods	Describe the processes used to decide which studies were eligible for synthesis.	2.1.
RESULTS		
Study selection	Describe the results of the search and selection process, from the number of records identified in the search to the number of studies included in the review, ideally using a flow diagram.	2.1.
Study characteristics	Cite each included study and present its characteristics.	Appendix
Results of syntheses	Present the results of all investigations of possible causes of heterogeneity among study results.	3
DISCUSSION		
Discussion	Provide a general interpretation of the results in the context of other evidence.	3
	Discuss any limitations of the evidence included in the review.	6
	Discuss any limitations of the review processes used.	6
	Discuss the implications of the results for practice and future research.	6
OTHER INFORMATION		
Support	Describe sources of financial or non-financial support for the review, and the role of the funders or sponsors in the review.	NA

5 CONCLUSION

This study utilised a rapid review for unearthing 102 different Lean Agri puzzle pieces across different agricultural industries. For example the food and beverage industry, timber, crops, mixed farms, red meat, textile, dairy, fruit, poultry, coffee, floriculture, horticulture, pesticides, vertical farming and equestrian were identified). Solving the puzzle highlighted the different possibilities of lean applications within agricultural industries.

This study found that many authors are well-known for publishing in the lean-agri space. It will be interesting to see how these researchers further develop the discipline in the future.

It was also found that most studies made use of "food", "manufacturing", "production", "supply chain" and "sustainability". This is evident in the improvements and integrations that the Lean philosophy has to offer the agricultural industry.

A few studies were found on the topic of lean management, indicating future (and needed) research in this area, as opposed to just the technical application of Lean in agri.

It was also found that Lean Agri is applied primarily in production/manufacturing type environments, like the food and beverage industry and the timber industry, and less on farm-based operations. It seems that little research has been done on understanding lean farming (as opposed to Lean Agri in general).

Given the upward trend and increase in publication over the years, it is evident that Lean-Agri is ascendant but more research is needed to further highlight its value and range of applications.

6 LIMITATIONS AND FUTURE RESEARCH

A rapid literature review allows for the review of a large body of literature. However, it may include limitations due to shortened timeframes, such as a lack of depth of analysis in the findings of each article, challenges in repeatability of the study and the potential for bias in interpretation of results [4].

Future research should now continue with a thorough systematic literature review to investigate the details of each study, as well as retrieve any studies that were missed.

While this study provided a full presentation of the current research of 102 studies, it did not focus on the detail of each of the studies. Future research should investigate the specific lean principles that were applied in each study. This will provide further guidance on the required research into Lean Agri.

This study has pointed out the application of lean in different agri-industries. It is suggested that future research focus on the in-depth analysis and investigation of each of the industry applications of Lean-Agri to determine the focus of further research.

It is commonly understood that Lean philosophy is quite popular in many spaces as there are numerous search results on academic databases yet, only 102 studies were found in the Lean agriculture space. It is worthwhile investigating why lean implementation is lagging behind in this application field.

The highest search results were found in the food and beverage industry and the timber industry, both of which are very "production-like" industries. Future research should focus on the application of Lean principles in non-production farm-based environments, eg. crop production, mixed farms, the red meat industry, the textile industry, dairy, fruit, and the fertiliser industry. Only two studies were found using the phrase "Lean farms". Future research should further investigate this concept and what a Lean farm would entail, by definition.

While there are several limitations to the study, it is important to understand the value that Lean philosophy can bring to any industry, especially agriculture. With the agricultural industry being one of the largest contributors to the South African GDP, it must continue to develop and grow for the betterment of the country. Lean offers an advantage that is worth more investigation and implementation in South Africa. Future research should explore the increased use of Lean-Agri in South Africa.

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APPENDIX

#	Crops
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FACTORS AFFECTING THE IMPLEMENTATION OF LEAN MANUFACTURING: A CASE OF AN INTERNATIONAL FOOD FLAVOURS MANUFACTURING COMPANY IN SOUTH AFRICA

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ABSTRACT

This research aims to identify the factors that affect the implementation of lean manufacturing (LM) and the influence of the identified factors on the operational performance in a food flavours manufacturing company in South Africa. A quantitative research approach was adopted to obtain an understanding of the lived experience on the shop floor. Current literature was reviewed, and a survey of a food flavours manufacturing company in South Africa was conducted to complement the knowledge gathered from the reviewed literature. Responses received represented 82% of the sample population and identified skills and training, leadership styles, change management, and employee involvement as critical factors influencing LM. Recommendations to management to enhance LM training, employee involvement, and communication were made as input to their LM strategy.

Keywords: Lean manufacturing, operational performance, factors, quantitative, food manufacturing

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1 INTRODUCTION

The advent of the Covid-19 pandemic globally and the local national lockdown situation introduced a tumultuous environment where businesses have had to navigate to remain competitive or otherwise face the possibility of shutting down. Before the full recovery of the global economy, the manufacturing environment has been further compounded by the situation in Europe, originating from the Russian invasion of Ukraine, which has escalated quickly and is having a significant industry-specific impact on inputs and raw material costs. In the local environment, in South Africa, there is pressure as a result of the unreliability of power supply from ESKOM, reduced demand as result of the increase in cost of living as disposable income is eroded.

Companies around the world face numerous challenges in their efforts to survive and compete. Solutions to these challenges that manufacturing companies, including those in the food manufacturing industry face, must be found by adapting their management style and finding new manufacturing strategies [1]. Lean Manufacturing (LM) is one such strategy widely adopted by manufacturing companies to enhance performance and gain a competitive advantage by reducing waste (for example, in human effort, production space, time to market, and inventory).

The Toyota Motor Company is widely seen as the founder of LM, thanks to the work of Taiichi Ohno, they progressively synchronised all their processes simultaneously to give high quality, fast throughput, and exceptional productivity, known as the Toyota Production System (TPS), which shaped what we call Lean today [2]. The primary goals of LM are to reduce costs, improve quality, and deliver goods and services more quickly by eliminating activities that add no value, which Taiichi Ohno defines as waste [3], [4].

1.1 Research Problem

The context in which an organisation operates as well as the challenges that exist may affect the successful implementation process of LM. There is little research in Southern Africa, specifically referring to effective adoption of LM in the food industry. The effect of LM on the performance of operations is under-researched in Southern Africa [5].

Only a few food processing companies, such as Nestle Nigeria Plc, have adopted lean management practises that have demonstrated significant improvements in the proficiency and performance of operations. Perhaps the slow uptake of lean may be related to the sector’s products, processes, or plants [5].

The background against which this research seeks to investigate the contextual factors which affect the implementation of LM in the food flavours manufacturing industry as a management tool for cost reduction and to contribute to why there is a slow uptake of LM in South Africa’s Food Manufacturing sector.

Research Questions

- What are the factors that affect lean manufacturing at a Food Flavours Manufacturing Factory?
- What is the impact of these identified factors on the performance of lean manufacturing at a Food Flavours Manufacturing Factory?
- What recommendations can be made to the management of Food Flavours Manufacturing Factory, as input to their lean manufacturing strategy?

1.2 Hypotheses

The hypotheses for this study are outlined in Table 1.

Table 1: Hypotheses defined for this study

Research question	Hypotheses	Number	Nine Continuous Depended Variables
What are the factors that affect lean manufacturing at a Food Flavours Manufacturing Factory?	A relationship exists between the chosen continuous dependent variables of the research.	H1.1 to H1.9	Understanding of Lean Manufacturing (UM) Stakeholders Relations (SR) Supply Function (SF) Internal Operations (IO) Employee Involvement (EI) Leadership (LS) Change Management (CM) Employee Performance (EP) Organisational Commitment (OC)
What is the impact of these identified factors on the performance of lean manufacturing at a Food Flavours Manufacturing Factory?	Each one of the 9 chosen Continuous Dependent Variables mean rank scores are identical per gender categories.	H2.1 to H2.9	
What is the impact of these identified factors on the performance of lean manufacturing at a Food Flavours Manufacturing Factory?	Each of the 9 selected Continuous Dependent Variables mean rank scores are identical per Age categories.	H3.1 to H3.9	
What is the impact of these identified factors on the performance of lean manufacturing at a Food Flavours Manufacturing Factory?	Each of the 9 selected Continuous Dependent Variables mean rank scores are identical per Employment Position categories.	H4.1 to H4.9	
What is the impact of these identified factors on the performance of lean manufacturing at a Food Flavours Manufacturing Factory?	Each of the 9 selected Continuous Dependent Variables mean rank scores are identical per Tenure in Current Position categories.	H5.1 to H5.9	
What is the impact of these identified factors on the performance of lean manufacturing at a Food Flavours Manufacturing Factory?	Each of the 9 selected Continuous Dependent Variables mean rank scores are identical per Education categories.	H6.1 to H6.9	

2 LITERATURE REVIEW

2.1 Introduction

LM practises have considerably increased the operational performance levels of companies concerning cost, quality, and delivery, particularly in the automobile industry [6]. Companies around the world face numerous challenges to survive and compete. Solutions to these challenges that manufacturing companies, including those in food manufacturing, face must be found by adapting their management styles and finding new manufacturing strategies [6]. Nonetheless, most of the available literature showed the historical narrow emphasis of the food manufacturing industry on matters of food security, neglecting excellence in operations [7]. Food manufacturing companies, understandably, are obligated [7] to comply with numerous strict food legislations such as the Food Safety System Certification (FSSC) 22000 and rigid customer demands; this may be due to their diverse industry methods [7;8].

2.2 Characteristics of the food industry context

The food sector companies are differentiated by different product structures. The raw materials are usually agricultural, such as milk, which can be used to produce various products, for example yoghurt, diverse types of milk, and cream products [9],[10]. Products differ as a result of differing customer requirements and specifications, which may be in the form of different packaging, labelling, or product recipes [11]. This diversity in product range necessitates an increase in the number of changeovers in the production process. Cleaning in Place (CIP) or cleaning-in-place is a very necessary and unique aspect of the food sector, performed between different batches to comply with quality requirements, adding to the changeover time [5;10]). In between recipe changes, it is mandatory to empty pipes and clean and sterilise equipment before new batches can be produced contamination-free [11]. Strict CIP and cleaning procedures in the food sector introduce challenges in the implementation of LM, especially where set-up time reduction is the required outcome, which can be achieved with a single minute of die exchange (SMED) tool.

2.3 Conceptual framework for the study

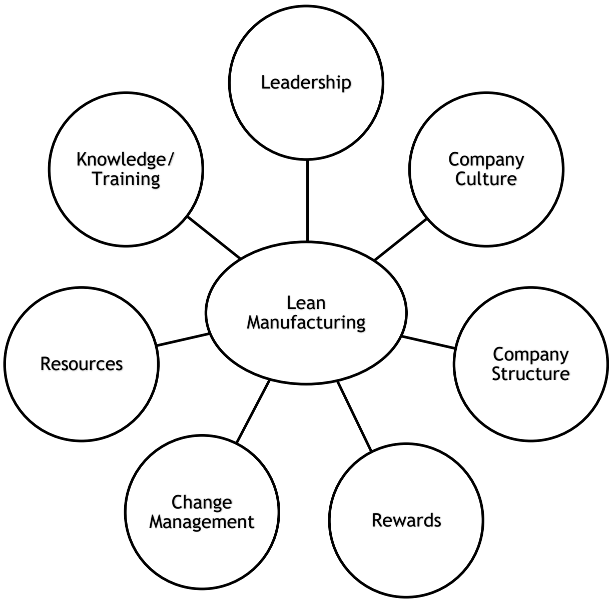

Figure 1: Factors affecting LM implementation

Lean outlines an essential framework that enhances efficiency and waste reduction in operations such as long setup times, equipment reliability through total productive maintenance, the elimination of rework and less conspicuous waste, and the reduction of variability exemplified by process times, delivery times, yield rates, staffing levels, and demand rates [14; 15]. Waste is any loss incurred by a company as a result of activities that cost it directly or indirectly and do not add value to a product or service [16], that is waste is anything that a customer is not willing to pay for.

2.4 Literature review

2.4.1 Factors affecting LM in South Africa

The South African industry faces enormous global competition from first-world countries such as Germany, owing to the latter's earlier adoption of LM techniques [17]. Despite the fact that the field of Industrial Engineering has existed in the country since 1961 and that the Lean philosophy is a symbol of Industrial Engineering, the practise has yet to be fully adopted in South African industry [17;18]. A realistic valuation of lean practise prototypes, including their effect on sustainable performance in the fruit and horticultural primary production context was conducted by [19]. They use a framework that is both holistic and comprehensive for LM and comprises the 10 dimensions of lean practice, which include supplier feedback, flow, pull, low set up, and total maintenance, to evaluate the prevalence of lean practices, including their correlation to farm size (plant), and sustainable performance in the context of the South African fruit horticultural sector. They conclude that the size of the farming operation impacts significantly on the level and depth of lean practise implementation as well as the extent of sustainable performance outcomes attained; the size of the farm (plant) is a significant factor of implementation, but this only applies for a subsection of lean practises [20;21].

2.4.2 Overview of factors affecting LM in Food Industry context

An analysis of empirical and theoretical literature by [22], there are three kinds of inhibiting factors: company inhibitors, human inhibitors, and technological inhibitors, distinguished as follow [22;23].

Table 2: Factors affecting LM implementation as compiled by [22]

Company inhibitor	Human inhibitor	Technological inhibitor
Plant size	Poor communication	Lack of technical resources
Company culture	Resistance to change	Absence of technological infrastructure
Lack of training	Job insecurity among employees	
High cost of implementation	Inability to see long term lean goals	
Lack of time	Low skill workers	
Insufficient labour resources	Willingness to achieve quick results	
No rewards and recognition	Suppliers not cooperating	
Lack of funds		
Failure of previous LM		

Adopted from: [22]

The most significant barriers to implementing lean are: (1) a lack of knowledge; (2) a lack of resources; (3) a lack of training; and (4) insufficient process control techniques for SMEs in the food processing industry [5;6].

It can be deduced from reviewed literature that company culture, management commitment, leadership style, change management (resistance to change), training, and resources are prevalent in the reviewed literature across borders.

2.4.3 Sources of waste

The three causes of waste which are related are mura, muri and muda, where when there is inconsistency in a process mura results; leading to the overburden of employees and equipment (muri) which results in non-value adding activities (muda) [4].

Taiicho Ohno from Toyota outlined the seven original types of waste based in the TPS, namely:

1. Transportation - the unwarranted transport of components under production.
2. Inventory - Heaps of components waiting to be completed or finished goods waiting to be shipped.
3. Motion – the unwarranted movement of people working on products.
4. Waiting – the unwarranted waiting by people to begin the next step.
5. Over-Processing the product with extra steps.
6. Over-Production of products not needed.
7. Defects in the product.
8. Underused people.

Table 3 is a representation of the relevant literature reviewed on LM in South Africa, including the food sector, is provided below:

Table 3: Lean management literature reviewed in South Africa

Author	Title	Source
Pearce et al. (2021)	Toward sustainable primary production through the application of lean management in South African fruit horticulture [19]	Journal Article
Maluleke (2019)	Implementation of Lean Production System in Gauteng Food Manufacturing Firm.	Thesis-Magister Technologiae – Peer reviewed
Vermaak (2008)	Critical success factors for the implementation of Lean thinking in South African manufacturing companies.	Thesis - Doctor Commercii in Strategic Management (peer reviewed)
Coetzee et. al. (2019)	The South African perspective on the lean manufacturing Respect for People principles.	Journal article
Mangaroo-Pillay and Coetzee (2020)	A systematic literature reviews (SLR) comparing Japanese Lean philosophy and the South African Ubuntu philosophy. [20]	Journal article
Dondofema, Matope and Akdogan (2017)	Lean Applications: A Survey of Publications with Respect to South African Industry. [17]	Journal article

Source: authors

This review was embarked on to assess and gain in-depth knowledge and understanding of the enabling and inhibiting factors of lean implementation that encourage or discourage LM in the food industry. The identified influential factors across borders from the reviewed literature, include:

- Company culture
- Leadership
- Skills and Training
- Company Structure
- Resources
- Multifunctioning Teams
- Compensation/ Rewards

- Change Agent

3 RESEARCH METHODOLOGY

The method of research is depicted as the map which gives direction to how the goals of the research are executed ensuring that the data gathering procedure is orderly and coordinated [23].

3.1 Quantitative Research Design

Saunders, Lewis and Thornhill [25] developed the Research Onion, which is used to guide this research design by adopting an approach that is philosophical, influenced by the positivistic philosophy.

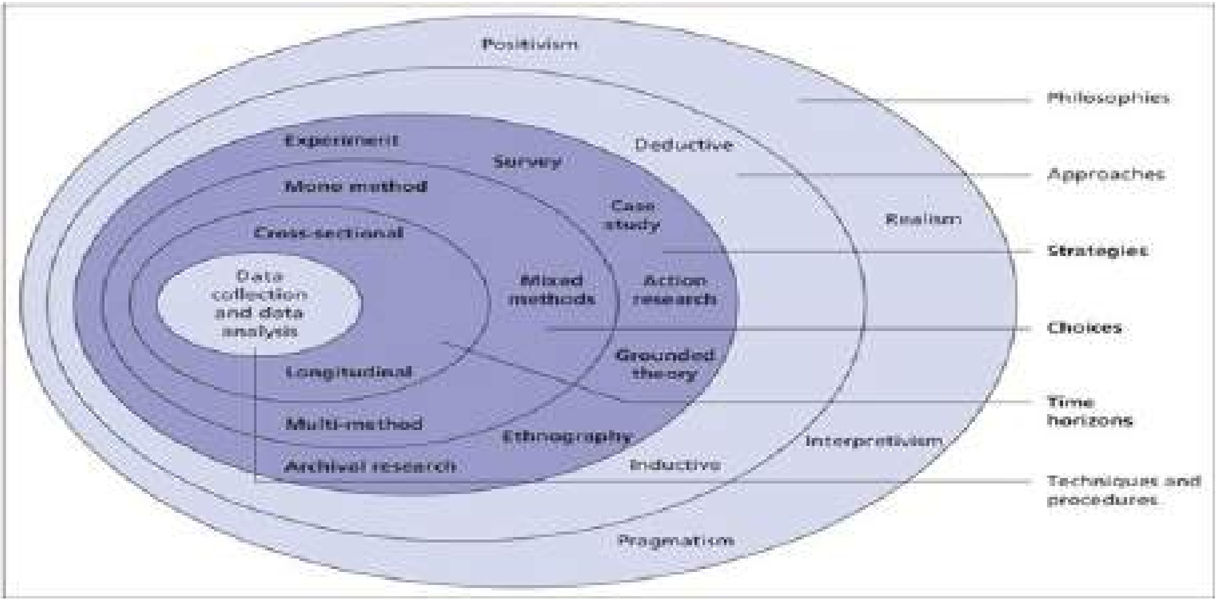

Figure 2: The Research Onion

Adopted from: Saunders, Lewis and Thornhill [25]

3.1.1 Philosophy adopted

The opinion of positivists is based on the commonality of human nature, which is not reliant on one's beliefs, culture, or historical background which will be adopted for this study [23].

3.1.2 Research approach

This approach was deductive and tested theory as it applied to the South African food manufacturing industry. The approach allows for the scrutiny of the problem and the context, resulting in the deduction of both the cause and effect; this process assists in investigating the phenomenon in its normal setting with a focus on cases that are contemporary [24].

3.1.3 Research strategy

The variables identified in the review of previous literature were tested in the context of the food factory in the South African environment by conducting a survey, a quantitative tool, at the case company. A survey questionnaire with pre-set questions relevant to LM was used to explore factors in the literature. Surveys are frequently used in business management research because they are reliable and allow for large quantities of data to be gathered [25;26].

3.1.4 Research choice

The mono method, as outlined in the research onion, was adopted for this research due to the time constraints of the research period.

3.1.5 Techniques and procedures

The techniques adopted after the collection of data via the survey to analyse the data were incorporate descriptive statistical analysis, which was conducted first, and then inferential statistical analysis [27;28].

This study used the systematic, sequential approach depicted in Figure 3. Beginning with a review of the literature.

Figure 3: Quantitative Research Road Map

Source: authors

3.2 Population

The population was not made up of subject matter experts but rather ordinary, experienced employees in their areas of expertise who are actively involved at the operations level, 82 employees out of the 100 completed the online surve.

Table 4: Target Population

Department	No of participants
Liquids & Powders plants	50
Creative and Development	10
QC/ QA	10
Customer service	12
Warehouse/ Stores	8
Sales	10

3.3 Sample

Propagates sampling as a process that selects a subset that represents the population, which allows the study to extricate significant information after which conclusions may be extrapolated [29;30]. This approach was used to achieve the target sample.

3.3.1 Convenience Sampling

Convenience Sampling - a technique for compiling information from a group of participants to whom the researcher has easy access. It is a commonly used tool as it is quick, straightforward, and economical. Participants are easy to approach in most cases to take part in the sample [31].

3.4 Data collection

This research used an online questionnaire, and made on-site observations through Gemba walks (Gemba walks a Japanese term denote the action of going to see the actual process, understand the work, ask questions and learn) [5], before and in anticipation of LM implementation to ascertain the value and obtain an overview of how the processes and operations will change subject to LM implementation [30]. As LM manufacturing has already been implemented, all employees were familiar with the terminology of lean.

3.5 Data Analysis

Content analysis was carried out to ascertain patterns, inclinations, preconceptions and premises. First, descriptive statistical analysis was conducted, followed by inferential statistical analysis [30].

3.5.1 Descriptive Statistics

Descriptive statistical analysis was conducted, where the collected quantitative data was summarised in graphics and tables.

3.5.2 Inferential Statistics

Inferential statistics is described as being involved with formulating interpretations founded on relations discovered in the sample and relations in the population [31].

3.6 Validity and Reliability

Validity and reliability were significant constructs utilised in determining whether suggestions in research are based on legitimate, dependable, precise, and credible data compilation and methods of analysis, must be both repeatable and dependable for them to be contemplated as being reliable [30].

3.7 Ethical Consideration

Ethical consideration was given to respect the respondent's rights in the interviews and during the Gemba walks and questionnaires; this includes how they were approached and interviewed, consent forms that were signed to show agreement to participate, and the data collected and used for this research.

4 RESULTS AND FINDINGS

The focus of the research was to establish the factors that affect the implementation of LM in a food flavours manufacturing factory. The research's objective was to provide senior management with insight into the internal factors that influence the implementation of LM in the company and to make recommendations that offer potential solutions to improve the company's competitive advantage. The quantitative study will inform management of the empirically developed and tested factors are indeed important and should be considered.

4.1 Limitations

This research is restricted to the case company, which is its main limitation, the response rate received was satisfactory (82 responses of 100) for the population however this may not be representative of an entire industry. The research approach and its findings are considered to be sound however, widening the investigation to include other companies in the food flavours manufacturing industry in South Africa would strengthen the validity and generalisation of the findings. The study aimed to provide insight to the internal factors that influence LM implementation, however it is limited in providing insight on how the company could benefit quantitatively.

4.2 Descriptive statistical analysis

The outcomes of the descriptive statistical analysis were presented, and the collected quantitative data was summarised in tables. The data was collected from a an identified population of 300 using the online survey questionnaire which was emailed to the respondents. In addition, he identified population for the study was 300 and the responses received were 82.

4.2.1 Continuous Improvement (CI) Methods Awareness

The CI methods awareness are the methods that the population is familiar with and use, which include Total Quality Management (TQM), Lean Manufacturing (LM), and Six Sigma, a reflection of improvement activities in the food industry. As LM manufacturing has already been implemented, all operational employees were familiar and trained with the terminology of lean.

The set of questions that evaluated Implemented CI Methods are presented in Table 5.

Table 5: Implemented CI Methods (n = 82)

Methods	Not intended to be used / unknown	Planned for use in subsequent year	Planned for use in 3 years	Already in use
Quality mission statement	8	3	3	68
	10%	4%	4%	83%
Quality vision statement	10	2	3	67
	12%	2%	4%	82%
Root Cause Analysis (Fishbone diagram)	16	1	3	62
	20%	1%	4%	76%
Standardised work sheet	20	4	3	55
	24%	5%	4%	67%
Standard work	21	3	4	54
	26%	4%	5%	66%
5 – why analysis	23	1	4	54
	28%	1%	5%	66%
Visual Management	21	3	5	53
	26%	4%	6%	65%
Notification system for quality and process problems (Andon)	28	3	4	47
	34%	4%	5%	57%
Just in time	27	4	7	44

Methods	Not intended to be used / unknown	Planned for use in subsequent year	Planned for use in 3 years	Already in use
	33%	5%	9%	54%
Plan-do-check-act PDCA cycle	32	3	6	41
	39%	4%	7%	50%
5S - method	38	4	2	38
	46%	5%	2%	46%
Value Stream Mapping	30	7	9	36
	37%	9%	11%	44%
Levelling production and schedules (heijunka)	39	0	8	35
	48%	0%	10%	43%
Pull system	46	5	6	25
	56%	6%	7%	30%
Takt Time	43	7	8	24
	52%	9%	10%	29%
Error Proofing (poka yoke)	46	10	6	20
	56%	12%	7%	24%
Gemba	56	1	7	18
	68%	1%	9%	22%
Kanban system	53	5	7	17
	65%	6%	9%	21%
Single minute exchange of die (change overs)	55	4	8	15
	67%	5%	10%	18%

The results indicate that the company practises TQM like many in the food industry, with 83% of respondents being familiar with the company's quality mission statement and 82% being familiar with the quality vision statement.

4.2.2 Understanding of Lean Manufacturing

Table 6 exhibits the set of questions that evaluated understanding of LM, the scale 1 to 5 represents the degree to which the respondents agreed or disagreed, with 1 being strongly disagree to 5 strongly agree.

Table 6: Understanding of LM

	Mode	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
I understand the concept of lean management.	4	0.91	3	2	10	45	22	82
			4%	2%	12%	55%	27%	100%
I am aware of this lean practice, in our company	4	1.02	4	7	18	39	14	82
			5%	9%	22%	48%	17%	100%
Our company is currently implementing lean manufacturing practices	4	0.92	2	5	29	32	14	82
			2%	6%	35%	39%	17%	100%
Our company has been implementing many of the lean	4	0.93	4	2	28	37	11	82

	Mode	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
manufacturing practices even though we do not call it lean			5%	2%	34%	45%	13%	100%
My colleagues have adequate knowledge of Lean Manufacturing	3	1.04	6	10	31	27	8	82
			7%	12%	38%	33%	10%	100%

Standard deviation (SD) is a measure of how dispersed the data is in relation to the mean. Low, or small, standard deviation indicates data are clustered tightly around the mean, and high, or large, standard deviation indicates data are more spread out [31].

The respondents (55%) agree they have an understanding of LM, 48% agree that they are only aware of the company's LM practice. The respondents (55%) agree they have an understanding of LM, 48% agree that they are only aware of the company's LM practice.

4.2.3 Lean Manufacturing

With regards to LM, many of the respondents indicated that the employee training programme on LM is not working (Mo = 2, SD = 1.07). This offers a possible solution to the question of why there is not more emphasis on operational improvements that could result from successful LM implementation.

The set of questions that measured LM is presented in Table 7.

Table 7: Lean Manufacturing

	Mode	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
8.5: Our company is currently implementing HACCP	5	0.92	2	1	13	29	37	82
			2%	1%	16%	35%	45%	100%
8.6: Our company is currently implementing FSSC 22000	5	0.89	2	0	15	32	33	82
			2%	0%	18%	39%	40%	100%
8.7: Our company is currently implementing NFS	4	0.95	2	2	28	28	22	82
			2%	2%	34%	34%	27%	100%
8.8: Our company is currently implementing ISO 9001: 2015	4	0.88	2	1	17	38	24	82
			2%	1%	21%	46%	29%	100%
8.9: Our company is currently implementing ISO 45000	4	0.99	3	3	28	29	19	82
			4%	4%	34%	35%	23%	100%
11: Do you think your employee training program on Lean Manufacturing is working?	2	1.07	10	29	26	12	5	82
			12%	35%	32%	15%	6%	100%
12: You are involved in problem identification & improvement of	4	1.03	4	10	18	39	11	82

	Mode	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
processes (be they Production; innovation; sales; procurement etc) of the company?			5%	12%	22%	48%	13%	100%
13: To what extent can the worker involvement in Lean Manufacturing (waste elimination) programs in your workplace be explained?	3	1.03	4	7	32	25	14	82
			5%	9%	39%	30%	17%	100%
14: Do you think the opinions and suggestions of employees are given due consideration?	3	1.26	6	16	32	6	22	82
			7%	20%	39%	7%	27%	100%

4.2.4 Stakeholders relationship scale

The set of questions that evaluated Stakeholders Relations is presented in Table 8.

Table 8: Stakeholders Relationship Scale

Customer Relations	Mode	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
We are in frequent contact with our customers.	4	0.92	3	3	10	46	20	82
			4%	4%	12%	56%	24%	100%
Our customers give us feedback on quality and delivery performance.	4	0.84	1	3	11	41	26	82
			1%	4%	13%	50%	32%	100%
We conduct customer satisfaction surveys regularly.	3	0.97	3	4	35	25	15	82
			4%	5%	43%	30%	18%	100%
We are in frequent contact with our Suppliers.	4	0.74	1	0	15	46	20	82
			1%	0%	18%	56%	24%	100%

The majority of the respondents strongly agree that they are in frequent contact with their customers (Mo = 4, SD = 0.92) and that they are in frequent contact with their suppliers (Mo = 4, SD = 0.94). The respondents agree that the customers give them feedback on quality and delivery performance (Mo = 4, SD = 0.84). Customer gratification is influenced by superior product quality, reasonable prices, and on-time supplies, [32,33].

4.2.5 Supply function

There are various requirements for the implementation of LM in a company, one of which is that the company must integrate its suppliers and customers [33].

The set of questions that measured Supply function is presented in Table 9.

Table 9: Supply Function Scale

Supplier Management	**Mode**	**SD**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	**N**
Our key suppliers deliver to our factory on just-in-time basis.	4	0.93	1	5	28	29	19	82
			1%	6%	34%	35%	23%	100%

Supplier Management	Mode	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
We take steps to reduce the number of suppliers in each category to reduce raw material variations.	4	0.92	2	5	29	32	14	82
			2%	6%	35%	39%	17%	100%
Our purchasing / supply function is centralised.	4	0.77	1	0	33	35	13	82
			1%	0%	40%	43%	16%	100%

The majority of the respondents agree that the purchasing/ supply function is centralised (Mo = 4, SD = 0.77) and that they take steps to reduce the number of suppliers in each category in order to reduce raw material variations. (Mo = 4, SD = 0.92).

4.2.6 Internal Operations

The set of questions that measured Internal Operations is presented in Table 10.

Table 10: Internal Operations Scale

	Mode	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
We use the pull production system.	3	0.91	1	6	41	20	14	82
			1%	7%	50%	24%	17%	100%
We use Kanban, squares, or containers of signals for production control.	3	0.93	3	9	41	20	9	82
			4%	11%	50%	24%	11%	100%
Production at station is pulled by the current demand of the next station.	3	0.86	1	8	40	24	9	82
			1%	10%	49%	29%	11%	100%
Products are classified into groups with similar routing requirements.	4	0.83	1	4	26	39	12	82
			1%	5%	32%	48%	15%	100%
Product families determine our factory lay out.	4	0.92	1	7	28	31	15	82
			1%	9%	34%	38%	18%	100%
We are working to lower set up times in our plant from one batch to the next.	3	0.89	2	4	33	31	12	82
			2%	5%	40%	38%	15%	100%
We monitor our production cycle time to respond quickly to customer requests.	4	0.91	2	5	20	40	15	82
			2%	6%	24%	49%	18%	100%
Our employees practice setups to reduce required time.	3	0.99	2	12	29	27	12	82
			2%	15%	35%	33%	15%	100%
Our processes on the shop floor are currently under Statistical Process Control.	3	1.02	3	7	35	21	16	82
			4%	9%	43%	26%	20%	100%
We use charts to show defect rates on the shopfloor.	3	0.92	4	8	42	21	7	82
			5%	10%	51%	26%	9%	100%

A total of 48% of the respondents agree that products are classified into groups with similar routing requirements (Mo = 4, SD = 0.83), 49% agree that they monitor the production cycle time to respond quickly to customer requests.

4.2.7 Employee Involvement

The set of questions that evaluated Employee Involvement is presented in Table 11.

Table 11: Employee Involvement Scale

	Mode	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
Shopfloor employees undergo cross-functional training.	3	0.98	4	6	32	29	11	82
			5%	7%	39%	35%	13%	100%
Shopfloor employees are crucial to problem-solving teams.	4	0.98	3	3	20	35	21	82
			4%	4%	24%	43%	26%	100%
Shopfloor employees lead product/process improvement efforts.	3	1.10	4	9	26	25	18	82
			5%	11%	32%	30%	22%	100%
I welcome change most of the time when it is clearly communicated.	4	0.64	0	0	7	38	37	82
			0%	0%	9%	46%	45%	100%

45% of the respondents strongly agree that they welcome change most of the time when it is clearly communicated (Mo = 4, SD = 0.64) and 43% agree that shopfloor employees are crucial to problem-solving teams (Mo = 4, SD = 0.98). Only 39% of the respondents neither agreed nor disagreed that shopfloor employees undergo cross-functional training (Mo=3, SD=0.98).

4.2.8 Leadership

In a study in Morocco, the participants interviewed by Farissi et al [36] identified the main inhibiting factors and attributed 80% of them to a lack of managerial commitment.

The set of question set that measured Leadership is presented in Table 12.

Table 12: Leadership Scale (n = 82)

	Mode	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
I have a positive working relationship with my line manager.	4	0.84	2	1	6	40	33	82
			2%	1%	7%	49%	40%	100%
My job allows me to advance my career.	4	1.07	3	7	12	33	27	82
			4%	9%	15%	40%	33%	100%
My manager is aware of my work problems and obstacles.	4	0.98	3	3	18	36	22	82
			4%	4%	22%	44%	27%	100%
Management behaviour in our company is related to subordinate satisfaction and task commitment.	4	0.91	3	3	29	35	12	82
			4%	4%	35%	43%	15%	100%
	4	1.11	3	11	21	27	20	82

	Mode	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
Management behaviour in our company is related to employee motivation.			4%	13%	26%	33%	24%	100%
Managers encourage the creation of new knowledge and ideas via the use of academic motivation.	4	1.04	4	7	25	31	15	82
			5%	9%	30%	38%	18%	100%
Management enhances employee competence and encourages transformation.	4	1.02	3	8	15	39	17	82
			4%	10%	18%	48%	21%	100%
Managers in the company build exceptional teams and influence performance.	4	1.01	3	7	21	35	16	82
			4%	9%	26%	43%	20%	100%
Employees feel trust, admiration, loyalty and respect toward their manager.	4	1.01	2	8	23	31	18	82
			2%	10%	28%	38%	22%	100%
The company actively promotes a culture of empowerment and motivation.	4	1.08	3	8	19	30	22	82
			4%	10%	23%	37%	27%	100%

Only 40% of the respondents strongly agree that they have a positive working relationship with my line manager (Mo = 4, SD = 0.84).

4.2.9 Change Management

One of the most important success factors of the LM implementation in the shoe factory study was cultural change management,[33].

The set of questions that measured Change Management is presented in Table 13.

Table 13: Change Management Scale (n = 82)

	Mode	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
Our company has a management of change policy which I am aware of.	4	1.11	5	6	24	28	19	82
			6%	7%	29%	34%	23%	100%
Our company communicates change to employee at the beginning (outset) of the journey.	4	1.09	4	10	14	37	17	82
			5%	12%	17%	45%	21%	100%
Our company communicates change effectively so that all employees affected understand.	4	0.95	1	9	17	38	17	82
			1%	11%	21%	46%	21%	100%
Our company provides training for the change where necessary.	4	0.87	2	3	8	45	24	82
			2%	4%	10%	55%	29%	100%
Our company communicates change effectively so that all employees are on board, cooperate and are supportive.	4	0.99	2	6	21	33	20	82
			2%	7%	26%	40%	24%	100%
	4	0.98	3	4	25	33	17	82

Our company motivates its employees throughout the change process.			4%	5%	30%	40%	21%	100%

Of the respondents 55% agree that our company provides training for the change where necessary (Mo = 4, SD = 0.87), and 46% agree the company communicates change effectively so that all employees affected understand (Mo = 4, SD = 0.95). This may suggest that the change management policy may not be well communicated, especially where more than 50% of the respondents have been with the company for less than 5 years.

4.2.10 Employee Performance Scale

Lean leadership may be thought of as a manner of sustaining and refining employee performance in lean production systems.

The set of questions that evaluated Employee Performance is presented in Table 14 below.

Table 14: Employee Performance Scale (n = 82)

	Mode	SD	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	N
My Colleagues adequately complete their assigned duties.	4	0.79	0	5	10	46	21	82
			0%	6%	12%	56%	26%	100%
My Colleagues execute extra effort to fulfil their tasks beyond expectation.	4	0.80	1	4	12	49	16	82
			1%	5%	15%	60%	20%	100%
My Colleagues always strive to achieve departmental goals.	4	0.84	1	4	9	44	24	82
			1%	5%	11%	54%	29%	100%
My Colleagues enjoy sharing information and skills with other colleagues.	4	0.94	2	3	16	36	25	82
			2%	4%	20%	44%	30%	100%
My Colleagues adhere to informal rules to maintain order.	4	0.81	1	3	19	44	15	82
			1%	4%	23%	54%	18%	100%
My Colleagues enjoy contributing solutions to solve departmental problems.	4	0.93	3	3	14	43	19	82
			4%	4%	17%	52%	23%	100%
My Colleagues are committed to their work.	4	0.83	2	1	7	42	30	82
			2%	1%	9%	51%	37%	100%
My Colleagues value interpersonal relationships.	4	0.84	2	2	14	46	18	82
			2%	2%	17%	56%	22%	100%
My Colleagues welcome feedback to help improve performance	4	0.89	2	3	12	43	22	82
			2%	4%	15%	52%	27%	100%

The majority of the respondents (60%) agree that, My Colleagues execute extra effort to fulfil their tasks beyond expectation (Mo = 4, SD = 0.80).

4.2.11 Organisational Commitment

It is the actions of management to deliberately promote a culture of CI that give rise to a higher commitment of employees to maintain lean, cooperation among cross-functional teams to attain process targets, and a keenness of the workforce to advance their performance continuously [37].

The set of questions that measured Organisational Commitment is presented in Table 15.

Table 15: Organisational Commitment Scale (n = 82)

	Mode	**SD**	Strongly disagree	Disagree	Neutral	Agree	Strongly agree	**N**
During the last 3 months, how do you rate your overall job satisfaction?	5	1.06	2	6	8	21	45	82
			2%	7%	10%	26%	55%	100%
A person should always be loyal to the organisation he/she works in	5	0.79	1	1	8	36	36	82
			1%	1%	10%	44%	44%	100%
One of the main reasons for me to continue to work in this company is loyalty and moreover moral obligations	4	0.95	1	5	20	31	25	82
			1%	6%	24%	38%	30%	100%
I can leave my job if I get a better job offer	5	1.13	3	10	22	23	24	82
			4%	12%	27%	28%	29%	100%
Spending most of his/her career in one institution is good for a worker	4	1.09	5	18	25	25	9	82
			6%	22%	30%	30%	11%	100%
It will not be logical to commit myself emotionally to one organisation	3	1.03	5	9	39	18	11	82
			6%	11%	48%	22%	13%	100%
As for my opinion, being loyal to the organisation is important	4	0.76	0	1	14	36	31	82
			0%	1%	17%	44%	38%	100%

The majority of the respondents (55%) strongly agree that they experienced overall job satisfaction during the last 3 months (Mo = 5, SD = 1.06), Job satisfaction in the company seems to be very good.

4.3 Analysis Inferential Statistical

The results of the inferential statistical methods are utilised to analyse the gathered quantitative data. Although the scales of this study were subjected to factor analysis, the results were not recorded.

4.3.1 Hypothesis testing

The first set of hypotheses was to determine the relationship between the eight continuous dependent variables and the dependent variable Internal Operations (IO).

Hypothesis H1.1 to H1.9

Hypothesis $H0_{1.1}$ to $H0_{1.9}$: There is no relationship between the selected continuous dependent variables of the study

It is clear that a significant, positive correlation exists between all the selected continuous dependent variables of the study. Upon this finding, the null hypotheses $H0_{1.1}$ to $H0_{1.9}$ are discarded, accepting the alternate hypotheses which denoted that a positive relationship exists between all the chosen continuous dependent variables of the study.

Hypothesis H2.1 to H2.9

Hypothesis $H0_{2.1}$ to $H0_{2.9}$: Each one of the 9 chosen Continuous Dependent Variables mean rank scores are not identical per gender category

Table 16: Gender Group Mean Score Assessment (n = 82)

	Dependent Variables	Mann-Whitney U	Wilcoxon W	Z	Asymp. Sig. (2-tailed)
H2.1	Understanding of Lean Manufacturing (UM)	588.000	1329.000	-2.318	**.020**
H2.2	Stakeholders Relations (SR)	669.000	1410.000	-1.570	.117
H2.3	Supply Function (SF)	687.000	1428.000	-1.405	.160
H2.4	Internal Operations (IO)	698.000	1439.000	-1.287	.198
H2.5	Employee Involvement (EI)	552.000	1293.000	-2.673	**.008**
H2.6	Leadership (LS)	716.000	1457.000	-1.117	.264
H2.7	Change Management (CM)	638.000	1379.000	-1.848	.065
H2.8	Employee Performance (EP)	627.000	1368.000	-1.953	.051
H2.9	Organisational Commitment (OC)	536.000	1277.000	-2.801	**.005**

Understanding of Lean Manufacturing: The female group has a median score of 3.4, while the male group has a score of 3.9. This means that men report a greater level Understanding of Lean Manufacturing than women.

Employee Involvement: The median score for Females is (3.17) and Males is (4.00). This means that males report a higher Employee Involvement than females.

Organisational Commitment: The median score for Females is (3.80) and Males is (4.30). This means that the males report a higher Organisational Commitment that females.

Hypothesis H3.1 to H3.9

Hypothesis $H0_{3.1}$ to $H0_{3.9}$: **Each one of the 9 chosen Continuous Dependent Variables mean rank scores are not identical per Age category**

The non-parametric Kruskal-Wallis Test (for testing more than two variables) (Pallant, 2020) [28] was applied to establish if there are meaningful variances in categorical variables' mean scores.

Table 17: Age Group Mean Score Comparison (n = 82)

	Dependent Variables	Chi-Square	df	Asymp. Sig.
H3.1	Understanding of Lean Manufacturing (UM)	4.344	3	.227
H3.2	Stakeholders Relations (SR)	2.024	3	.567
H3.3	Supply Function (SF)	5.504	3	.138
H3.4	Internal Operations (IO)	2.966	3	.397
H3.5	Employee Involvement (EI)	3.617	3	.306
H3.6	Leadership (LS)	5.236	3	.155
H3.7	Change Management (CM)	4.460	3	.216
H3.8	Employee Performance (EP)	1.620	3	.655
H3.9	Organisational Commitment (OC)	9.247	3	**.026**

Due to space constraints, only results of significance are shown in detail. Only one variance of statistical significance was found between the dependent variables across the categorical independent variable age groups.

Hypothesis H4.1 to H4.9

Hypothesis $H0_{4.1}$ to $H0_{4.9:}$ Each one of the 9 chosen Continuous Dependent Variables mean rank scores are not identical per Job Level category

The non-parametric Kruskal-Wallis Test (for testing more than two variables) was applied to establish if there are relevant variances in categorical variables' mean scores. The outcomes of the means rank-score comparison of the categories of job level on the nine dependent variables of the study are reported in Table 18.

Table 18: Job Level Group Mean Score Comparison (n = 82)

	Dependent Variables	Chi-Square	df	Asymp. Sig.
H4.1	Understanding of Lean Manufacturing (UM)	4.735	3	.192
H4.2	Stakeholders Relations (SR)	10.380	3	**.016**
H4.3	Supply Function (SF)	9.941	3	**.019**
H4.4	Internal Operations (IO)	8.116	3	**.044**
H4.5	Employee Involvement (EI)	4.400	3	.221
H4.6	Leadership (LS)	1.375	3	.711
H4.7	Change Management (CM)	9.907	3	**.019**
H4.8	Employee Performance (EP)	2.698	3	.441

H4.9	Organisational Commitment (OC)	6.855	3	.077

Four statistically significant differences were found between the dependent variables and the categorical independent variable gender groups.

Stakeholders Relations (SR): Using the Kruskal-Wallis Test post hoc analysis (see Table 19) reveals that the distribution of Stakeholders Relations is not identical across categories of Job Level as there is a statistically significant difference (n = 82; p = 0.016) in categories of Job Level with Stakeholders Relations.

Table 19: Stakeholders Relations Comparison between Current Job Level

Sample 1 - Sample 2	Test Statistic	Std Error	Std Test Statistic	Sig	Adj-Sig
Junior Management (supervisory)-Senior or Middle management	-9.187	7.349	-1.250	.211	1.000
Junior Management (supervisory) - Operational	-15.135	6.535	-2.316	.021	.123
Junior Management (supervisory) - Support Staff	-23.827	8.004	-2.977	.003	.017
Senior or Middle management - Operational	5.948	7.349	.809	.418	1.000
Senior or Middle management - Support Staff	-14.640	8.681	-1.686	.092	.550
Operational – Support Staff	-8.692	8.004	-1.086	.277	1.000

The outcomes of the Kruskal-Wallis test post hoc analysis showed that there are statistically significant differences in the Stakeholders Relations levels between the Job Level categories Junior management and Supporting Staff. This means Supporting Staff gives higher Stakeholders Relations scores than Junior management (supervisory).

Supply Function (SF): Table 20, reflects on the analysis of the Kruskal-Wallis Test which reveals that the distribution of Supply Function is not identical across categories of Job Level which resulted from a statistical significant variance (n = 82; p = 0.019) in categories of Job Level with Supply Function.

Table 20: Supply Function Comparison between Current Job Level

Sample 1-Sample 2	Test Statistic	Std Error	Std Test Statistic	Sig	Adj-Sig
Junior Management (supervisory)-Senior or Middle management	-12.552	7.326	-1.713	.087	.520
Junior Management (supervisory) - Support Staff	-15.346	7.978	-1.923	.054	.327
Junior Management (supervisory) - Operational	-19.904	6.514	-3.055	.002	.013
Senior or Middle management - Support Staff	-2.794	8.654	-.323	.747	1.000
Senior or Middle management - Operational	7.352	7.326	1.004	.316	1.000
Support Staff - Operational	4.558	7.978	.571	.568	1.000

The outcomes of the analysis using the Kruskal-Wallis Test post hoc revealed that the Supply Function levels differed statistically substantially (p = 0.013) between the Job Level categories Junior management (supervisory) (Mean rank = 30.15, n = 26) and Operational (Mean rank = 50.06, n = 26). This means Operational Staff gives higher Stakeholders Relations scores than Junior management (supervisory).

Internal Operations (IO): The Kruskal-Wallis Test post hoc analysis revealed that the distribution of Internal Operations differs across classes of Job Level as there is a statistical difference of significance in classes of Job Level with Internal Operations. Based on this information it seems that employees on a lower job level give a higher score for Internal Operations.

Change Management (CM): Table 21 reflects on the Kruskal-Wallis Test post hoc analysis reveals that the distribution of Change Management is not identical across classes of Job Level as there exists a statistically significant difference (n = 82; p = 0.019) in classes of Job Level with Change Management.

Table 21: Change Management Comparison between Current Job Level

Sample 1 – Sample 2	Test Statistic	Std Error	Std Test Statistic	Sig	Adj-Sig
Junior Management (supervisory)-Senior or Middle management	-10.768	7.402	-1.455	.146	.874
Junior Management (supervisory) - Operational	-15.577	6.582	-2.367	.018	.108
Junior Management (supervisory) - Support Staff	-23.058	8.061	-2.860	.004	.025
Senior or Middle management - Operational	4.809	7.402	.650	.516	1.000
Senior or Middle management - Support Staff	12.290	8.743	-1.406	.160	.959
Support Staff - Operational	-1.7481	8.061	-9.28	.353	1.000

The outcomes of the Kruskal-Wallis Test post hoc analysis revealed that there exists a statistically significant difference in Change Management levels (p = 0.025) between the Job Level categories Junior management (supervisory) (Mean rank = 30.67, n = 26) and Supporting Staff (Mean rank = 53.73, n = 13). Supporting staff give higher scores for Change Management than Junior management (supervisory).

Hypothesis H5.1 to H5.9

Hypothesis $H0_{5.1}$ to $H0_{5.9}$: Each one of the 9 chosen Continuous Dependent Variables mean rank scores are not identical per Current Position Tenure category

Reported in Table 22 below are the outcomes of the means rank scores comparison of the categories of Current Position Tenure on the nine dependent variables of the research.

Table 22: Current Position Tenure Group Mean Score Comparison (n = 82)

	Dependent Variables	Chi-Square	df	Asymp. Sig.
H5.1	Understanding of Lean Manufacturing (UM)	4.228	3	.238
H5.2	Stakeholders Relations (SR)	2.575	3	.462

	Dependent Variables	Chi-Square	df	Asymp. Sig.
H5.3	Supply Function (SF)	6.174	3	.103
H5.4	Internal Operations (IO)	2.325	3	.508
H5.5	Employee Involvement (EI)	2.221	3	.528
H5.6	Leadership (LS)	3.730	3	.292
H5.7	Change Management (CM)	3.083	3	.379
H5.8	Employee Performance (EP)	2.612	3	.455
H5.9	Organisational Commitment (OC)	3.218	3	.359

The Kruskal-Wallis Test revealed that the distribution of nine dependent variables is same across categories of current position tenure as there is no difference ($n = 82$; $p > 0.05$) in categories of current position tenure with the nine dependent variables.

Hypothesis H6.1 to H6.9

Hypothesis $H0_{6.1}$ to $H0_{6.9}$: Each of the 9 selected Continuous Dependent Variables mean rank scores are not identical per Education category

Table 23 below reflects on the outcomes of the means rank scores comparison of the categories of Education on the nine dependent variables of the research.

Table 23: Education Group Mean Score Comparison (n = 82)

	Dependent Variables	*Chi-Square*	*df*	*Asymp. Sig.*
H6.1	*Understanding of Lean Manufacturing (UM)*	*9.370*	*3*	***.125***
H6.2	*Stakeholders Relations (SR)*	*9.300*	*3*	***.026***
H6.3	*Supply Function (SF)*	*3.579*	*3*	*.311*
H6.4	*Internal Operations (IO)*	*4.703*	*3*	*.195*
H6.5	*Employee Involvement (EI)*	*5.570*	*3*	*.134*
H6.6	*Leadership (LS)*	*7.152*	*3*	*.067*
H6.7	*Change Management (CM)*	*8.534*	*3*	***.036***
H6.8	*Employee Performance (EP)*	*3.123*	*3*	*.373*
H6.9	*Organisational Commitment (OC)*	*16.077*	*3*	***.001***

Four statistically significant differences were found between the dependent variables across the categorical independent variable gender groups.

Understanding of Lean Manufacturing: The Kruskal-Wallis Test post hoc analysis revealed that the distribution of Understanding of Lean Manufacturing is different across categories of Education as there exists a statistically significant difference ($n = 82$; $p = 0.025$) in categories of Education with Understanding of Lean Manufacturing.

Stakeholders Relations: Table 24 below revealed that the distribution of Stakeholders Relations differs across categories of Education as there exists a statistically relevant difference ($n = 82$; $p = 0.026$) in categories of Education with Stakeholders Relations.

Table 24: Stakeholders Relations Comparison between Education

Sample 1-Sample 2	Test Statistic	Std Error	Std. Test Statistic	Sig	Adj. Sig
Undergraduate-Diploma/ degree	5.150	8.291	.621	.534	1.000
Undergraduate-Master's degree or equivalent or more	13.900	12.168	1.142	.253	1.000
Undergraduate-Grade 12 or less	21.338	8.869	2.406	.016	.097
Diploma/ Degree-Master's degree or equivalent or more	-8.750	10.284	.851	.395	1.000
Diploma/ Degree-Grade 12 or less	-16.188	6.029	-2.685	.007	.044
Master's degree or equivalent or more-Grade 12 or less	7.438	10.755	.692	.489	1.000

Change Management: The outcomes of the Kruskal-Wallis Test post hoc analysis utilising a Dunn's technique with Bonferroni correction for multiple comparisons revealed that the distribution of Change Management is not the same across categories of Education as there exists a statistically significant difference (n = 82; p = 0.036) in categories of Education with Change Management.

Organisational Commitment: Table 25 below revealed that the distribution of Organisational Commitment is dissimilar across categories of Education as there exists a statistically significant difference (n = 82; p = 0.001) in categories of Education with Organisational Commitment.

Table 25: Organisational commitment comparison between education

Sample 1-Sample 2	Test Statistic	Std. Error	Std. Test Statistic	Sig	Adj. Sig
Diploma/Degree-Undergraduate	-11.910	8.345	-1.427	.154	.921
Diploma/Degree-Master's degree or equivalent or more	-14.976	10.351	-1.447	.148	.888
Diploma/Degree-Grade 12 or less	-23.955	6.069	-3.947	.000	.000
Undergraduate-Master's degree or equivalent or more	3.067	12.247	.250	.802	1.000
Undergraduate-Grade 12 or less	12.048	8.927	1.349	.177	1.000
Master's degree or equivalent or more-Grade 12 or less	8.979	10.825	.829	.407	1.000

On the basis of this outcome the alternate hypothesis is discarded and the null hypotheses 6.9 is acknowledged which stated that Organisational Commitment mean rank scores differ per Education category.

5 DISCUSSION AND SUMMARY OF FINDINGS FROM THE REVIEW OF LITERATURE

There are numerous requirements for the successful implementation of lean practises in a company, one of which is that there ought to be a strong commitment from top management, [33]. In a study in Morocco, the participants interviewed by Farissi et al [36] identified the main inhibiting factors and attributed 80% of them to a lack of managerial commitment.

The conclusions from the literature reviewed concerning factors that affect the implementation of LM in various countries were conducted to assess and gain in-depth knowledge and understanding of the enabling and inhibiting factors of lean implementation that encourage or discourage LM in the food industry. The identified influential factors across borders include:

Company Culture	Leadership	Skills and Training	Company Structure
Resources	Employee Engagement	Compensation/ Rewards	Change Management

Plant, product, and process in the food industry are contextual factors to be considered in the implementation of lean. The context of the food industry is built around very dissimilar groupings of products with diverse degrees of perishability and various manufacturing lead times; thus, manufacturers must constantly balance the risk of waste versus reduced product quality, risking stock-outs and disgruntled customers [14].

It can be concluded that Skills and Training, Stakeholder Relations, Employee engagement, Change Management, Leadership, Employee Performance and employee characteristics diversity have influence on LM. Further, it can be concluded that the participants have a clear understanding of the company's quality mission statement and quality vision statement and used the Fishbone diagram, (a LM tool for problem solving). That the identified factors identified, skills and training, change management, stakeholder relations, employee engagement, employee performance and leadership all have a positive correlation with LM. It can be concluded that an improvement on any of these factors will influence positively the performance of LM at the food flavours manufacturing company.

6 RECOMMENDATIONS

It is therefore recommended that efforts towards improving communication of policies such as the change management. Enhancing communication will improve stakeholder relations, it was observed from the survey that most of the respondents agree that they are in frequent contact with their customers and that they are in frequent contact with their suppliers.

7 MANAGERIAL IMPLICATIONS

These findings give insight to management on the factors affecting LM implementation, based on this insight, it is recommended that managers purposefully engage employees in problem identification and solutions, involve the shopfloor employees in the improvement process as they have first-hand experience. Also, the training program be revised, enhanced, and implemented to improve the knowledge and skill base of the employees.

8 CONCLUSION

To conclude, the research answered the research questions and satisfied the research objectives as well as provided recommendations to management as an input to their LM implementation strategy.

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Appendix 1: Survey questionnaire

- **Annexure D: Survey Questionnaire**

Part A: CONSENT FORM

Please Note:

- All responses to the survey are confidential.
- No names will be link to any data.
- All data collected are strictly for research purposes only.

1) * Please indicate your willingness to participate in this research study, by indicating your preference below:

I am willing to participate

I am not willing to participate

Part B: GENERAL INFORMATION

Please note we collect the demographical data for research purposes only.

2) * Your Gender

Male

Female

Prefer not to say

3) * Your Age Category

18-25 years

26-30 years

31-40 years

41-50 years

51-60 years

61 years or above

4) * What is your employment position in the company?

Senior Management

Middle management

Junior Management (supervisory)

Operational

Support Staff

5) * Number of years serving in the CURRENT position

0 to 5 years

6 to 10 years

11 to 15 years

16 to 20 years

21 years or more

6) * What is your highest academic qualification?

Grade 12 or less

Undergraduate

Diploma/Degree

Master's degree or equivalent or more

7) * During the last 3 month, how do you rate your overall job satisfaction?
Very low 2 3 4 5 Very High

SECTION C: LEAN CULTURE

The purpose of lean manufacturing is to eliminate waste and enhance the value of products produced thereby increasing the company's competitiveness. An example of waste is any form of Re-Work, it can be corrected by doing this right the first time.

- *Transportation - the unwarranted transport of components under production.*
- *Inventory - Heaps of components waiting to be completed or finished goods waiting to be shipped.*
- *Motion – the unwarranted movement of people working on products.*
- *Waiting – the unwarranted waiting by people to begin the next step.*
- *Over-Processing the product with extra steps.*
- *Over-production of products not needed.*
- *Defects in the product.*
- *Under-utilised people*

8) * To what extent do you agree with the following statements when considering your company?

Lean Manufacturing	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
I understand the concept of lean management.					
I am aware of this lean practice, in our company					
Our company is currently implementing lean manufacturing practices					
Our company has been implementing many of the lean manufacturing practices even though we do not call it lean					
Our company is currently implementing HACCP					
Our company is currently implementing FSSC 22000					
Our company is currently implementing NFS					
Our company is currently implementing ISO 9001: 2015					
Our company is currently implementing ISO 45000					

9) * Based on the following table, which of the following has been implemented?

	Not intended to be used / unknown	Planned for use in subsequent year	Planned for use in 3 years	Already in use
Quality vision statement				
Quality mission statement				
Value Stream Mapping				
Takt Time				
Pull system				
Just in time				
Kanban system				
Standard work				
Standardised work sheet				
Levelling production and schedules (heijunka)				
Single minute exchange of die (change overs)				
Error Proofing (poka yoke)				
Visual Management				
Notification system for quality and process problems (Andon)				
Root Cause Analysis (Fishbone diagram)				
5 – why analysis				
Plan-do-check-act PDCA cycle				
5S - method				
Gemba				

Please indicate your level of agreement with the following statements.					
10) *My colleagues have adequate knowledge of Lean Manufacturing	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
11) *Do you think your employee training program on Lean Manufacturing is working?	Not really	Not quite enough	Reasonable training program	Enough training programs	More than enough training program

12) *You are involved in problem identification & improvement of processes (be they Production; innovation; sales; procurement etc) of the company?	Strongly disagree	Disagree	Neutral	Agree	Strongly agree
13) *To what extent can the worker involvement in Lean Manufacturing (waste elimination) programs in your workplace be explained?	Very Poor	Poor	Fair	Good	Very Good
14) * Do you think the opinions and suggestions of employees are given due consideration?	Not at all. Supervisors and managers do not care about employees' opinions.	Sometimes Supervisors and managers listen to their subordinates' opinions.	Supervisors and managers in many cases listen to opinions of employees.	Supervisors and managers always listen to opinions of employees from some employees.	Supervisors and managers always listen to opinions of employees from all levels, and they are responsive.

15) * To what extent do you agree with the following statements regarding the use of Lean Manufacturing practices when considering your company.

Customer Relations	Strongly Disagree	Disagree	Neutral	Agree	Strongly Agree
We are in frequent contact with our customers.					
Our customers give us feedback on quality and delivery performance.					
We conduct customer satisfaction surveys regularly.					
Supplier Relations					
We are in frequent contact with our Suppliers.					
Our key suppliers deliver to our factory on just-in-time basis.					

We take steps to reduce the number of suppliers in each category to reduce raw material variations.					
Our purchasing / supply function is centralised.					
Internal Operations					
We use the pull production system.					
We use Kanban, squares, or containers of signals for production control.					
Production at station is pulled by the current demand of the next station.					
Products are classified into groups with similar routing requirements.					
Product families determine our factory lay out.					
We are working to lower set up times in our plant from one batch to the next.					
We monitor our production cycle time to respond quickly to customer requests.					
Our employees practice setups to reduce required time.					
Our processes on the shop floor are currently under Statistical Process Control.					
We use charts to show defect rates on the shopfloor.					
Employee Involvement					
Shopfloor employees undergo cross-functional training.					
Shopfloor employees are crucial to problem-solving teams.					
Shopfloor employees lead product/process improvement efforts.					
I welcome change most of the time when it is clearly communicated.					

16) * To what extent do you agree with the following statements regarding the use of Lean Manufacturing practices when considering your company.

Leadership/ Management	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
I have a positive working relationship with my line manager.					
My job allows me to advance my career.					
My manager is aware of my work problems and obstacles.					
Management behaviour in our company is related to subordinate satisfaction and task commitment.					
Management behaviour in our company is related to employee motivation.					
Managers enable the generation of new knowledge and ideas through the use of academic motivation.					
Management enhances employee competence and encourages transformation.					
Managers in the company build exceptional teams and influence performance.					
Employees feel trust, admiration, loyalty and respect toward their manager.					
The company actively promotes a culture of empowerment and motivation.					
Change Management					
Our company has a management of change policy which I am aware of.					
Our company communicates change to employee at the beginning (outset) of the journey.					
Our company communicates change effectively so that all employees affected understand.					
Our company provides training for the change where necessary.					
Our company communicates change effectively so that all employees are on board, cooperate and are supportive.					
Our company motivates its employees throughout the change process.					

17) * To what extent do you agree with the following statements:

My Colleagues……

Employee Performance	**Strongly Disagree**	**Disagree**	**Neutral**	**Agree**	**Strongly Agree**
..adequately complete their assigned duties.					
..execute extra effort to fulfil their tasks beyond expectation.					
..always strive to achieve departmental goals.					
..enjoy sharing information and skills with other colleagues.					
..adhere to informal rules to maintain order.					
..enjoy contributing solutions to solve departmental problems.					
..are committed to their work.					
..value interpersonal relationships.					
..welcome feedback to help improve performance					
Organisational Commitment					
A person should always be loyal to the organisation he/she works in					
One of the main reasons for me to continue to work in this company is loyalty and moreover moral obligations					
I can leave my job if I get a better job offer					
Spending most of his/her career in one institution is good for a worker					
It will not be logical to commit myself emotionally to one organisation					
As for my opinion, being loyal to the organisation is important					

IS THE NORMAL DISTRIBUTION FOR DURATION OF ACTIVITIES ADEQUATE FOR ANALYSIS AND SIMULATION OF A CAR WASH FACILITY?

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ABSTRACT

Many vehicle owners use car wash facilities for washing and cleaning of their vehicles. The daily throughput of cars determines the revenue and profit for the car wash owner. A queue of cars waiting to enter the washing bay and a queue of cars waiting to enter the drying bay develop regularly. A simulation model was developed to study the effect of using non-symmetric probability distributions like the lognormal and gamma input distributions on the total time in the facility which determines the daily throughput of vehicles. Actual duration of the washing and drying processes was measured and used as input parameters for a discrete event simulation. Results showed that using right skewed triangular input distributions gives longer washing and drying durations, causing longer total time in the facility and reduction of throughput. Right skewed distributions are recommended as input for simulation of this type of facility.

Keywords: Car wash facility, Monte Carlo simulation, discrete-event simulation, probability distributions

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1 INTRODUCTION

1.1 Background

Vehicles are an important part of an industrial economy in most countries worldwide. In December 2022 there were about 12 million vehicles registered with the National Traffic Information System (Natis) of South Africa [1]. In Gauteng alone there were about 4,5 million vehicles registered. About a third of South African households own and drive a car. It is the most popular way of commuting from home to work for many citizens. It is therefore no surprise that car wash businesses are well established in South Africa and all cities and major towns have at least one car wash facility. There are about ten car wash facilities within a 10km radius of the author's residence in Centurion, Gauteng. Washing and cleaning the interior of a car also is a maintenance activity that is required regularly

A washing facility typically comprises a location for washing the car and a location to dry the exterior and vacuum the interior. Other equipment and material include high pressure pumps, water hoses, dryers, vacuum cleaners, soap, polishes, and other chemicals. Electricity, water, and a sewer discharge point are necessities. All car wash facilities require some manual labour, but manual car washes are labour intensive with 10 to 20 washers and cleaners, depending on the size of the business and facility. There are also by-laws of the town council and safety and environmental regulations that must be considered by car wash business owners e.g., soap and chemical used in the washing process should be discharged into the sewer and not the stormwater system [2].

Car wash facilities usually offer different options for its customers. Some only require a quick wash while most customers make use of a 'special offer' that comprises a wash, dry and vacuum. Vehicles that arrive at the wash facility also differ significantly in size and shape. Normal sedans are abundant, but it seems that the SUV's are increasing in number [1]. Other categories include four-by-four vehicles and microbuses and therefore different pricing strategies are available [3].

1.2 Problem Statement

Car wash owners operate the business to ensure a profit at the end of the financial year. The profit is directly proportional to the throughput of cars which is a function of the duration of the wash, dry and vacuum processes or activities. A customer that arrives at the wash facility and finds that the queue of cars is too long might decide to find a different facility or just wait in the queue. A car wash owner could determine which processes are limiting the throughput by observing the operations daily. One option to increase the throughput is to hire more workers to perform the washing or drying processes. Simulation models are popular for studying and analysing complex industrial processes, and facilities. A process and simulation model can be used as a 'what if' tool to study the effect of changes in the inputs on the output performance.

This paper discusses the development of a simulation model for a typical car wash facility and how the model was applied to determine the effect of changing the interarrival rate of cars. The model was also used to study the effect on output of using different probability distributions for the wash and drying steps of the total process. The primary objective of this research study was to analyse a car washing facility by means of Monte Carlo simulation and discrete event simulation and to evaluate outputs for different input distributions. Sub-objectives were:

- To determine the total time distribution i.e., from the moment that the customer joins the queue to the moment that he leaves the premises;
- To determine the difference in total time and waiting time for different distributions e.g., normal, lognormal, triangular, and gamma distributions.

2 THEORY AND LITERATURE

All human endeavour involves uncertainty and scientists and engineers must consider this uncertainty in projects, operations, and maintenance. Uncertainty is modelled by means of probability. The performance of a car wash business involves uncertainty in the duration of the activities or processes. An important parameter is the total time that a vehicle is on the premises, from the time of arrival until exiting. The overall process can be divided into sub-processes and the duration of each process can be modelled by means of probability distributions. The literature review for this study focused on the modelling of a car wash facility, queueing systems, probability distributions, Monte Carlo simulation and discrete event simulation.

2.1 Car wash facilities

Car wash facilities have varying configurations. Some use automatic washing machines (usually rollers) and dryers while others use hand washing, drying, and vacuuming. Some have only one wash bay while others have two wash bays. The number of drying bays varies from about 4 to 10. There is also variation in the type and size of vehicles that arrive at the car wash facility. The time to wash and to dry such vehicles will thus also vary. In this study it was not feasible to collect the washing and drying durations for different car types and sizes due to time constraints. The owner of the car wash business is concerned with the total time that a vehicle is in the system, the total throughput in an hour or day, the maximum number of vehicles in the queue, and the total cost associated with the operations [4].

2.2 Queueing systems and models

Queueing theory dates to the early 20th century. Research and analysis led to the development of mathematical queueing models which are recognised today as the foundation of queueing theory. A simple queueing system is a server system where customers arrive to receive some service and leave when finished. In the context of this paper, the customer is the driver of the vehicle that arrives at the washing facility which has two 'servers' i.e., the wash service and the drying and vacuuming service. If a vehicle arrives at the wash bay and it is busy, it joins the queue. If the wash step cannot keep up with the rate of arrivals, a queue will build up to the maximum space available [5].

Most queueing models accept a steady state situation where the arrival rate and server rate can be accepted as constant and probabilistic behaviour of the arrivals and service duration need not be considered. In practice though this is hardly ever the case and probabilistic models have therefore been developed to deal with the inherent variation in such systems.

2.3 Monte Carlo Simulation (MCS)

Monte Carlo Simulation is a 'static' simulation that uses random sampling of distributions to produce a distribution of outcomes e.g., the total project cost and total duration, total annual cost for a maintenance department, or total duration of a maintenance task. MCS methods have become popular amongst project managers, operations and maintenance managers, and financial managers. The MCS method is well documented and discussed in various textbooks [6], [7], 8]. Various software programmes for performing simulations are available to model uncertainty in the cost or duration of activities. Two well-known software applications that automate the MCS method are @Risk [9] and Crystal Ball [10]. Some add-ins that provide MCS functionality for MS Excel are also available e.g., SimVoi [11] and RiskAmp [12]. Visser and Howes [13] used a MCS to determine the optimal workforce for a company involved in servicing and repairing imaging equipment at medical facilities throughout the Gauteng province. Meyer and Visser [14] used historical data for duration of project phases in mining industry projects to improve estimates for future projects.

2.4 Discrete event simulation (DES)

Banks [15] defined discrete event simulation models as "*a system for which some variable changes only at a discrete set of points in time*". A repairable system could typically be in an operational or running state and when a failure occurs it changes to a stopped state. When a repair or replacement is completed the system changes to a running state again. A DES is useful to model failures and repairs and determine the availability of a system from the failure times and repair times. Two discrete event simulation software programmes, GoldSim [16] and Arena [17], are often used to model a variety of manufacturing processes like cars arriving at a service station for fuel or at a workshop for a service or repairs.

Vàzques-Serrano et al. [18] reviewed 231 papers on the application of DES in healthcare. The study found that the DES was mostly used in emergency departments and medical centres to determine the allocation of resources and to improve duration of processes and efficiency.

Revina and Trifonova [19] used a DES to model the processes in a car service centre. Optimisation with the simulation model identified the bottlenecks in the service centre. Changes were subsequently made to the staff schedule, allocation of workers to work, and the number of posts. The changes led to an increase in the profit of the business by a factor of 1,9.

Greasely [20] described a methodology to implement a DES using a spreadsheet. A case study of a supermarket is used to explain how a spreadsheet can be used to model the system and how to use it in an educational context.

2.5 Probability distributions for modelling duration

Udoumoh and Ebong [21] discussed several probability distributions that are suitable for use in a MC simulation. The normal, lognormal, triangular gamma and Weibull distributions are included in their study. McLaughlin [22] as well as Evans et al. [23] compiled a comprehensive collection of probability distributions and formulas to calculate the density function (PDF), cumulative distribution function (CDF), mean value, and standard deviation.

The normal distribution, also known as the Gaussian distribution, is one of the most popular distributions used in MCS, general engineering, and science. It is a continuous and symmetric distribution with two parameters i.e., the mean value, μ, and the standard deviation σ. The distribution does not perform well when activities are severely right skewed [6]. Random variates for the normal distribution can be calculated with the norminv(rand(); μ; σ) function of Excel, where rand() is the random number generator provided by Excel [23].

The lognormal distribution is a non-symmetric, right-skewed distribution that is useful to model the duration of activities or tasks. Many tasks often take longer than planned since unexpected failures of equipment and tools occur. The distribution has two parameters i.e., the mean value, μ, and the standard deviation σ. Random variates can be calculated using the Excel function lognorm.inv(rand(); μ; σ) [23].

The triangular distribution is bounded on the left and right and can be symmetric, left skewed, or right skewed depending on the values of the three parameters that determine the shape of the distribution [23]. The three parameters of the triangular distribution are typically a (lower bound), m (mode), and b (upper bound) [23]. Forbes et al. [24] provide formulas for calculating the random variates for the triangular distribution.

$$T = \left\{a + \sqrt{\rho(b-a)(m-a)}\right\} \text{ for } 0< \rho <F(m) \quad (1)$$

$$T = \left\{b - \sqrt{(1-\rho)(b-a)(b-m)}\right\} \text{ for } F(m)\leq \rho <1 \quad (2)$$

Where $F(m)$ = (m-a)/(b-a) and ρ is a random number between 0 and 1.

The gamma distribution is skewed and often used in reliability to model failure times of equipment [23]. It has a shape parameter, $k > 0$, and a scale parameter, $\theta > 0$. The density function can have many different shapes depending on the values of the parameters. Random variates can be determined using the Excel function gamma.inv(rand(); k; θ) [23].

The Gumbel distribution is also known as the Extreme Value distribution (Type I) and has a location parameter $\mu > 0$ and a scale parameter $\beta > 0$ [23]. This distribution is mainly used in the analysis of extreme values e.g., flood levels in rivers and earthquake damage. A random variate, T, for the Gumbel distribution was calculated using equation 1 from Forbes et al. [22].

$$T(\rho, \mu, \beta) = \mu - \beta \cdot ln\left[ln\left(\frac{1}{\rho}\right)\right] \qquad (3)$$

where ρ is a random number from 0-1 and β and μ are the parameters of the Gumbel distribution.

The Weibull distribution is used extensively for modelling reliability of assets due to its versatility regarding the failure rate. It has two parameters i.e., a shape parameter, β, and a 'characteristic life' parameter, η [23]. The Weibull distribution is also useful to model task or activity duration since it is one of a few distributions that is skewed towards the left (negative skewness) for some values of the parameters. It is therefore not suitable for right-skewed activities [4]. A random variate, T, for the Weibull distribution was calculated using equation 2 [see 24].

$$T(\rho, \beta, \eta) = \eta \cdot \left[ln\left(1 - \frac{1}{1-\rho}\right)\right]^{\frac{1}{\beta}} \qquad (4)$$

where ρ is a random number, β is the shape parameter and η the characteristic life parameter of the Weibull distribution.

2.6 Comparison of probability distributions

Ferson et al. [25] said "*the results of probabilistic risk analyses are known to be sensitive to the choice of distributions used as inputs, an effect which is undoubtedly even stronger for the tail probabilities*". Some probability distributions are called fat-tailed which can be defined as a distribution that exhibits a large skewness or kurtosis. The occurrence of very large random variates is more likely for fat-tailed distributions like the lognormal, gamma, and Gumbel distributions than for the normal distribution.

Hajdu and Bokor [26] performed MC simulations with uniform, triangular and beta distributions and noted: "*the use of different distributions with the same three-point estimation has a smaller effect on the project duration than a 10% difference in the values of the three-point estimation*". Visser [27] found that the output distribution of a simulation depends on the complexity of the system being modelled, the distribution selected for the inputs, and the values for the parameters of the distribution selected. Wood [28] said: using the same input data as the mean and variance values, the output distributions for the normal, lognormal, and triangular distributions could vary by as much as 10%. This contradicts the findings of Hajdu and Bokor [26].

Balasooriya and Abeysinghe [29] compared the results of a simulation with the gamma and Weibull distributions using the same data set. They found that even though distribution fitting produced similar goodness of fit values, it was important to choose the best distribution for analysis and simulation purposes. Kundu and Manglick [30] said: "*The lognormal and Weibull distributions are the most popular distributions for modelling skewed data*". They developed a method to select between the gamma or lognormal distribution when failure data are available. The ratio of maximum likelihood was used to determine the better of the two distributions. Alzaid and Sultan [31] studied the problem of fitting given data to a gamma or lognormal distribution and selecting the better of these two distributions. They found that the gamma distribution gave a better fit than the lognormal in many situations. The method was tested with an actual data set. Monte Carlo simulation with 10000 trials was used to determine goodness of fit.

3 MODEL FOR VEHICLE WASHING FACILITY

The steps in the overall car wash process were observed visually and a block flow diagram or process map of the washing facility used for this case study is shown in Figure 1.

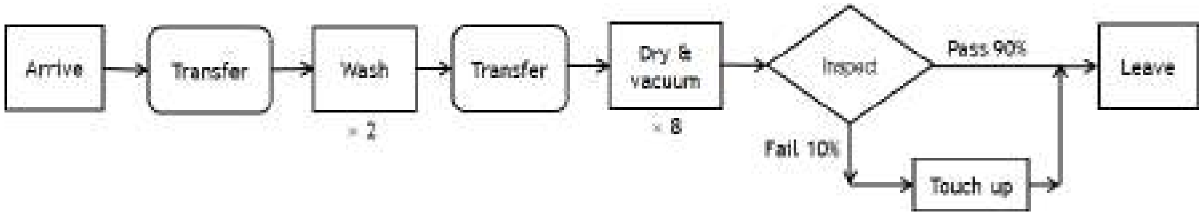

Figure 1. Block diagram for vehicle washing facility

Upon arrival at the facility, a vehicle joins the queue if both washing bays are occupied. As soon as one of the wash bays is open, the vehicle in the front moves from the waiting area into the wash bay where the washing activity is started. The time to transfer to the wash bay was measured 5 times and a minimum and maximum value of 12-15 seconds were allocated for this duration. The mean time and standard deviation for the wash process was obtained from actual data. When the wash step is finished, the vehicle proceeds to any of the drying bays that is available. If not, the car must wait until a bay is open. This transfer time was also observed 5 times and minimum and maximum values of 18-24 seconds were allocated for this duration. The mean duration and standard deviation for the drying process was obtained from actual data. When the drying stage is finished, a supervisor performs a brief inspection of the quality of work. The duration of this activity was measured 10 times and an average duration of 40 seconds was used as a constant in the simulation. If the quality check is positive, the vehicle leaves the premises. If negative, the supervisor or other worker performs a touch-up and the vehicle leaves. The duration of the touch up activity was measured, and an average value of 30 seconds was used as a constant in the simulation.

4 RESEARCH METHODOLOGY

4.1 Time data for vehicles

This project involved a case study of one car washing facility. The first step in the study was to obtain primary data for the duration of the wash and the drying/vacuuming steps of the process. Some 31 duration values were measured for the drying step and 16 duration values were measured for the washing step on three days of observation. The days chosen were days that the washing facility is very busy i.e., on Saturdays and Friday mornings. Descriptive statistics were calculated for this data to obtain the mean time and standard deviation for the wash and drying steps.

Six probability distributions i.e., normal, lognormal, gamma, Gumbel, Weibull, and triangular distributions, were fitted to the duration data of the drying process. The duration data was ranked from lowest to highest and a rank number, i, was assigned to each value. Breneman et al. [32] proposes a predictor for the cumulative distribution as the ratio of the rank number and the total number of data points as shown in equation 3.

$$F(i) = \frac{i}{N} \tag{5}$$

Guess values for the parameters of each distribution, based on the mean and standard deviation values as calculated with Excel AVERAGE and STDEV.P functions, were assumed and 31 values of the cumulative distribution was calculated using the formula for the cumulative distribution function in Excel i.e., norm.dist(i; μ; σ; true). The difference between the F(i) and the density function was squared and added for all 31 points. The Excel Solver add-in was used to vary the values of μ and σ until the minimum value for the sum of the squares for all data points is achieved. This process was repeated for all six distributions.

4.2 Performing a Monte Carlo Simulation in Excel

A mean value of 5,75min for the wash process and 18min for the drying process was used for the normal distribution. Standard deviation values of 1,0min for the wash process and 3,0min for the drying process were used. The total time for a car in the system was calculated by adding the distributions for all processes. The inverse variates for the distributions were then calculated for 50000 trials or repetitions. Usually about 10000 trials are adequate but 50000 was used in this case study to ensure credible results. The mean value, standard deviation and skewness values for these trials were calculated using standard Excel functions. Parameters for the lognormal, triangular, gamma and Gumbel distributions were calculated from the mean and standard deviations mentioned earlier.

4.3 Performing a Discrete Event Simulation

Estay [33] describe a process to perform a discrete-event simulation (DES) using a spreadsheet. It was applied to a simple system with two processes in a healthcare scenario. Elizandro and Taha [34] developed a discrete event simulation for an industrial system with Excel and visual basic. Quintão et al. [35] discuss the results of a discrete event simulation for a car wash facility using Arena software. Analysis of actual data indicated that queue congestion and long waiting times occur. The simulation minimised the queue length and reduced the waiting time by optimising the resources of the system.

The car wash facility used in this case study has two processes. The first column in the spreadsheet indicates the numbers of the cars that arrive over a period of 4 hours, for example 50 cars. The next column could indicate the inter-arrival times for the 50 cars as determined from the inverse of the exponential distribution. Further columns in the worksheet are needed for the wash time calculated from the inverse of the distribution and the drying time from the inverse of the drying time distribution. The arrival times for each car is noted in a separate column, the first car can be advanced to the wash bay, and the start time for this car is noted in a separate column. The finish time for the car is the start time for the wash plus the duration of the wash. There should be two columns for the two parallel wash bays and 8 columns for the 8 parallel wash bays. The simulation can be automated to increase the speed of processing by using specialist software available from several software developers.

5 RESULTS

5.1 Primary data

Sixteen duration values were captured for the washing operation and 31 duration values for the drying process. The actual data for the wash and drying processes is shown in Table 1.

Table 1: Duration data for wash and drying activities

Number	Dry (min)	Wash (min)
1	15,0	2,084
2	17,0	3,000
3	18,0	3,167
4	17,0	2,917
5	22,0	2,250
6	17,0	2,667
7	20,0	2,500
8	19,0	3,000
9	20,0	3,250
10	23,0	2,834
11	15,0	2,500
12	13,0	4,000
13	19,0	3,834
14	15,0	2,750
15	18,0	2,750
16	15,0	2,500
17	18,0	
18	16,0	
19	21,0	
20	18,0	
21	22,0	
22	23,0	
23	15,0	
24	19,0	
25	15,0	
26	23,0	
27	17,0	
28	21,0	
29	14,0	
30	17,0	
31	14,0	
Mean	17,936	5,750
Std. Dev.	2,920	0,995

The 31 data points for the drying activity were used to fit six probability distributions. The SOLVER add-in for Excel was used to determine the mean, standard deviation, and least squares values for these distributions as shown Table 2.

Table 2: Parameters and least squares values for six distributions

Distribution	Mean (min)	Std. Dev. (min)	Least squares value
Triangular	17,732	3,003	0,0473
Gamma	17,751	3,193	0,0489
Lognormal	17,524	1,198	0,0490
Normal	17,631	3,178	0,0528
Gumbel	18,002	3,525	0,0561
Weibull	17,478	3,260	0,0663

From this data the triangular distribution provides the best fit and the Weibull distribution the worst fit for the drying process. However, the least square values do not differ much and any of these six distributions could be used in a simulation to model the drying activity duration. The mean value of 17,936 minutes (Table 1) for drying was rounded to 18 minutes and the standard deviation of 2,92 was rounded to 3,0 minutes. The mean value of 5,75 minutes for drying was taken and the standard deviation of 0,995 minutes was rounded to 1,0 minutes. The minimum and maximum values for the two transfer times, inspection time and touch-up duration were selected based on the duration measured for 5 cars. The following values in Table 3 were used for the MCS and the DES.

Table 3: Input values used for MCS and DES simulations

Activity/process	Distribution	Parameter 1	Parameter 2
Transfer 1 (s)	Uniform	18	24
Washing (min)	Normal	5,75	1,0
Transfer 2 (s)	Uniform	12	15
Drying (min)	Normal	18,0	3,0
Inspection (s)	Constant	30	-
Touch up (s)	Uniform	30	40

For the lognormal, triangular and gamma distributions, the parameters in Table 3 for the washing and drying processes were calculated from the mean and standard deviation values of the normal distribution. The other durations remained the same.

5.2 Results of Monte Carlo Simulation

The total time for a car to move from the queue to the final process and leave the facility was modelled using a Monte Carlo simulation in Excel. The inverse cumulative distributions were used to calculate the variates for five probability distributions. Inverse distribution functions are available in Excel for the normal (norm.inv), lognormal (lognorm.inv) and gamma (gamma.inv) distributions. Equation 3 was used to calculate the inverse for the Gumbel distribution and equation 4 was used for the inverse of the Weibull distribution. The inverse function for the triangular distribution is available from Breneman et al. [31].

The output of the MC simulation is a histogram of the probability density function for the total time that the car takes from the moment that it enters the wash bay until it leaves the facility. Some parameters for the total time distribution like the mean, standard deviation and skewness are calculated in Excel. The 90% (P90) and 95% (P95) probabilities are also shown in the summary of the relevant parameters in Table 4.

Table 4: Summary output of Monte Carlo simulation in Excel

Parameter	Normal	Lognormal	Triangular	Gamma	Gumbel
Mean (min)	24,820	24,826	24,847	24,818	24,834
Std Dev. (min)	3,170	3,156	3,171	3,159	3,179
Skewness	+0,020	+0,436	+0,327	+0,284	+1,051
P90 (min)	28,905	28,954	29,350	28,914	28,983
P95 (min)	30,078	30,383	30,473	30,254	30,722

The mean and standard deviation values do not differ significantly since the same values were used for all five simulations with different distributions. The skewness varies from 0,020 for the normal distribution to 1,051 for the Gumbel distribution. All the distributions for the total time are right-skewed. The P95 values differ from 30,078 for the normal distribution to 30,722 for the Gumbel distribution. The differences in P90 and P95 values are not significant, and it can therefore be concluded that for a MCS of the total time for this car wash facility, the normal distribution would be adequate. A data analyst who wants to run a MCS for some other washing facility should obtain some data points for the washing and drying processes, calculate the mean and standard deviations, and use these values and a normal distribution.

5.3 Results of Discrete Event Simulation

The same values for the mean duration and standard deviation for the washing and the drying processes were used for the discrete event simulation (DES). The distributions for the transfer times and inspection time were also the same. The DES was run for the normal, lognormal, triangular and gamma distributions for the washing and drying processes. The inter-arrival times used were 5,0 minutes, 4,0 minutes, and 3,5 minutes. The main output of the simulation is the total time in the system for 100 trails. The maximum total time in the system, the average waiting time, the maximum waiting time, the average number of cars in the queue waiting to enter the wash bay, and the maximum number of cars in the queue waiting to enter the wash bay were determined. These values are shown in the charts in Figures 2 to 6 below.

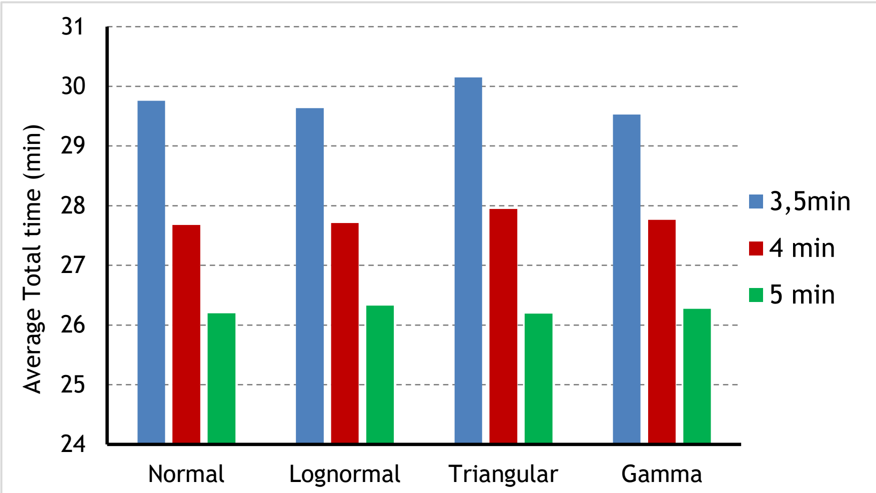

Figure 2: Average total time in facility for different arrival rates

From Figure 2 it is noticed that the average total time for 100 trials increases for all four distributions as the inter-arrival rates decrease, from 26,2 minutes to 29,8 minutes for the normal distribution. The triangular distribution has the longest total time of 30,1 minutes.

The average of the maximum times and 100 trials was calculated and is shown in Figure 3 for the four distributions and three inter-arrival times.

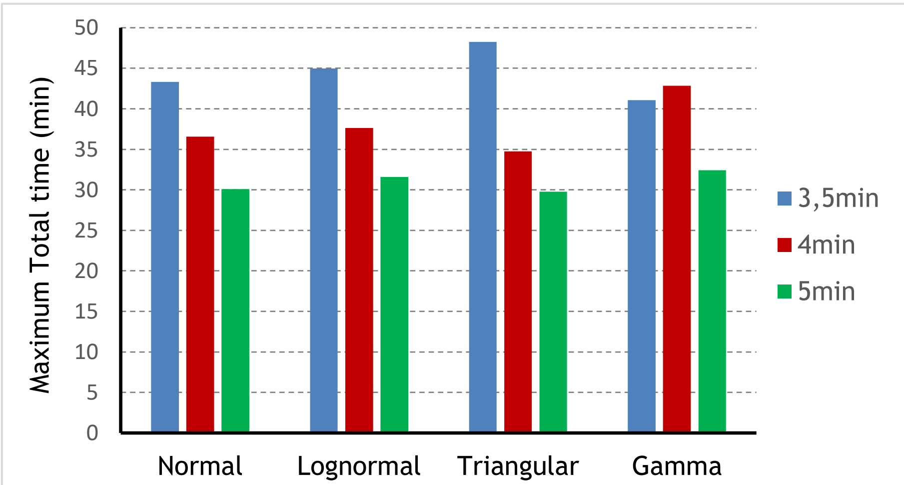

Figure 3: Average of maximum time in washing facility for 100 trials

The average maximum time in the system varies from 30,1 to 43,3 minutes for the normal distribution, and from 29,8 to 48,2 minutes for the triangular distribution. The tail of the skewed distributions produces longer durations for the wash and drying processes than that of the normal distribution. In practice, using a normal distribution in DES will underestimate the total time in the system.

The largest total waiting time for the cars in 100 trials is shown in Figure 4. The maximum waiting time increases as the arrival rate increases, which is to be expected. For an inter-arrival time of 3,5 minutes, the maximum waiting time increase from 18,3min for the normal distribution to 23,3 minutes for the triangular distribution. This represents a 25% increase.

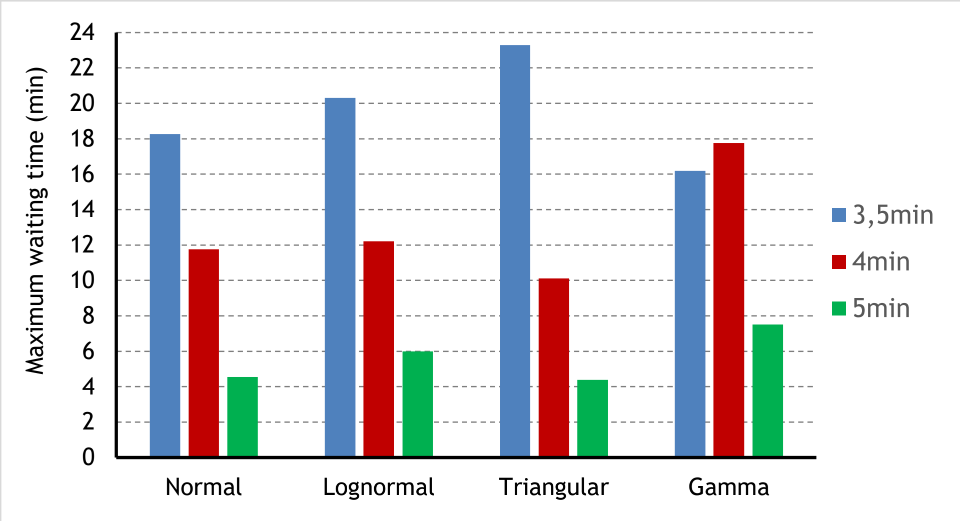

Figure 4: Maximum waiting time in 100 trials for different arrival rates

The maximum number of cars waiting in the queue to enter the process is shown in Figure 5 for three arrival rates and four distributions. For an inter-arrival time of 5 minutes (12 cars per hour) the normal, lognormal, and triangular distributions have a largest queue of just over 1 car. However, for an inter-arrival time of 3,5 min (about 17 cars/hour) the number of cars in the queue to enter the wash bay increases to 8,6 for the normal distribution and 10,4 for the triangular distribution.

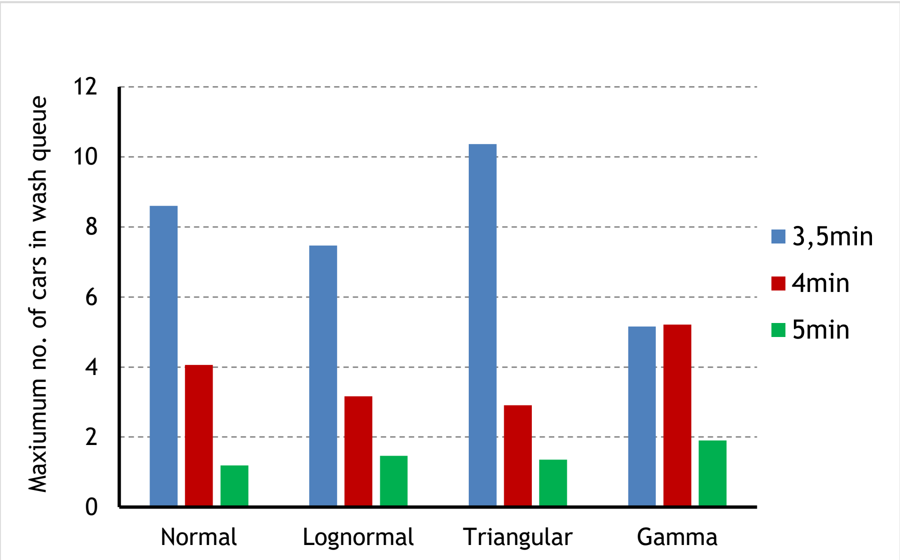

Figure 5: Maximum number of cars waiting in the queue for the wash process

The maximum number of cars that can be accommodated in the queue is 10, therefore some customers might pass and come back later or look for some other washing facility close-by.

5.4 Summary of findings

The distribution fitting indicated that the triangular distribution had the best fit and the gamma distribution the second best fit for the measured data. The MCS showed a slight increase in the total time that the vehicle is in the system as measured by the P90 and P95 values for the triangular distribution compared to the values for the normal distribution, but this total time excluded the waiting time. For the DES, it was observed that the total time that a vehicle spends in the system increases as the inter-arrival time decreases. The waiting time for the vehicles also increases as well as the number of cars waiting to enter the wash bay. The total time in the system and the total waiting time for the lognormal, triangular, and gamma distributions is mostly higher than when the normal distribution is used.

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Process duration data was collected for the washing and drying steps of a car wash process. Descriptive statistics indicated mean and standard deviation values for the wash process for the drying process. The skewness of 0,27 for the drying process indicated that the data is not normally distributed. A curve fit using the least squares method showed that the triangular distribution has the best fit for the data and the Weibull distribution has the worst fit. A MC simulation for the process using different distributions for the wash and drying steps showed only small differences in the P90 and P95 values for the cumulative distribution for the total duration of the car in the washing facility.

The same values for the average and standard deviation for the wash and the drying step of the car wash system that were used for the MC simulation were used for a discrete event simulation (DES). Values were determined for the average time that a customer spends in the system from the moment that he/she joins the queue until he/she leaves the premises. The total waiting time was also determined for three values of the interarrival time of cars that arrive at the car wash facility.

The main objective of the study was to analyse the car wash system by means of a Monte Carlo simulation and a discrete event simulation. The sub-objectives were to determine the total time that a vehicle spends in the system, the waiting time in the queue, and the number of vehicles in the queue. The main and sub-objectives were achieved, and the DES showed that the normal distribution might not be adequate for this car wash system since it underestimates the maximum total time in the system, the maximum waiting time in the queue, and the maximum number of vehicles in the queue. A right-skewed distribution more accurately predicts the output parameters.

6.2 Recommendations

The following improvements are suggested for a more realistic model and simulation experiment for a car was facility:

- Obtain more duration data for the wash and the drying steps of the process. A hundred data values will lead to more accurate values for the mean and standard deviation values of both processes.
- The current policy is to direct cars from the wash bays to drying bays sequentially. The model in this paper just directs a car from the wash bay to any open drying bay randomly. The model could be modified to direct cars sequentially.
- A third wash bay and a ninth drying bay could be added to the facility. This will ease the pressure on the work teams when the arrival rate of cars increases. It would require additional workers and an increase in the cost; therefore, a cost-benefit analysis should be done before such an addition is implemented.

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INCREMENTAL AND END-STATE DEEP-LEVEL MINE VENTILATION PLANNING METHOD COMPARISON WITH THE USE OF A CALIBRATED DIGITAL TWIN

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ABSTRACT

South Africa hosts some of the deepest and most complex mines in the world. Consequently, effective ventilation of underground areas is challenging. The expansion of deep-level mines offers additional hazards in the ventilation system that need to be managed proactively. Hazards include high temperatures, dust pick-up and gas build-up. Currently, most gold mines in South Africa are nearing the end of their planned life-of-mine (LOM). This means that new deepening projects must be implemented to extend the LOM. This study presents a comparison between incremental and end-state planning with the use of a calibrated digital twin. The main contribution of this study is indicating the effect of incremental planning when planning the installation of important infrastructure. This emphasises the importance of effective planning methods to ensure the success of the overall future of the mine.

Keywords: Deep-level mine; Digital twin; Ventilation; Hazard identification; Hazard mitigation

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1 INTRODUCTION

South Africa has the largest reserves of platinum-group metals (PGMs), manganese, chromite and gold [1]. South Africa also houses six of the top ten deepest mines in the world [2]. The extreme depths of these mines are mostly due to the depletion of the original ore reserve [1]. These mines expanded deep into the earth and are now reaching the end of their life-of-mine (LOM). Figure 1 illustrates the current LOM and depth of all the major gold- and PGM mines in South Africa in 2023.

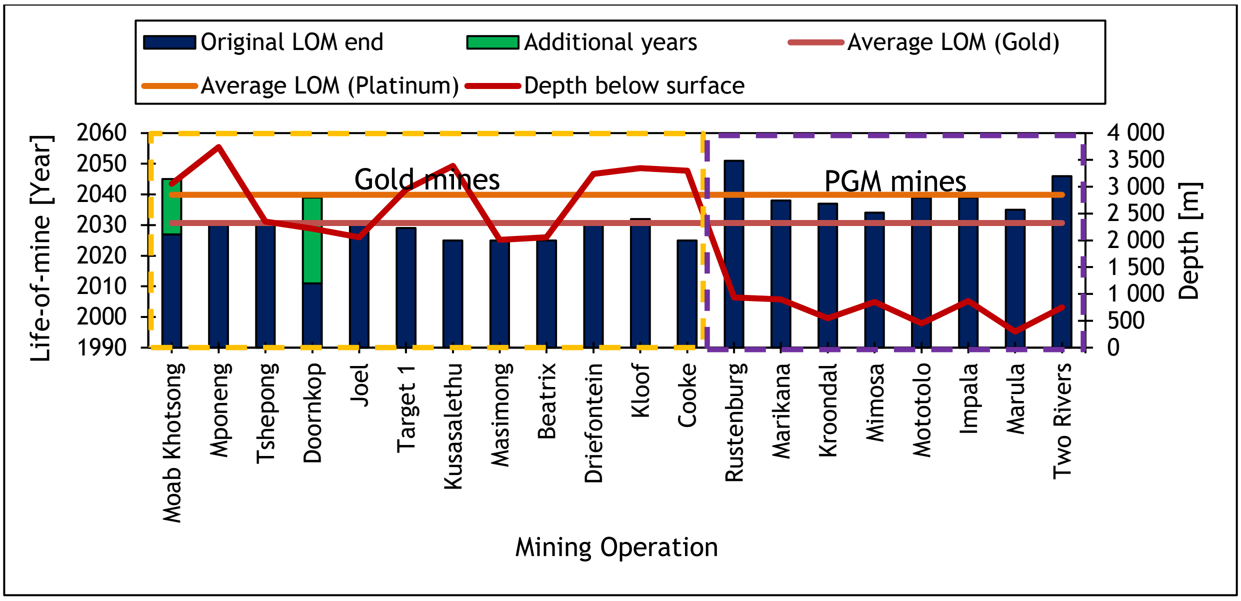

Figure 1: LOM and depth of major gold- and PGM mines in South Africa [3-5].

Figure 1 shows that most of the gold mines are nearing their end of life by 2030 and are reaching depths over two kilometres deep [3-5]. The PGM mines have a longer LOM and are much shallower than gold mines with most not even reaching one kilometre in depth [5]. Figure 1 also shows that the LOM of some of the mines were extended [3] by deepening projects which were not part of the original LOM plan [3].

One of the main challenges with further deepening of these mines is the planning of the ventilation system [6] [7]. The ventilation system is the primary means of cooling the mine and providing a sustainable working environment. It becomes more and more challenging to ventilate and cool deep-level mines due to the increase in virgin rock temperature (VRT) [6]. Figure 2 illustrates the increase in VRT as the depth below surface increases, for the Witwatersrand, Klerksdorp, Free state, Bushveld complex and Plats reef regions.

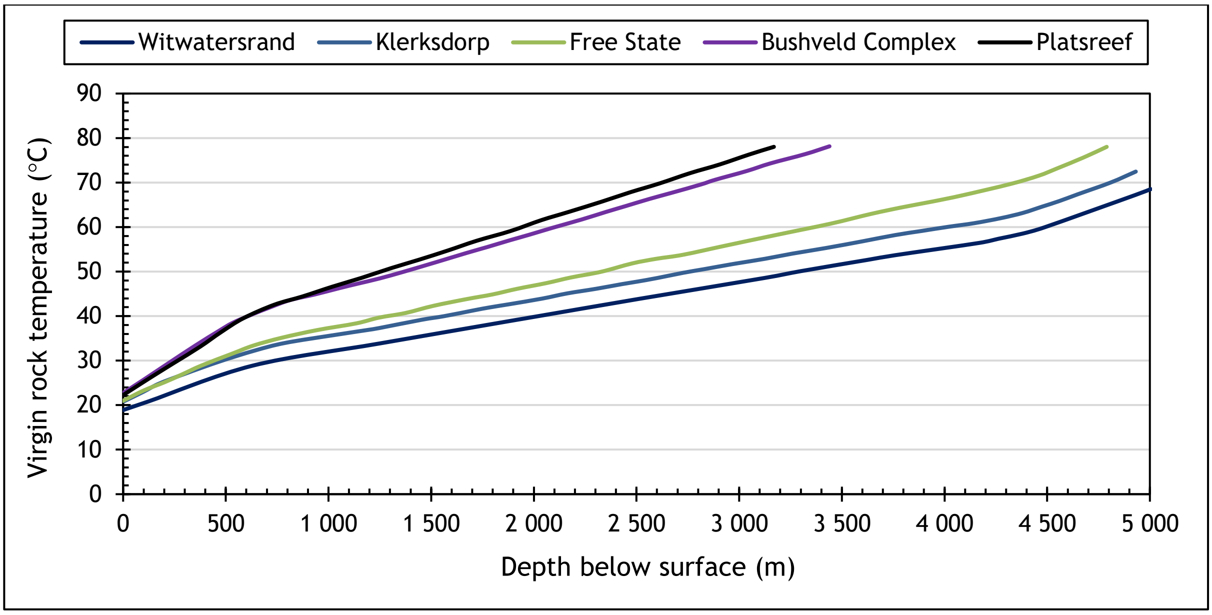

Figure 2: VRT increase as depth below surface increases [6]

The increase in depth below surface of South African gold mines increases the risk of heat exposure to underground workers making it imperative that heat be mitigated effectively [6-9]. The health and safety of underground workers should always take priority. There have been various studies which illustrated the properties and guidelines for a safe working environment [7] [8] [10-14].

These studies indicated three major hazards that can occur in ventilation systems, namely high temperature, gas build-up, and dust pollutants in the air [7] [8] [10-14]. These hazards can cause various illnesses that can prove fatal to underground workers [8] [15] [16]. There are various mitigation tactics that have been deployed which mainly entail detection and control [17-19]. These tactics are reactive and not preventative but will always remain necessary due to the occurrence of unforeseen events.

There are other tools that can be used to help prevent hazards occurring in ventilation systems. Tools such as digital twins which can be defined as cyber-physical copies of actual system can be used to simulate an actual system [20]. Digital twins have been utilised in many instances to help plan and improve various deep-level mining systems including ventilation [20-23], refrigeration [24], and compressed air [25].

Therefore, digital twins can be used in effective planning to avoid these hazards entirely. This study will compare two planning methods, namely incremental- and end-state planning [26-29]. Incremental planning is when a system is planned in set increments as a system is developed. This ensures that the system will operate as required during each stage of development. The end-state planning method entails the planning of the system when it is fully developed and ensures that the system will operate as required when fully developed.

2 PROBLEM AND OBJECTIVES

The incremental and end- state planning methods have been used in various studies to plan ventilation systems [26-29]. There are, however, limitations to each of these methods. The problem therefore exists to know when each of these methods should be used and what results to expect when mitigating hazards. There is, however, no clear distinction found in literature to aid in choosing the correct method for a given scenario.

Consequently, the objective of this paper is to apply both methods on the planning of a deep-level case study mine ventilation system for comparison to aid future mine ventilation system expansion projects in South Africa.

3 METHOD FOR IDENTIFYING VENTILATION HAZARDS

This study will utilise the hazard identification and mitigation method previously developed [9] and summarised in Figure 3.

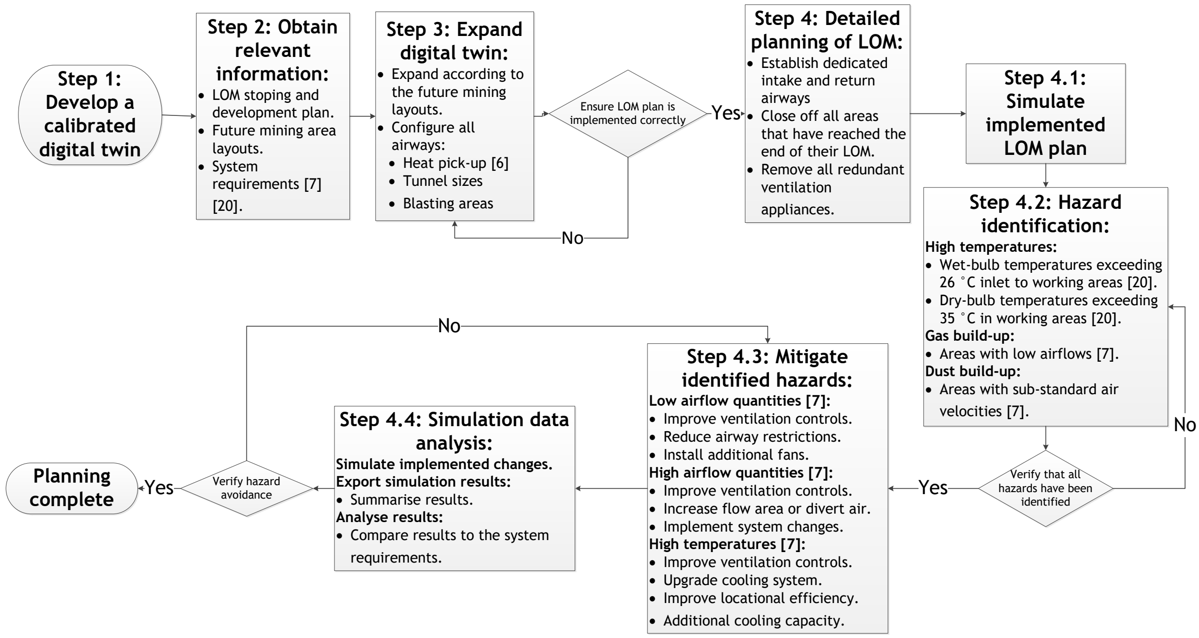

Figure 3: Summary of the mine ventilation hazard identification and mitigation method previously developed [9]

Figure 3 shows what steps are taken to effectively identify and mitigate hazards. The strategy was described in more detail in a previous study. The objective of this study is how this strategy can be used in incremental and end-state planning methods. Figure 3 does not mention the incremental- and end-state methods. This method can, however, be utilised for both planning methods as follow:

- Incremental planning:
    - o Evaluate LOM plan to effectively divide the system development into increments.
    - o Expand the digital twin in Step 3 (Figure 3) to represent the mine for each of the increments.
    - o Complete the method in Figure 3 for each of these increments.
- End-state planning:
    - o Expand the mine to the point in the LOM where it is fully developed.
    - o Complete the method in Figure 3 on the fully developed mine.

The results section of this paper illustrates how the strategy is utilised in both methods and what information was gathered and displayed. The results obtained from these two methods was then used to see which of the two planning methods are most effective in deep-level mine ventilation LOM planning. This is the main objective and contribution of this study.

4 RESULTS & DISCUSSION

Figure 3 illustrates the strategy which was applied to a case study mine. This section will describe each step and how it was applied in both the incremental and end-state planning methods. The results of both planning methods will also be compared during each step before being summarised in the discussion section to validate that the main objective of this study has been achieved.

Step 1: Develop a calibrated digital twin

The first step, according to Figure 3, is to develop a calibrated digital twin. This digital twin is used as a base model to which the future expansions of the mine will be added later. This means that this step will be identical for both incremental and end-state planning methods.

The digital twin that is developed and calibrated for this study by using the method previously developed by Jacobs (2020) with the use of Process toolbox (PTB) [20]. Figure 4 illustrates the calibrated ventilation digital twin of the mine evaluated in this paper.

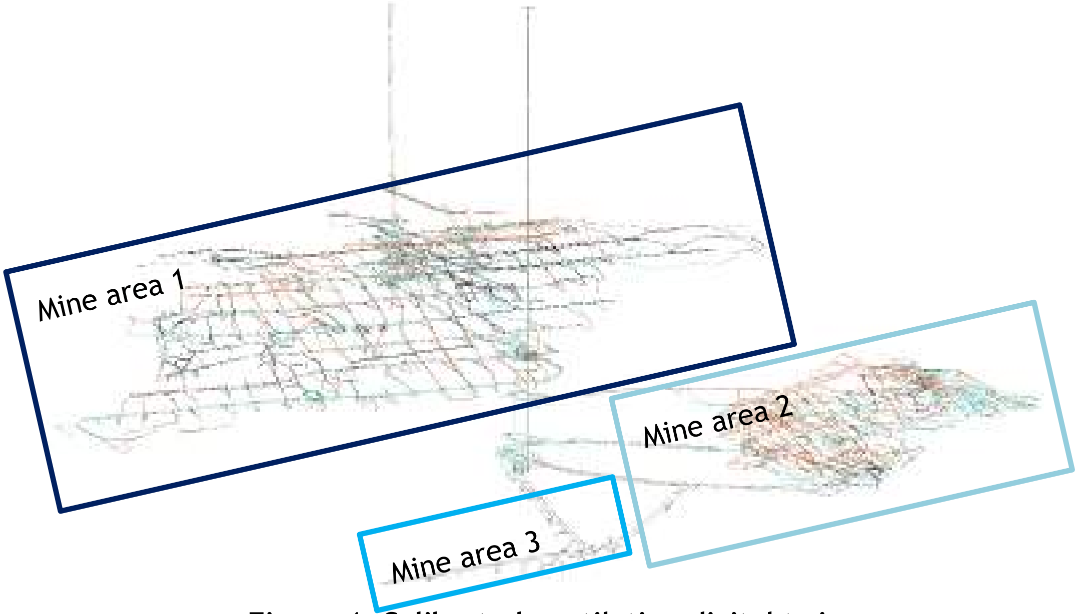

Figure 4: Calibrated ventilation digital twin

The calibration, for the purpose of this paper, can be summarised by evaluating:

- The average surface and underground booster fan pressures and total flows – 98% accurate.
- The average station flow and temperatures – 92% accurate.
- The average working area inlet temperatures and flow – 97% accurate.

This yielded an overall accuracy of 96% when compared to the performance of the actual ventilation system. The current actual system and its digital twin exhibit identical responses and can therefore be utilised to predict the performance of the system as the mine expands and develops.

Step 2: Obtain relevant information

The information obtained will be utilised for both planning methods. The means by which it is used will however differ as follows:

Step 2.1: The LOM stoping and development plan

The LOM plan includes various information which is used to estimate the planned tonnes of ore extracted at each active area within the mine. Figure 5 illustrates the planned ore to be extracted from the mine evaluated in this study.

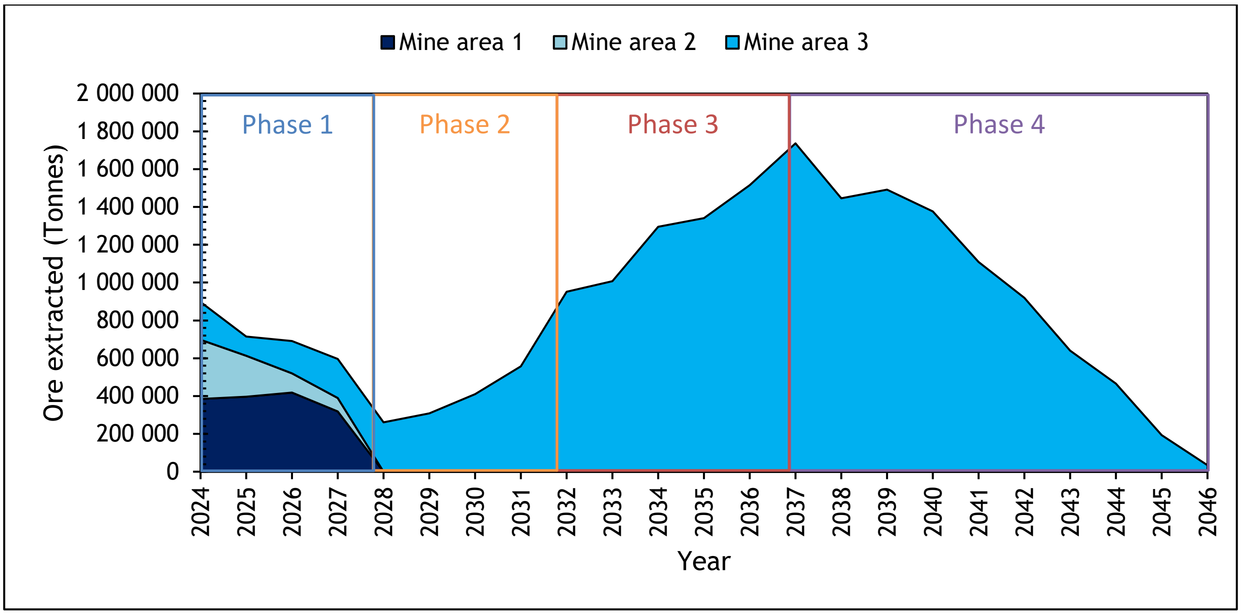

Figure 5: Planned ore extracted during case study's LOM

Figure 5 shows the phases of development of the case study mine evaluated in this paper. Mine areas 1 and 2 will no longer produce gold at the end of phase 1. Mine area 3 is still in the development phase during phase 1 and is the future of the mine. The success of phase 1 determines the overall future of the LOM plan. Therefore, for the purpose of this study, focus will only be placed on phase 1. This information is utilised in both planning methods and the difference between the methods are as follows:

Incremental planning method:

The LOM plan is divided into a chosen increment, based on a variety of factors, such as the scale and complexity of the mine plan, the mining method, and the level of detail required [27] [30]. The smaller the increment, the more detail can be added to the ventilation plan. As noted by Mamghaderi (2021), smaller increments could also increase the complexity and cost of the mine design [26]. Therefore, larger increments may be simpler and more efficient, but some detail to the plan will be sacrificed.

This study will utilise 6-month increments since the LOM plan is divide into years and 6 months will ensure that two instances of each year is planned. Figure 6 illustrates the planned ore extracted during phase 1, distributed into 6-month increments.

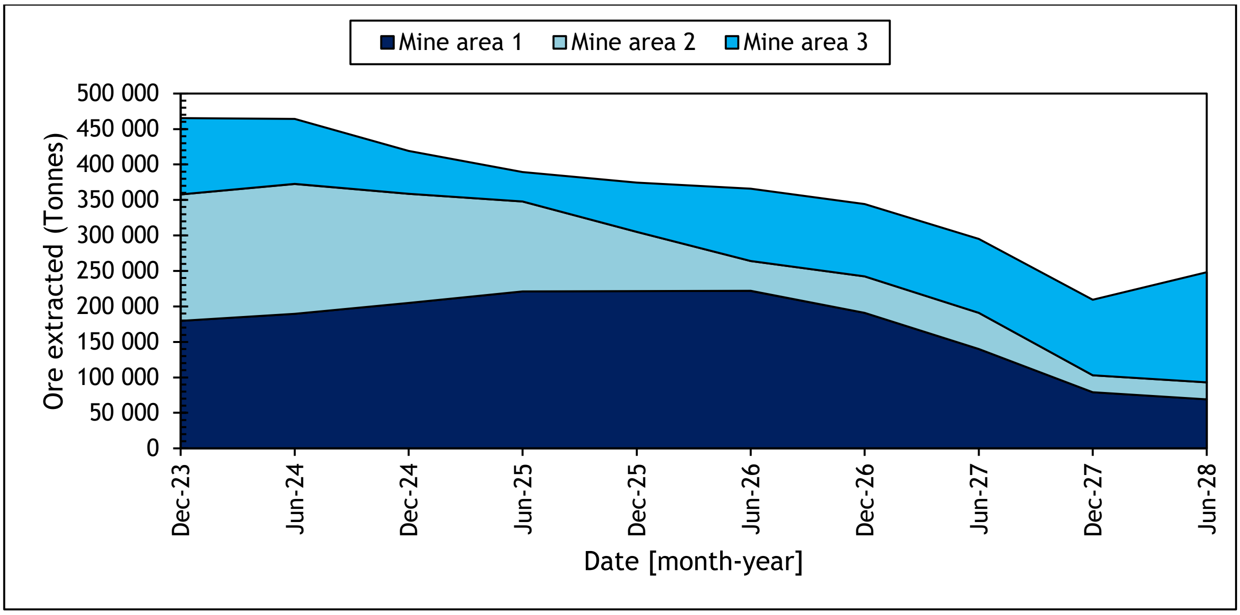

Figure 6: Planned ore extracted divided in 6-month increments

Figure 6 shows an overall decrease in production in especially in mine areas 1 and 2, but is also shows the increase in production in mine area 3 in more detail. This information will be utilised in the incremental planning method.

End-state planning method:

End-state ventilation planning involves the development of a ventilation system that can accommodate the end-of-mine-life (EOML) [29]. This involves factors such as mine closure, ore depletion, and changes in mining methods [29]. This is ideally done through simulation or other prediction models which predict the future state of the mine [29]. There has also been studies which have optimised ventilation systems for the EOML scenario in terms of airflow requirements, energy consumption, and capital cost [28]. This study will consider the EOML scenario as the end of phase 1 of the mine. This means that this study will consider June 2028 as the EOML, as indicated in Figure 6.

Step 2.2: The future mining area layouts

Mine areas 1 and 2 are not expanded during phase 1 since these are existing areas that are being mined out until the end of their LOM. Therefore, the only expansion of the digital twin that is required is at mine area 3. Figure 7 illustrates the future layout of mine area 3.

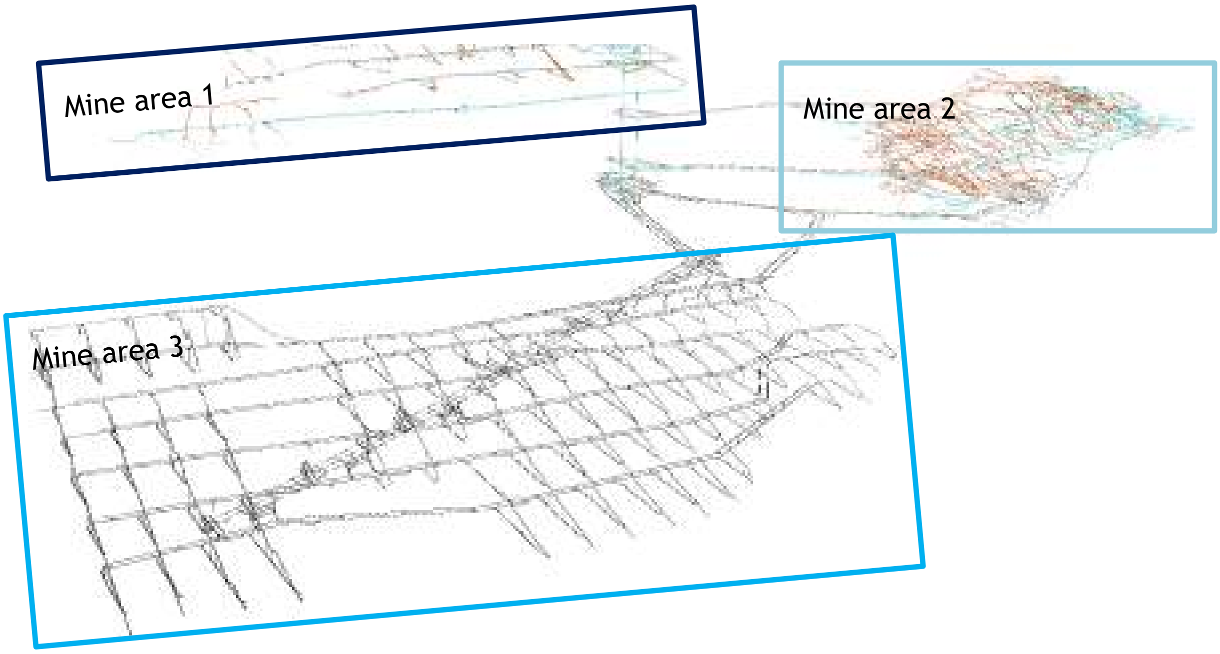

Figure 7: Mine area 3 EOML layout

Figure 7 shows the planned layout of the mine by 2046. This is a concept layout and is not necessarily what the mine area would look like at the end of the LOM. This is because the ventilation system has not been designed in detail to meet all the ventilation requirements. This layout is therefore only used as a base layout on which the ventilation system is planned.

Step 2.3: System requirements

The refrigeration and air flow quantity requirements for phase 1 should be determined to ensure that the existing infrastructure can accommodate the LOM plan. Figure 8 and Figure 9 illustrate the refrigeration- and air flow quantity requirements, respectively, for each mine area.

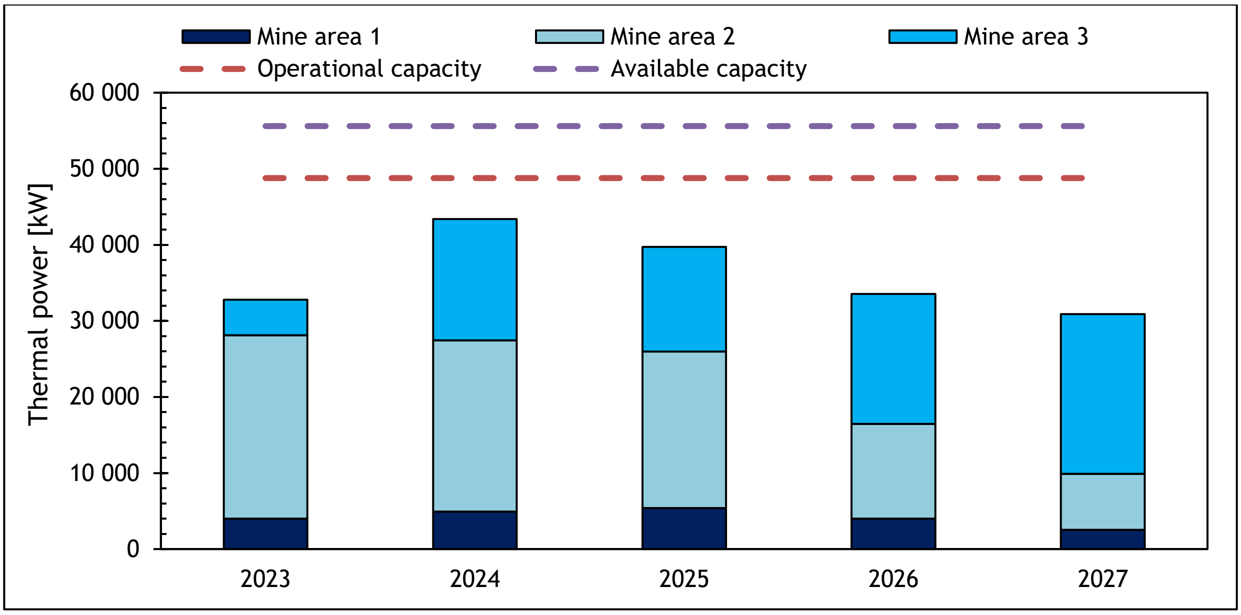

Figure 8: Refrigeration requirements for phase 1

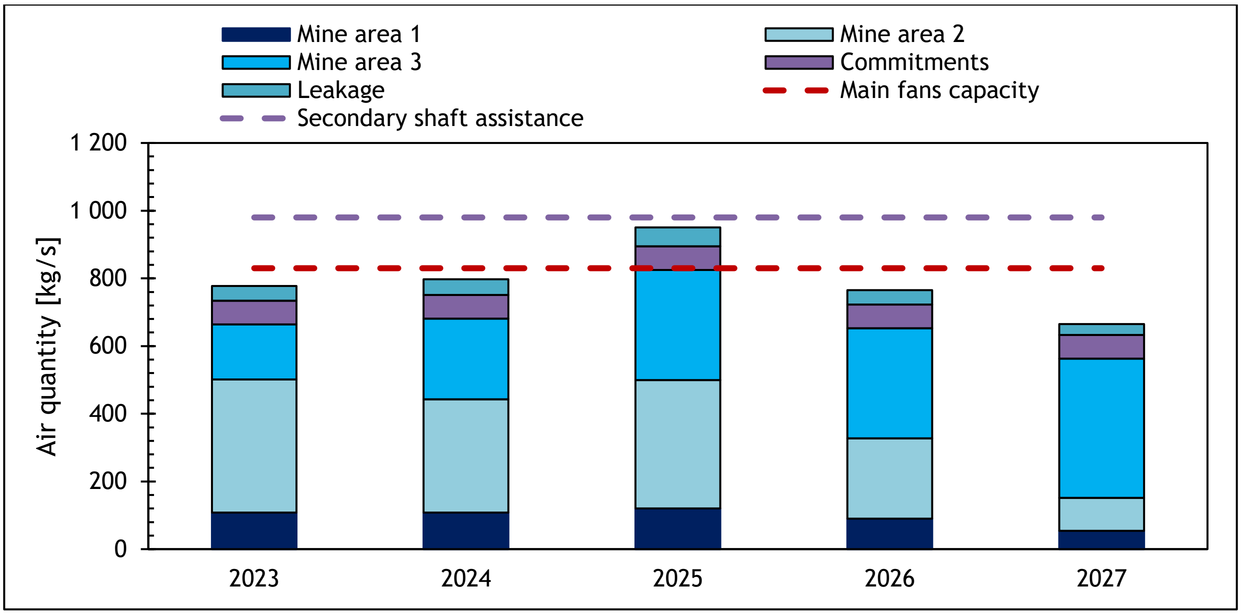

Figure 9: Air flow quantity requirements for phase 1

Figure 8 and Figure 9 show that the existing infrastructure will be able to accommodate the LOM plan during phase 1. It is also important to note that there are key performance indicators (KPIs) that should be evaluated during the planning process. The KPIs in this study are air temperature, air flow quantity, and air velocities. Table 1 indicates the requirements for the main KPIs.

Table 1: KPI requirements mine ventilation planning

KPI	Requirement
Air temperature	Stoping areas intake: • Wet-bulb < 26 °C • Dry-bulb < 35 °C Development end intake: • Wet-bulb < 28 °C • Dry-bulb < 37 °C Other accessible areas: • Wet-bulb < 32.5 °C • Dry-bulb < 37 °C
Air flow quantity	Stoping areas intake: • 15 m^3/s Conventional development ends: • 0.4 $m^3/s/m^2$ Trackless development ends: • 0.08 $m^3/s/kW$
Air velocities	Intake airways: • Conveyor belt airways – 4 m/s • Horizontal airways – 7 m/s • Shafts – 18 m/s Return airways: • Horizontal airways – 12 m/s • Shafts – 30 m/s • Ventilation holes – 30 m/s

Meeting these KPIs ensures proper ventilation and mitigates hazards like high temperatures, gas accumulation, and dust build-up.

Step 3: Expand digital twin

The model is expanded in different ways when implementing incremental or end-state planning. The difference in the planning methods is as follow:

End-state planning:

The end-state planning method requires the digital twin to be expanded to the end of phase 1. Figure 10 illustrates the expansion of the digital twin to the end of phase 1.

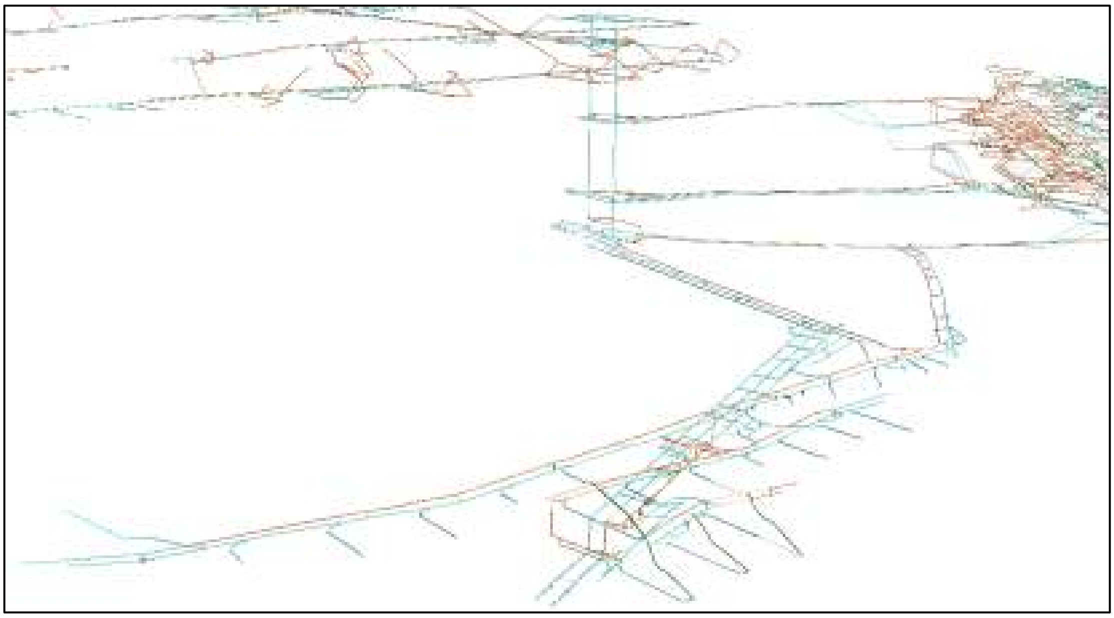

Figure 10: Digital twin expansion to end-state of phase 1

Figure 10 shows the digital twin model that will be used in the end-state planning method. The benefit of the end-state method in this step of the implemented strategy is that there is only one simulation model with its set of outputs to optimise.

Incremental planning method:

The expansion of the digital twin in the incremental planning method required the expansion to be divided into 6-month increments. Figure 11 illustrates the expansion and is colour coded to distinguish the increments.

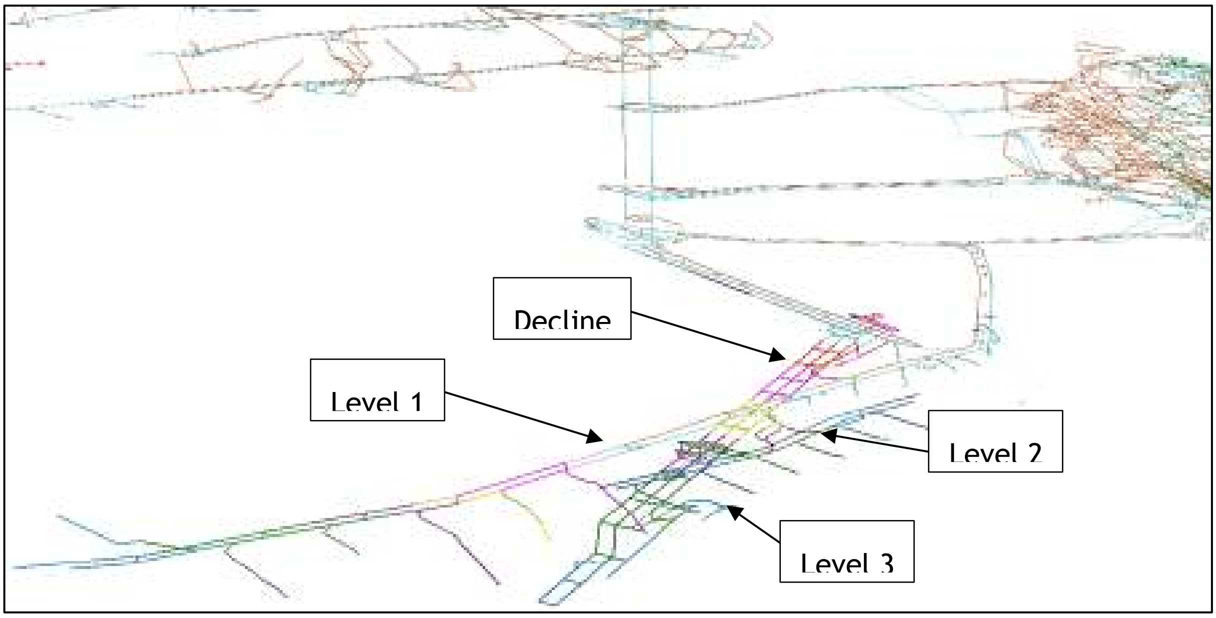

Figure 11: Digital twin expansion of phase 1 divided into 6-month increments

Figure 11 shows the 6-month increments in the mine's development during phase 1. This means that there will be 10 different simulations, each with their own set of outputs to optimise. This increases the detail to which the ventilation system is planned and designed.

Step 4: Detailed planning of LOM

The detailed planning of the LOM plan will now be completed by implementing both planning methods. It should be noted that the end-state model was designed according to standard ventilation practices. This includes:

- Force ventilation with auxiliary fans and steel ducting at all development ends.
- Force-exhaust ventilation at the decline where trackless diesel machinery is used.

There are also locations planned where bulk air coolers (BACs) and secondary booster fans are installed. The size and performance specifications were also determined from the heat load and airflow requirements, illustrated in Figure 8 and Figure 9. This information is used when optimising the ventilation plan.

The planning methods are implemented as follows:

End-state planning method:

As mentioned previously, the end-state planning method only requires one digital twin model with one set of outputs to optimise. The main areas that are being focused on are the decline airways, the horizontal development ends, and the stoping areas. Firstly, it can be seen in Figure 11 that there are three declines, namely the conveyor, service, and material declines. These declines provide fresh intake air to two active levels. There are also three development ends located on a level above these two levels which receives fresh air from the horizontal airways connected to the main intake shaft.

The focus is first placed on the airflow quantity supplied to each of these areas. Figure 12 illustrates the results from the end-state simulation model.

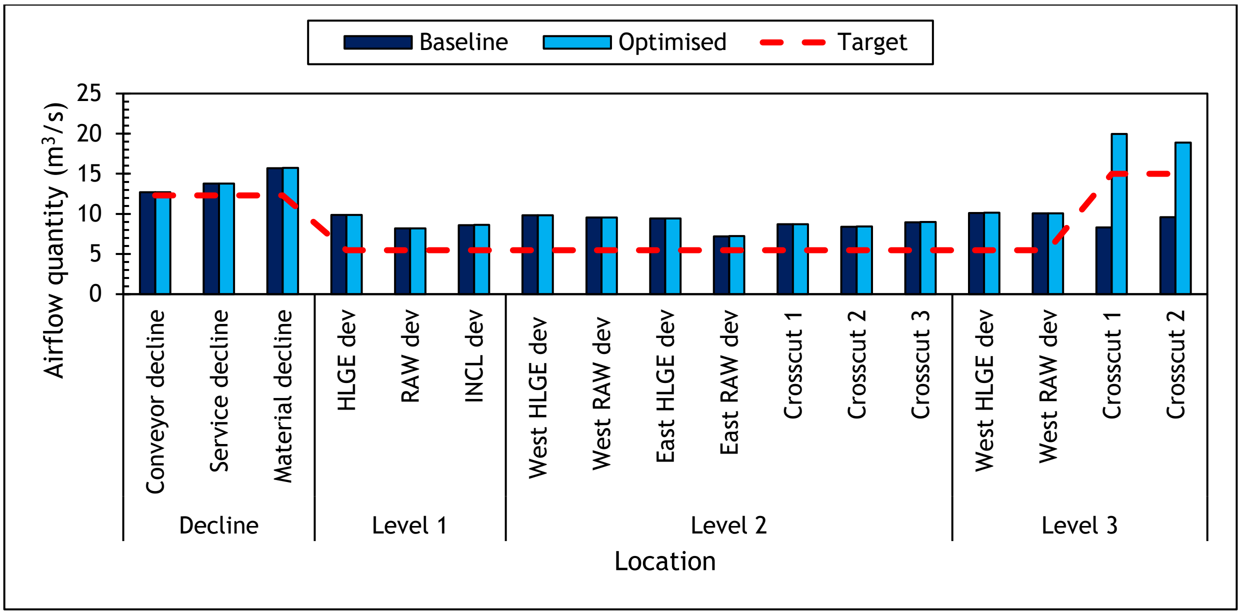

Figure 12: Airflow quantity at key locations (End-state planning method).

Figure 12 shows that the decline areas receive enough air to remove all the diesel particles. There are also sufficient air volumes being supplied to all development ends. The only areas which did not receive enough air were the two crosscuts on level 3. This was rectified by placing two 45 kW fans in tight circuit with a low-pressure door at each of these crosscuts. It should be noted that all areas in the model were evaluated to identify areas with stagnant airflow. There were no areas identified and therefor no areas are at risk of gas build-up. Figure 13 illustrates the air wet-bulb temperature results from the end-state model.

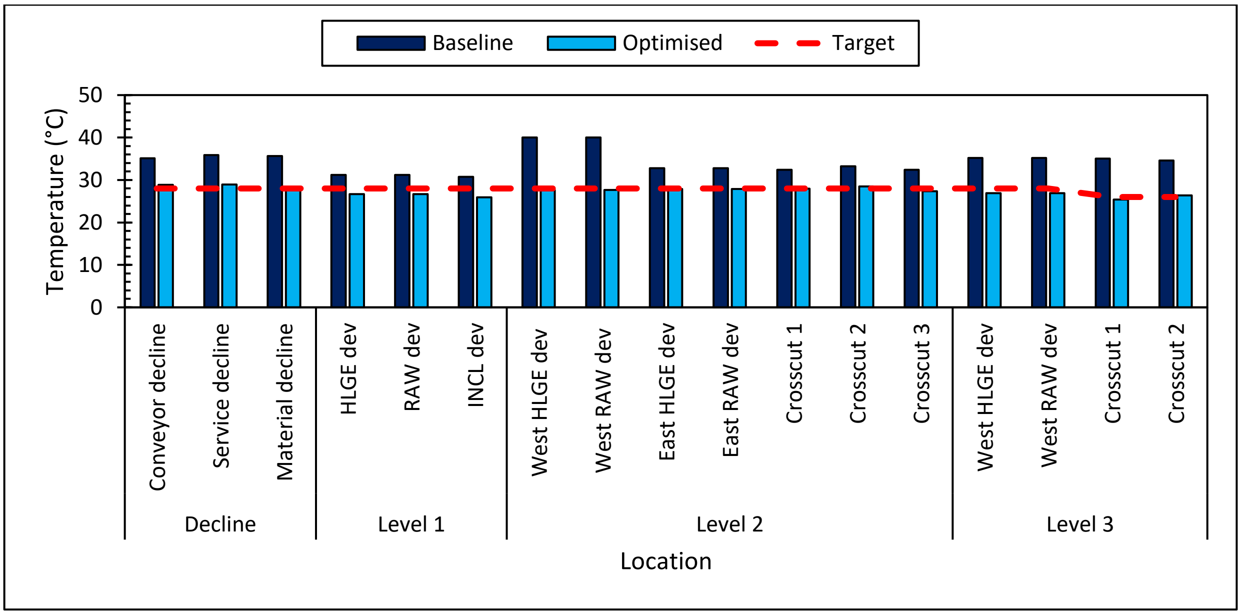

Figure 13: Air wet-bulb temperature at key locations (End-state planning method).

Figure 13 shows that all areas are above their target temperatures. The decision was then taken to start up all the planned BACs. It was also necessary to place a spot cooler in crosscut 2 of level 3. This resulted in all areas achieving their target temperatures.

This concluded the end-state planning method, and all hazards were mitigated. The incremental planning method will now be implemented, and focus will be placed on the same areas.

Incremental planning method:

The incremental planning method requires a different simulation model for every 6 months during phase 1 of the project. Each of these models yielded results that should be optimised. The focus is again firstly placed on the airflow supply to each of the key areas. Figure 14 illustrates the airflow quantity results of each of the simulated increments.

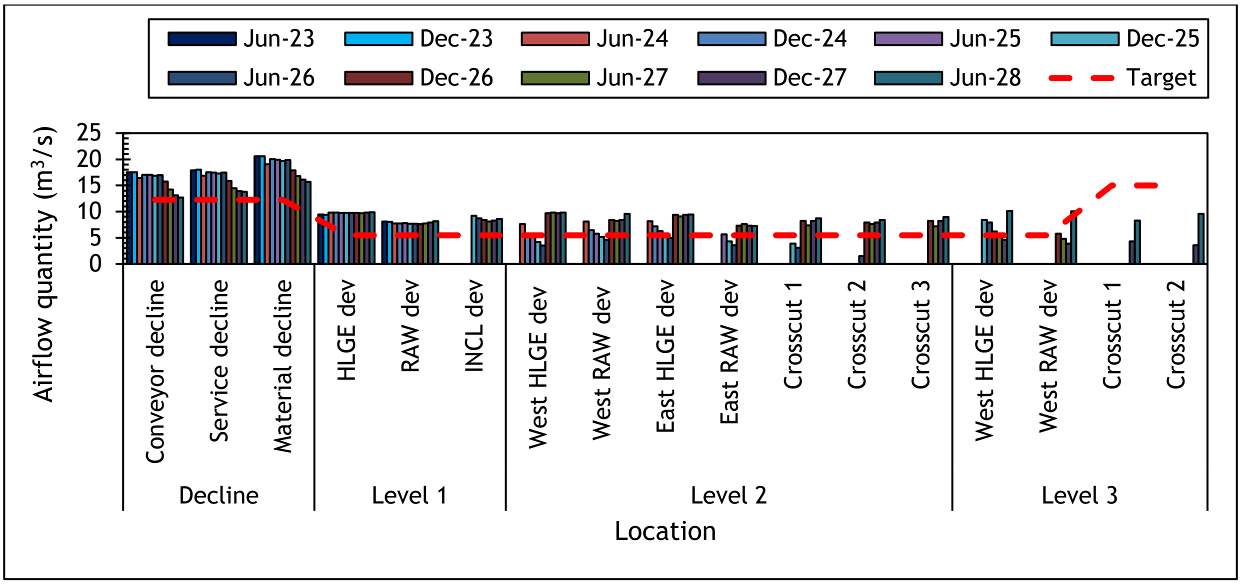

Figure 14: Airflow quantity at key locations (Incremental planning method).

Figure 14 shows that enough air will be supplied to the decline area development ends. There are also no shortfalls with air supply to the developments on level 1. Level 2 and level 3 do, however, have problems from December 2025. The next step will be to evaluate the air temperature results. Figure 15 illustrates the air wet-bulb temperature results.

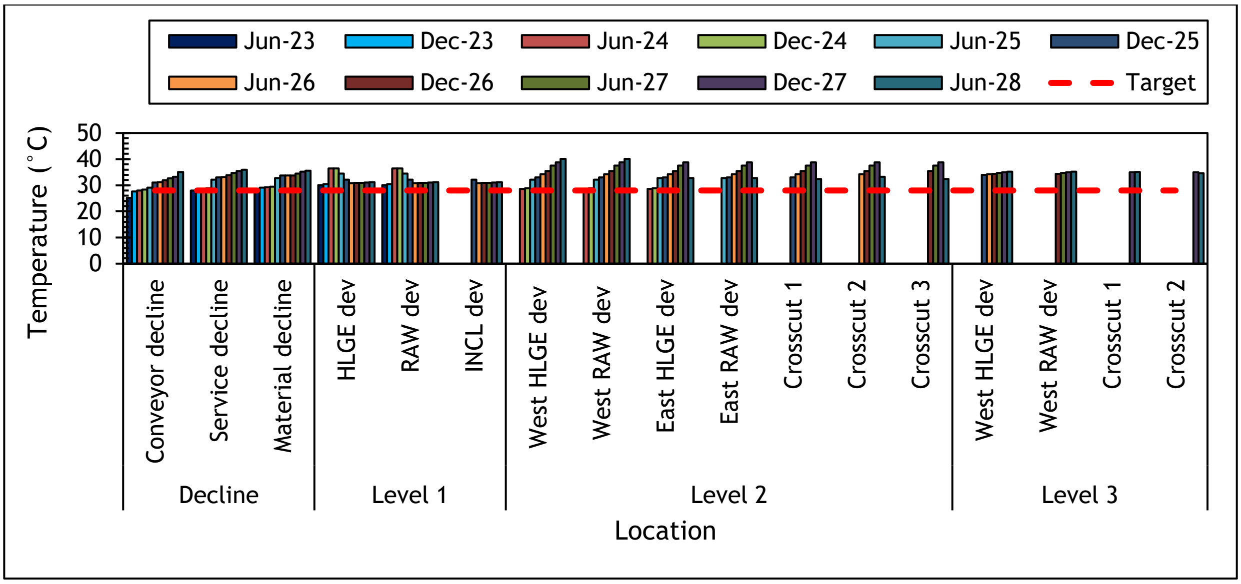

Figure 15: Air wet-bulb temperature results (Incremental planning method).

Figure 15 shows almost all areas will exceed the target temperatures. There are also excessive temperatures well above the legal limit [14] identified at level 2 and level 3. There also seems to be a decrease in temperature at level 1. This is mainly due to the closing of production areas which discharged hot air into the intake airway. The largest issue identified was the long distances that air had to be supplied by means of a force ventilation system. Figure 16 illustrates the excessive distances before the first planned ventilation hole.

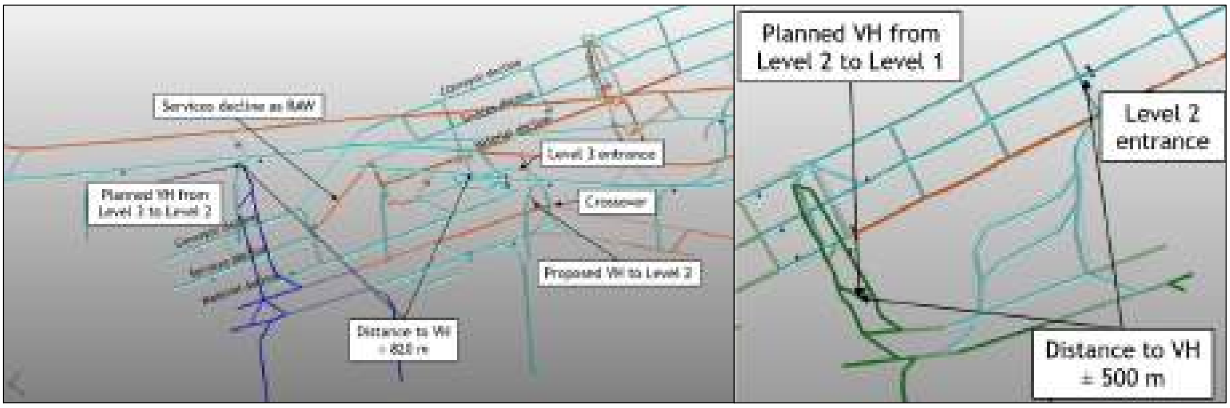

Figure 16: Identified issue on levels 2 and 3.

Figure 16 shows that the distances are more than 500 meters. The force ventilation system, which uses 45 kW fans, can only supply fresh air a distance of 250 meters. This is evident in Figure 14 where the target airflow quantity is not achieved after exceeding this distance. These issues can only be rectified by moving the planned ventilation hole (VH) closer to the entrance of the level. This, along with switching the planned BACs and booster fans on, will help achieve the desired airflows and air temperatures.

The benefit of incremental planning is not only establishing how to mitigate hazards but also establishing a deadline. This helps with planning the logistics surrounding the installation and commissioning of all ventilation and cooling infrastructure. Table 2 describes the timeline to commission the planned infrastructure.

Table 2: Timeline of commissioning of planned ventilation infrastructure

June 2023	• No actions required.
December 2023	• Start the first 2 MW BAC at the decline.
June 2024	• Start the second BAC at the decline. • Start the 2 MW BAC on level 1.
December 2024	• Start the first planned secondary booster fan.
June 2025	• Establish the newly planned VH from level 2 to level 1. • Start the third 2 MW BAC at the decline.
December 2025	• Establish the newly planned VH from level 3 to level 2.
June 2026	• No actions required.
December 2026	• Start planned 1 MW BAC on level 2.
June 2027	• Start planned 1 MW BAC on level 3.
December 2027	• Install 2 x 45 kW fans at crosscut 1 on level 3 in tight circuit.
June 2028	• Install 2 x 45 kW fans at crosscut 2 on level 3 in tight circuit.

Table 2 is the timeline that must be followed to ensure that all targets are met on-time. This will ensure that all hazards are avoided and mitigated before they occur, thereby ensuring a safe working environment as the mine is developed.

5 DISCUSSION

The two planning methods both yielded positive results in achieving the desired airflow supply and air temperatures. The main results can be summarised as:

- Insufficient ventilation during development phase if end-state planning method is followed.
- Planning and management of infrastructure is improved with the use of the incremental planning method.
- Both methods illustrated the same amount of cooling and airflow required with the only difference being when it is required and distributed.

There are benefits and shortfalls to both planning methods. Table 3 indicates the comparison between the two planning methods.

Table 3: Comparison between the end-state and incremental planning methods

End-state planning method		Incremental planning method	
Benefits	**Shortfalls**	**Benefits**	**Shortfalls**
Only one simulation model required.	Limited detail in development plan.	Increased detail in development plan.	Multiple simulation models.
Planning time is reduced.	Only information is what infrastructure is required by the EOML.	Timeline developed to commission critical infrastructure.	Increased planning time.
	Risk of delays in development due to hazards.	Reduced risk to delays in production due to a set hazard mitigation plan.	
	Airflow and temperature requirements only quantified for EOML.	Temperature and airflow requirements quantified at each increment.	

Table 3 shows the main comparison point between the two planning methods. The most important being the fact that there is a reduced risk in delays in production due to the detailed hazard mitigation plan. The incremental planning method is therefore best suited for the planning of the ventilation system of a large development such as the one discussed in this paper. The end-state planning method remains valid and is ideal for time-constrained situations when assessing the feasibility of planned infrastructure to support suitable working conditions. The main objective of this study was to compare the two planning methods. Table 3 summarised the main benefits and shortfalls and thus the objective is achieved.

6 CONCLUSION

The comparison between two ventilation planning methods discussed in this study yielded interesting results. The methods were both able to mitigate all identified hazards. There were, however, major problems identified through the incremental method, which were not identified by the end-state method, illustrated in Figure 16.

The risk of a delay in the development of the mine is reduced and safe working conditions throughout development is assured. The end-state planning method does have benefits such as the ability to evaluate the planned infrastructure. The incremental planning method does, however, have the added benefit of creating a timeline of when the planned infrastructure is to be installed.

In conclusion, when planning deep-level mines with a long LOM, the incremental planning method proves to be the most suitable approach for ventilation systems. Its adaptability and flexibility makes it well-suited for accommodating the evolving needs of such complex mining operations over extended periods of time.

Additionally, it is worth noting that the incremental planning method can be successfully applied to any deep-level mine ventilation system. By utilizing this method, mine planners can ensure the efficient and sustainable functioning of ventilation systems throughout the entire lifespan of the mine, ultimately contributing to the safety and productivity of the workforce in deep-level mining environments.

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IMPROVING DEEP-LEVEL MINE UTILITY USAGE THROUGH DYNAMIC BASELINES

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ABSTRACT

South African deep-level gold mining operations are extremely stressed due to the ever-increasing energy tariffs. These operations are complex systems with services' (compressed air and water) pipelines reaching lengths of over 100 km to supply end-users. Harsh underground conditions tend to cause inefficiencies due to leakages and misuse. Due to the complex nature of the system, identifying inefficiencies can be difficult and time-consuming. Furthermore, services' monitoring is only done up until the half level splits. However, inefficiencies tend to occur closer to the working areas. Therefore, it is proposed to install flow/pressure meters in each working area and isolate it as a business unit. Dynamic zero-waste baselines were developed for each business unit to monitor service water consumption. Through this, an annual energy cost benefit of approximately R19 million was achieved. Comparing actual consumption against dynamic zero-waste baselines will help to keep personnel accountable for inefficiencies in their area.

Keywords: Zero-waste baseline, responsibility allocation, dynamic approach, deep-level mine, water reticulation system, inefficiency detection, energy savings

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1 INTRODUCTION

1.1 Background

The sustainability and profitability of the gold mining industry in South Africa are in question due to the ever-increasing operating costs [1]. Between 2013 and 2022, the average operating cost of South African gold mines have increased by approximately 54% [2], [3]. This can mainly be attributed to South Africa's electricity cost tariff that has increased by approximately 653% from 2007 to 2022, compared to inflation's increase of 129% over the same period [4]. Therefore, if South African gold mining operations are to extend their life-of-mine (LOM), there is a need to investigate and exploit alternative opportunities to decrease operational costs [5].

1.2 Service water in South African deep-level mining

The South African gold mining industry is extremely energy-intensive, consuming approximately 30% of the total power supplied by South Africa's power utility, Eskom [6]. The water reticulation system on deep-level gold mines consumes as much as 39% of the total energy consumption allocated per operation. Figure 1 depicts the electricity distribution on a typical South African deep-level gold mine, with the "pumping" (25%) and "refrigeration" (14%) utilities representing the total energy consumed by the water reticulation system [7].

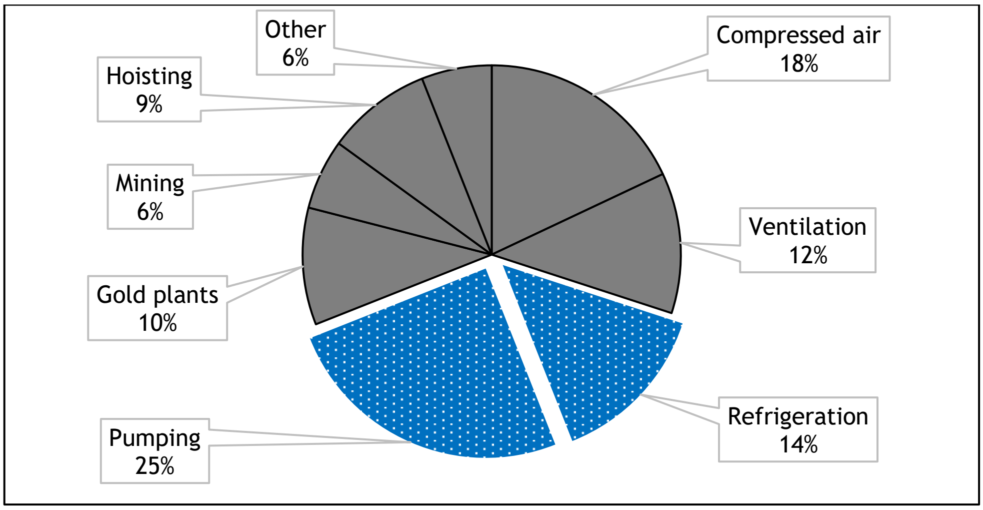

Figure 1: Electricity distribution on a typical deep-level gold mine [7]

South African gold mining operations are complex systems, reaching operational depths of up to 4 000 m [7]. This results in service pipelines reaching lengths of up to 100 km to supply end-users with service water [8], [9]. Figure 2 illustrates the complexity of deep-level mines using a typical gold mining layout.

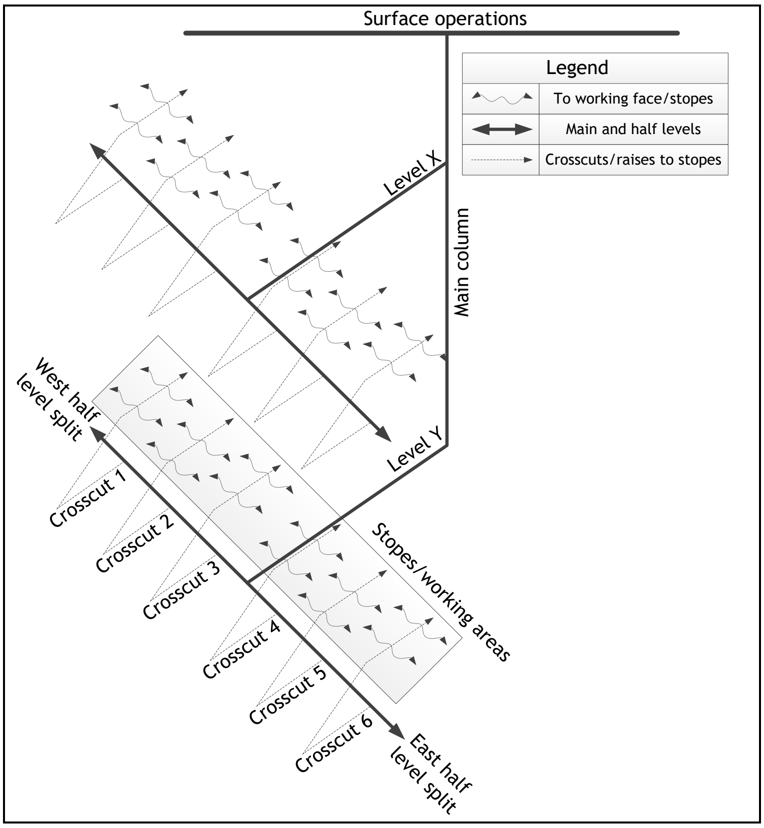

Figure 2: Typical deep-level gold mine layout

The service water is used for underground air cooling and mining activities which include the cooling of rock drills, cleaning/sweeping, and dust suppression [10]. These activities occur in the stopes/working areas depicted in Figure 2.

The water demand relies on the designated mining shifts and the equipment allocated for various activities occurring during each duty cycle. [11]–[13]. The process of underground mining is divided into a number of steps that occur in shifts throughout the day and night, forming a 24-hour cycle. The typical mining shifts (along with their duration) of a South African gold mine are as follow (with the main water-consuming equipment noted for each shift) [11]–[14]:

- Drilling (from 06:00 to 14:00):
  - Rock drills are used to drill holes in the rockface for inserting explosives. Service water is used to cool down the drill bits of the rockdrills.
- Explosive charge-up and blasting (from 14:00 to 16:00):
  - Explosives are inserted into the drilled holes, whereafter the rockface is blasted. No personnel are allowed near the blasting site during this time which means that theoretically, no water should be consumed.
- Non-entry period (from 16:00 to 21:00):
  - Following the blasts, a waiting period has been allocated to allow for dust and harmful gasses to be ventilated out of the mine. Again, no personnel are permitted underground during this period which means that no water should be consumed in the working areas.
- Cleaning and sweeping (from 21:00 to 04:00):
  - Waterjets are used to move broken rock to the collection point. The gold-bearing rock will be transported out from underground to be treated at the gold plants.

- Shift change (from 04:00 to 06:00):
    - This entails the change between the drilling and cleaning/sweeping shift. Personnel that worked during the cleaning/sweeping shift will make their way out of the stopes to the main shaft to be hoisted from the mine. The drilling shift personnel will start to make their way to the stopes. Theoretically, no water should be consumed during this period as personnel are on-route to and from the stopes.

Each mining operation may have different timetables for the listed duty cycles but consist of the same method of operation. Therefore, these schedules are merely an example of a typical mining schedule, and deviations are expected for each mining operation. It should be noted that the only water users that consume water continuously throughout the day, regardless of the mining shift, are underground cooling units such as bulk air coolers and mobile cooling units.

1.3 Service water inefficiencies

In an ideal world, the water supply should match the demand when referring to the law of mass conservation [15]. However, studies have found that approximately 50% of the total consumed water demand can be attributed to system inefficiencies [16], [17]. Inefficiencies can mainly be attributed to:

- Leaks [18]–[21], and
- Misuse and malpractice [18], [19], [22]–[26].

In addition to the cost implications, inefficiencies negatively affect system performance. These can include operating pressures, water availability and storage [20], [25], [27]. Seeing that the system performance is negatively affected, control room operators start up additional equipment on surface to account for the inefficiency losses. This results in additional energy usage where the cost implications thereof requires justification by the appointed upper-level management [20], [27].

Therefore, it is of critical importance that these inefficiencies are mitigated. However, before inefficiencies can be mitigated, they must be identified. This is a very difficult and time-consuming process due to the complex nature, harsh environment, and magnitude of South African gold mining operations [17], [19].

1.4 Current inefficiency identification and monitoring

Most inefficiencies tend to occur closer to the stopes/working areas where the gold-bearing ore is mined [20], [28], [29]. However, services monitoring is typically limited to the half-level split, making it impractical to identify exactly where the inefficiencies are located by merely using metered data. In addition, further processing of the data is required to be able to quantify inefficiencies [19].

Existing inefficiencies detection- and quantification methods are summarised below:

1. **Intensive underground audits**
   Underground audits involves the process where personnel must go underground and visually detect inefficiencies [22], [24], [30]–[33]. This method is very resource-intensive, impractical, and dangerous as auditors may need to enter abandoned and dangerous areas to locate these inefficiencies [20], [22], [34]. Auditing one level can typically take a team an entire day, which means that only the data of the specific day will be available [19]. This prevents effective and continuous monitoring.
2. **Step testing**
   Step testing is classified as a manual method where flowmeters are installed upstream of the tested area [19], [35], [36]. Certain areas will be isolated individually to

determine which areas have the largest leakage rate. Recent case studies used step testing to identify inefficiencies [37]–[39]. The pitfall is that inefficiency detection can only be done when no mining activities are present, and therefore this method does not identify inefficiencies while mining activities are underway.

3. **Zero-waste baselines**
   A zero-waste baseline is defined as a theoretical minimum consumption that is used to measure the amount of wastage of a particular system [15], [34].
   A recent study conducted by Van der Merwe [40] made use of zero-waste baselines to identify inefficiencies. Van der Merwe used the best operating point of the mining equipment to develop a zero-waste baseline. This baseline was simulated to develop a theoretical baseline. Actual data was compared to the baseline to identify wastages.
   Even though Van der Merwe's study delivered promising results, the baselines were only constructed per level. This means that inefficiencies are indicted too broadly and is still too far from the working areas. Equipment performance varies under various conditions. Using the best operating point will thus not suffice. In addition, certain factors affect the water usage throughout the day and may differ daily [40],[41]. These factors should also be accounted for as inaccurate baselines will become obsolete [42].
4. **Hardware- and software methods**
   Hardware-based methods require equipment such as sensors, optical fibres, hydrophones, or radar systems to identify inefficiencies [32], [43]. Software-based methods use extensive datasets for processing [32], [44]–[48]. These methods have proven to be time-consuming, resource intensive, and expensive [49].
5. **Benchmarking**
   Benchmarking has been proven to be a powerful tool which involves comparing the actual performance of an entity to that of a reference performance [45], [50]–[53]. A recent study conducted by Du Plooy [32], [34] developed a benchmarking model that used a mining level's compressed air consumption and production. However, this method prioritised levels based on their production. Auditors were still required to locate leaks in pipe columns of up to 10 km long.

Previous research has proven helpful in the process to identify inefficiencies on mine services, but localised leak detection remains largely unexplored.

It is worth noting that Zietsman [19] highlighted concerns about installing additional instrumentation near working areas in South African mines due to associated capital implications. However, the continuous increase in electricity tariffs and significant wastage factors have compelled South African mining operations to undertake drastic measures to reduce operating costs and ensure the longevity of their operations. The potential savings benefits outweigh the initial capital expenditure.

A recent survey conducted by Axora [54] revealed that only 60% of mining budgets allocated to digital transformation are utilised, with the remaining 40% left unused due to a lack of understanding regarding potential benefits of digital solutions. This indicates that mining operations are not fully aware of the potential benefits that can be achieved by installing flowmeters in close proximity to the working areas. By closely monitoring these areas, inefficiencies can be detected much faster than previous methods, allowing for precise identification at the stope/working area level.

1.5 Problem statement and objectives

The absence of accurate inefficiency detection methods in South African gold mining operations hampers the ability to identify and address inefficiencies effectively, resulting in increased operational costs and reduced sustainability.

The literature revealed the necessity for enhanced localised inefficiency detection near working areas in underground mines. Zero-waste baselines has proved to successfully identify wastages. However, seeing that conditions underground differ daily, the static approach followed by previous researchers will not suffice.

An effective solution is needed to dynamically identify, mitigate, and monitor system inefficiencies in deep-level gold mine service water networks.

To achieve this, each working area must be treated as a separate business unit. Flow- and pressure sensors need to be installed in close proximity to the working areas to monitor the service water consumption of each entity. This approach will facilitate the development of a dynamic zero-waste baseline, incorporating equipment performance under specific conditions, equipment time-of-use, and personnel activity. The implementation of this innovative inefficiency detection method will lead to quicker and more effective identification of inefficiencies, ultimately promoting service sustainability.

The objectives of the method can be summarised as:

- Development and implementation of dynamic zero-waste baselines
- Inefficiency detection and continuous monitoring for sustainability
- Energy- and water savings through inefficiency identification and rectification

This paper will develop a novel and more effective inefficiency management method, focussing on the detection of inefficiencies.

2 NOVEL INEFFICIENCY DETECTION METHOD DEVELOPEMENT

The proposed method to solve the objectives of this paper will be developed in this section. The steps are displayed in Figure 3 and will be briefly discussed.

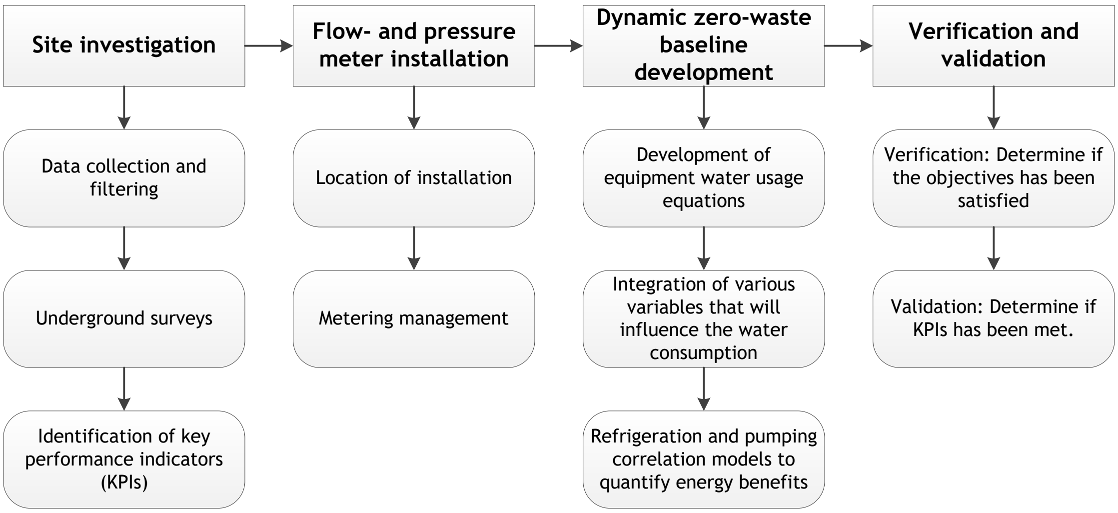

Figure 3: Proposed method development for inefficiency detection

2.1 Site investigation

The initial phase involves an extensive examination of the system, encompassing the process of data gathering and filtering. The essential data to be collected includes equipment lists of water users, their respective locations, and specification sheets. Additionally, stoping and development plans, mining standards, missing persons locator (MPL) networks, mining schedules, and flow/pressure readings obtained from installed sensors are also deemed as critical data required. Underground surveys will be conducted to identify typical wastages in working areas.

Key performance indicators (KPIs) will be identified that should be met to validate the method.

2.2 Flow- and pressure meter installation

To strategically position the sensors, the stoping and development plan will be utilised to identify areas with the longest operational life and planned tonnes.

The flow- and pressure sensors will be installed after the continuous water users (bulk air coolers and mobile cooling units) to only monitor the water to the stopes/working areas as illustrated in Figure 4.

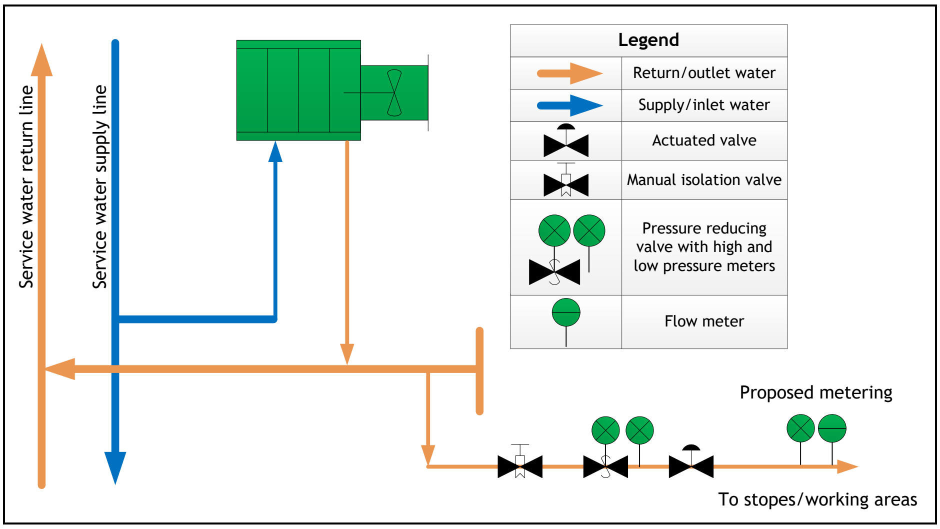

Figure 4: Typical water flow layout to working areas

When the working area closes, the metering will remain in place until the area has been entirely blanked off. This will prevent abandoned areas from wasting service water. It will be the responsibility of the person in charge of the abandoned area to move the metering to the next operational business unit.

2.3 Dynamic zero-waste baseline development

In this section, the dynamic zero-waste baseline will be developed. The developed baseline should be accurate to prevent the baseline from becoming obsolete (mentioned in section 1.4).

Firstly, correlation models will be employed to establish a formula that quantifies water usage for the equipment across varying water pressures, leveraging the information provided in the specification sheets of the equipment. Table 1 presents an example of the typical data extracted from the equipment specification sheets for rockdrills, showcasing the water usage corresponding to different water pressures.

Table 1: Equipment specification sheet example

Point	Pressure [bar]	Water usage [l/min]
A	0.50	3.50
B	1.00	3.80
C	1.50	3.90
D	2.00	4.30
E	2.50	4.80
F	3.00	5.20
G	3.50	5.60

The correlation between water usage and pressure is then examined, followed by the selection of the most suitable trendline that exhibits an r-square (R^2) value closest to one [55]. A typical example, using the data in Table 1, is shown in Figure 5.

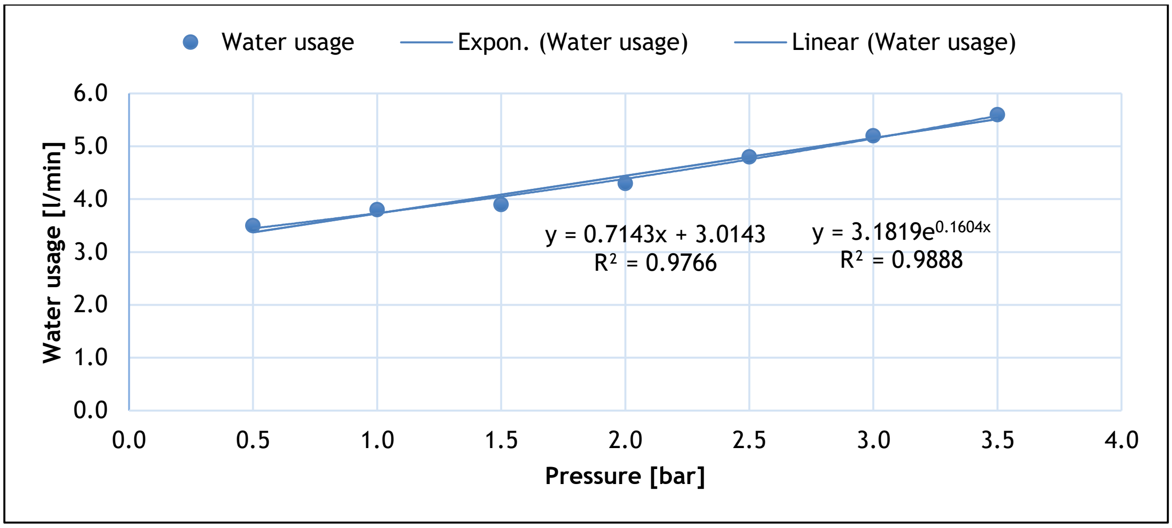

Figure 5: Example of the correlation between water usage and pressure for rockdrills

The known pressures from the specification sheet will be used in the developed formula to calculate the water usage. The calculated water usage should then be compared to the actual/specification sheet's water usage to determine the accuracy. A typical example is shown in Table 2. The model accuracy will be determined by using the Mean Absolute Percentage Error (MAPE) [56]. MAPE indicates the absolute error between the predicted and actual value by using Equation 1 [56]. A MAPE of smaller than 10% is considered a highly accurate model [57].

$$MAPE = \frac{1}{n}\sum_{t=1}^{n}\left|\frac{A_t - F_t}{A_t}\right| \tag{1}$$

Here:

$MAPE$ - Mean absolute percentage error [%]

n - number of entries [-]

A_t - Actual value

F_t - Predicted value

Table 2: Example of MAPE between actual/specification sheet and calculation

Point	Pressure	Actual/specification sheet: Usage	Calculation: Usage	MAPE
A	0.50	3.50	3.45	1.50%
B	1.00	3.80	3.74	1.70%
C	1.50	3.90	4.05	3.78%
A	2.00	4.30	4.39	1.99%
B	2.50	4.80	4.75	1.01%
C	3.00	5.20	5.15	0.99%
A	3.50	5.60	5.58	0.39%

A simulation model is then developed to test and confirm the accuracy of the develop formula at different operating pressures.

The water pressure within the designated business unit will be utilised in conjunction with the derived equation to determine the water usage of the equipment, accounting for variations in water pressures throughout the day. It should be noted that certain water users, such as waterjets, employ power packs to elevate the water pressure to the designated operating pressure, resulting in consistent water usage during operation. Consequently, it becomes necessary to allocate the water user to the corresponding specified mining shift during which it is utilised. The underground surveys and case study investigation will assist with the equipment time-of-use which should correlate to the information provided in section 1.2.

The MPL data will be used to determine the personnel activity in the specific business unit. MPL networks is an occupancy detection method. The system is used to track employees' last location in case of an emergency [58]. Personnel is tracked by means of strategically placed antennae and receivers underground. Personnel that go underground will be equipped with a cap-lamp which is fitted with a short-range radio frequency identification tag. As the worker walks by the antennae underground, the receivers detect the cap-lamp and stores the data [58].

The system will determine the water allocation to the working areas throughout the day based on the personnel activity. Fixed schedules are not sufficient to determine the required water allocation, seeing as it only provides information relevant to the levels, and not sufficient detail on what is happening in the working areas. Personnel have planning meetings before entering their working area, which differs for each business unit. As indicated in section 1.2, it is theoretically expected that no water should be consumed during shift changes as personnel transition to- and from working areas. However, it should be noted that rockdrills will consume water during drilling shifts, while waterjets will utilise water during the cleaning/sweeping shift.

By incorporating these factors, the dynamic zero-waste baseline will be established, which will dynamically adjust according to the personnel activity and fluctuating water pressures. These factors will vary daily, resulting in a distinct baseline for each day. Consequently, a more precise and realistic baseline can be formulated. Furthermore, with the data available, the baseline will be able to update hourly, resulting in instantaneous inefficiency detection.

Next, the energy wastage will be determined by using the correlation models for the pumping- and refrigeration systems. The correlation is determined by Equation (**2**.

$$Correlation\ factor = \frac{E}{Q} \tag{2}$$

Here:

$Correlation\ factor$ – correlation between the energy consumed to pump/cool water [kWh/l/s]

E – energy consumed [kWh]

Q – water pumped/cooled [l/s]

The actual water consumption per business unit will be compared to the corresponding baseline water consumption to assess the amount of pumping- and refrigeration energy that is wasted, which correlates to the water volumes wasted. Utilising the pumping- and refrigeration correlation factors, immediate impacts can be identified and promptly communicated to the appropriate personnel for necessary action. This facilitates quicker and more efficient feedback loops.

2.4 Verification and validation

The method will undergo verification and validation to determine the efficacy thereof in addressing the problem at hand. The identified method objectives will serve as a criterion for the verification, whereas the identified KPIs will be compared to the outcomes of the implemented method for validation.

3 IMPLEMENTATION AND RESULTS

The developed method will be implemented on a case study (Mine X) to determine the effectiveness thereof.

3.1 Site investigation

As this paper focusses on the reduction of energy- and water consumption, the identified KPIs are:

- Pumping- and refrigeration energy consumption, and
- Water consumption.

3.2 Flow and pressure meter installation

The stoping and development plan was used to determine where flow- and pressure meters should be installed. The capital costs amount to approximately R60 000 per business unit. Initially, three specific areas have been identified for the installation of flow- and pressure sensors. The results will be showed for a working area (Business unit 1) with an operational life of 25 months. All other working areas/business units were calculated on the same principle.

3.3 Dynamic zero-waste baseline development

The waterjets have a constant water flow of 160 l/min when operated. The rockdrills' water usage will differ based on the supplied water pressure. From the rockdrills' specification sheet, the exponential correlation, with a R^2 value of 0.9975, between the rockdrills' water usage (y-axis) and pressure (x-axis) is displayed in Figure 6. This was calculated by using Microsoft Excel.

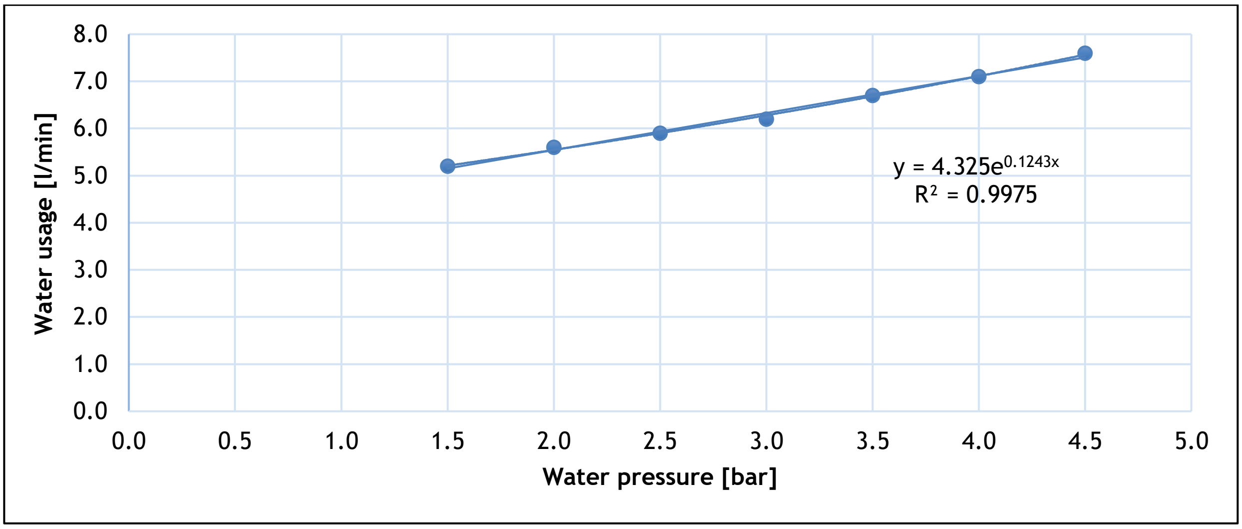

Figure 6: Correlation between water usage and pressure for rockdrills

Equation 3 has been derived from the equation seen in Figure 6 to represent the water usage of rockdrills at various pressures.

$$Q = 4.325xe^{0.1243xP} \quad (3)$$

Here:

Q – Water usage [l/min]

P – Water pressure [bar]

(**3**) was utilised to calculate the water usage at the specified pressures mentioned in the specification sheet and subsequently compared with the actual/specification sheet water usage to confirm the accuracy thereof as seen in Table 3. The model accuracy was calculated as 99.61% using MAPE, therefore, it can be concluded that the formulated equation is accurate and reliable.

Table 3: Developed formula compared to the actual/specification sheet for rockdrills

Pressure [bar]	Actual/specification sheet water usage [l/min]	Calculated water usage [l/min]	MAPE
1.50	5.20	5.21	0.22%
2.00	5.60	5.55	0.98%
2.50	5.90	5.90	0.02%
3.00	6.20	6.28	1.27%
3.50	6.70	6.68	0.26%
4.00	7.10	7.11	0.15%
4.50	7.60	7.57	0.44%

In addition, the rockdrills and waterjets were also incorporated into a simulation model to check and confirm the accuracy of the developed formula (equation (**3**). The Process Toolbox (PTB)[1] simulation software was used. The water pressure values as seen in Table 3 were integrated into the simulation model to determine the water usage and subsequently compare it with the water usage calculated using the developed formula. The MAPE between the simulation model and the developed formula has been calculated as 2.12%, confirming that the accuracy of the developed formula is acceptable.

Figure 7 illustrates the MPL data along with the mining shift schedule for Business unit 1.

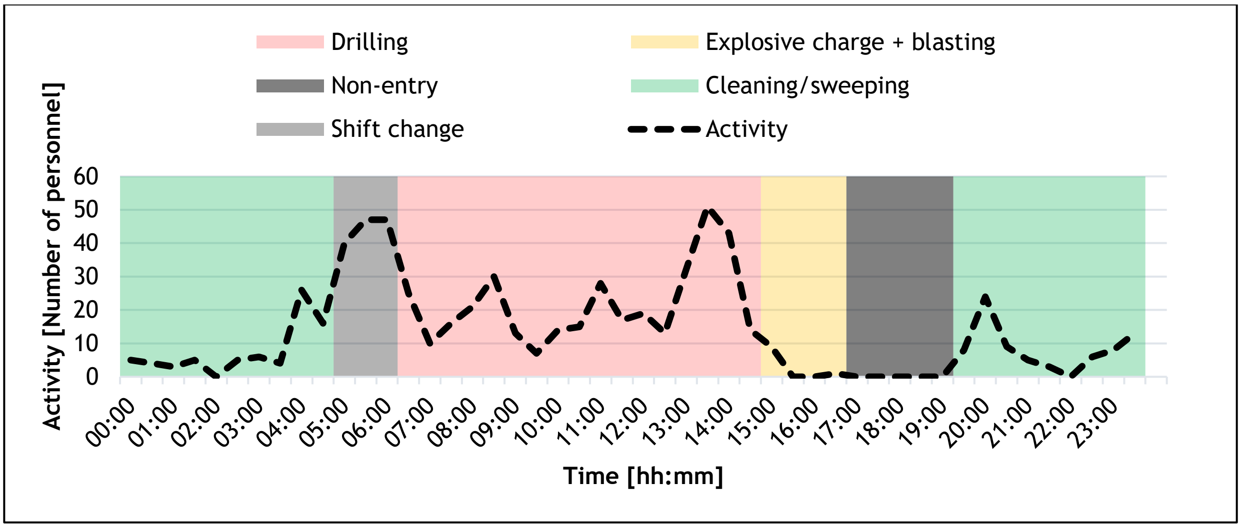

Figure 7: Personnel activity during different mining shifts

The dynamic zero-waste baselines were constructed for Mine X. Figure 8 showcases the dynamic zero-waste baselines for Business unit 1 over five distinct days. These baselines vary daily due to several factors mentioned previously.

[1] PTB is a user-friendly thermal hydraulic simulation software package that enables users to design, analyse and optimise a system's performance which is owned by MCI (Pty)©.

Each business unit possesses unique factors that impact the baseline differently, although the underlying principles on which they were developed remain consistent.

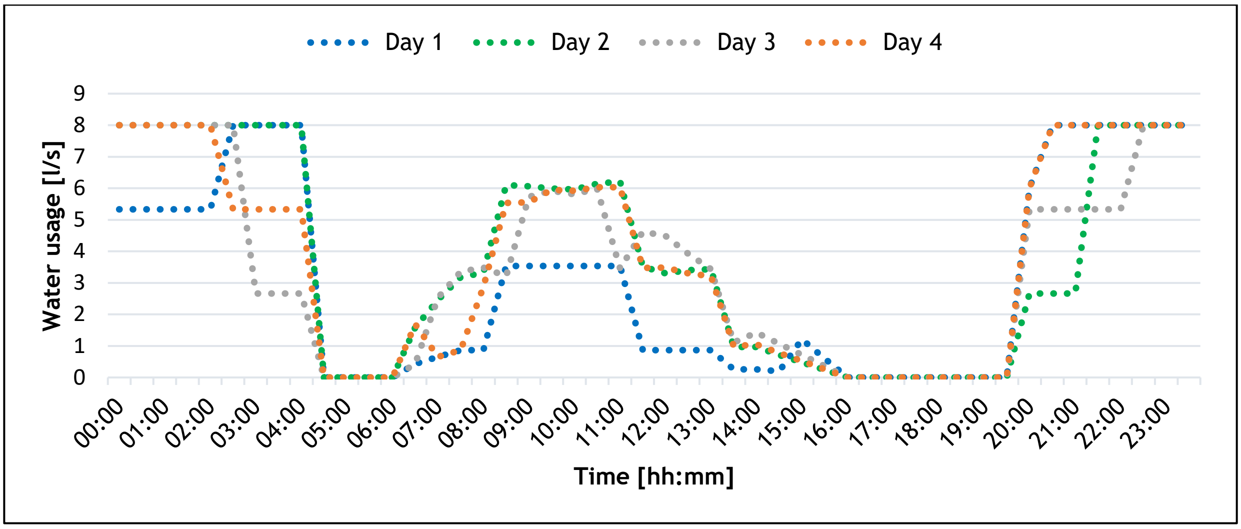

Figure 8: Dynamic zero-waste baselines for business unit 1

Figure 9 and Figure 10 depicts the pre- and post-implementation results for Business unit 1 (results before and after the rectification of identified inefficiencies). Here the measured actual water usage, as captured by the installed flow meter, is displayed alongside the corresponding dynamic zero-waste baseline. Additionally, the MPL data for the particular scenario is also depicted in the figures. This visual representation provides a comprehensive view of the real-time water flow, the baseline comparison, and the personnel activity recorded by the MPL system for the specified day.

When referring to the pre-implementation results depicted in Figure 9, we see that water was still consumed during periods where no personnel was working. This mean that the water consumed during these times are contributed to wastages. Furthermore, additional water was used during the drilling and cleaning/sweeping shifts.

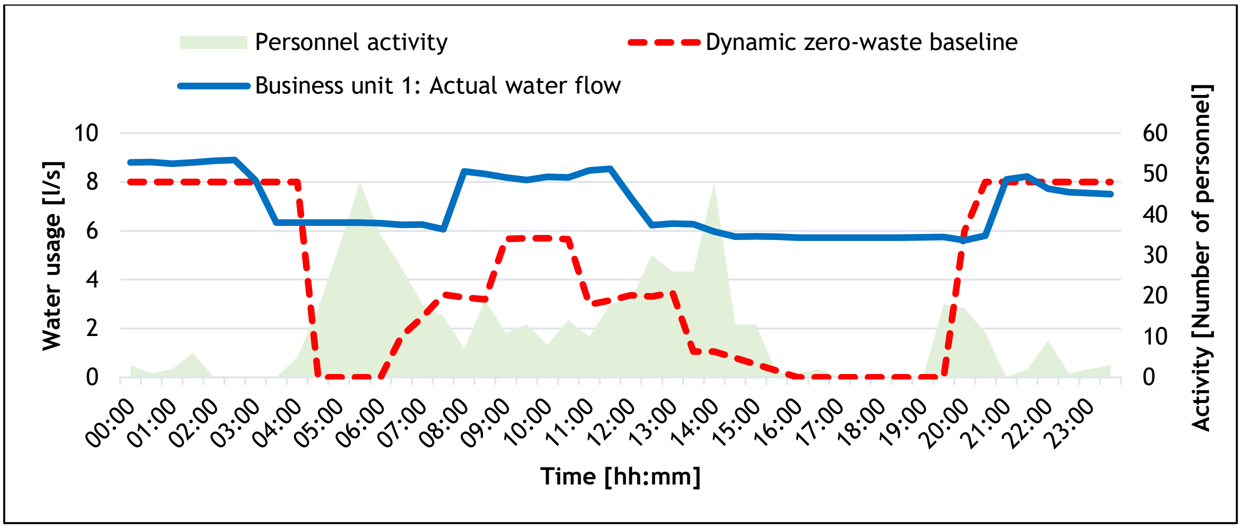

Figure 9: Business unit 1 pre-implementation results

These wastages, as seen in Figure 9, were identified using the developed method and attended to which resulted in the water being closed during periods when no water should be consumed (during shift changes and non-entry periods). This is seen in the post-implementation results shown in Figure 10. However, water is still wasted when personnel are working which requires attention.

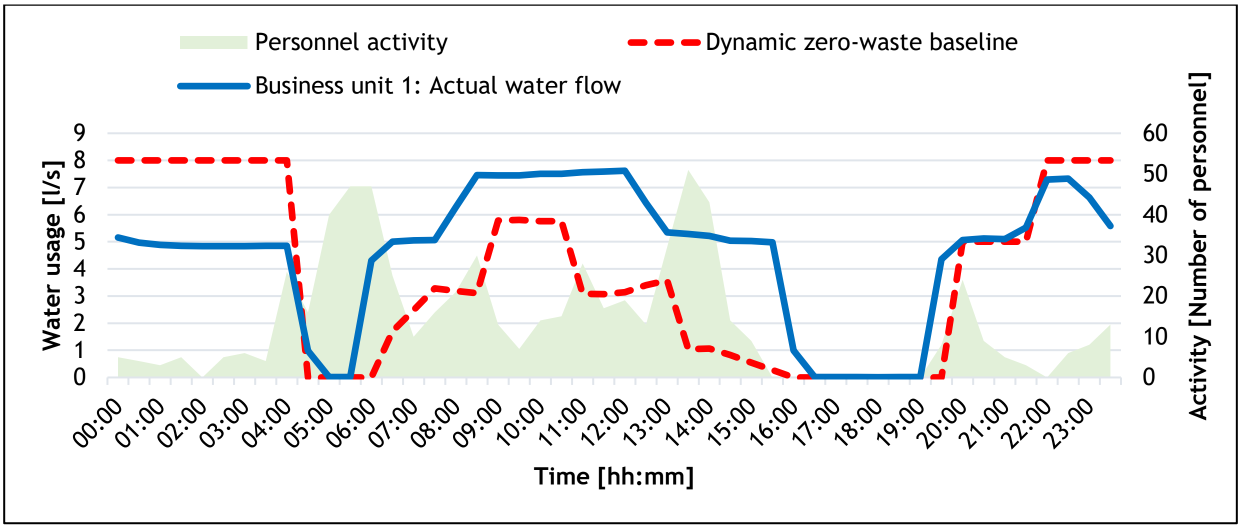

Figure 10: Business unit 1 post-implementation results

After an audit conducted based on the findings showed in Figure 9 and Figure 10, wastages seen has been attributed to 25 mm open hoses, waterjet guns that are left open and general leaks as depicted in Figure 11.

Figure 11: Identified inefficiencies on Business unit 1[1]

The mine pumping- and refrigeration correlation factors was determined by using equation (**2.** These correlations are displayed in Table 4.

Table 4: Mine X pumping- and refrigeration correlation factors

System	Correlation [kW/l/s]	Comment
Refrigeration	9.59	kW to cool 1 l/s to 4°C
Pumping	11.16	kW to pump 1 l/s

This information, together with the electricity tariffs were used to estimate the cost implications for the pre- and post-implementation results (actuals compared to baselines for each scenario). For Business unit 1, the daily water and energy wastage can be seen in Table

[1] Personnel photos taken during underground audit.

5. From this, it is clear that the wastages were reduced from the pre-implementation to the post-implementation.

Table 5: Pre- vs post-implementation daily wastages for Business unit 1

	Water wastage [l/day]	Pumping energy cost wastage [R/day]	Refrigeration energy cost wastage [R/day]	Total energy cost wastage [R/day]
Pre-implementation	264 041	R2 580	R2 217	R4 797
Post-implementation	72 811	R656	R611	R1 267
Savings	191 229	R1 924	R1 606	R3 530

This equates to an annual benefit of approximately R2.9 million for Business unit 1. The return-on-investment of the flow- and pressures meters for this specific business unit was calculated as 1 month.

The results from all the implemented business units were extrapolated to determine the average combined annual pumping- and refrigeration energy cost benefit for Mine X as seen in Table 6.

Table 6: Mine X average energy cost benefits (combined business units)

Average business unit daily energy saving [R]	R1 550
Level daily energy saving [R]	R26 350
Level annual energy saving [R]	R6 300 000
Mine X annual energy saving [R]	R19 100 000

3.4 Verification and Validation

The developed method was implemented on Mine X. The success of the method will be determined by performing the verification and validation step using the identified criterion.

By comparing the outcomes of the implemented method to the objectives thereof, the verification will be completed. The outcomes and objectives are summarised below.

- Objective: Development and implementation of dynamic zero-waste baselines.
- Outcome: Dynamic zero-waste baselines were developed and implemented on Mine X.

- Objective: Inefficiency detection and continuous monitoring for sustainability.
- Outcome: By using the developed dynamic zero-waste baselines together with the installed flow- and pressure meters, wastage was identified as seen in the pre- and post-implementation results.

- Objective: Energy- and water savings through inefficiency identification and rectification.
- Outcome: Energy- and water savings was achieved through the implementation of this method. For Business unit 1, a daily energy cost saving of R3 530 (191 Ml of water) was achieved. The data from all business units was extrapolated to determine the energy cost saving for Mine X. This resulted in an annual benefit of approximately R19 million.

For the validation of the method, the identified KPIs were compared to the outcomes.

- KPI: Pumping- and refrigeration consumption
- Outcome: A combined daily pumping- and refrigeration energy reduction of 2 240 kWh was achieved on Business unit 1. The extrapolated benefit on Mine X was calculated as 12 100 MWh.

- KPI: Water consumption
- Outcome: 191 Ml daily water reduction has been achieved on Business unit 1.

The method can be deemed successful as the criterion for the verification and validation has been met.

4 CONCLUSION

Over the past nine years, the operational costs of gold mining operations in South Africa have witnessed a significant increase of 54%. Extensive analysis has revealed that inefficiencies in services play a pivotal role in driving these escalating costs. Consequently, the exploration of inefficiency detection, particularly in localised areas near the working sites, has emerged as a pressing need.

To address this challenge, flow- and pressure sensors were strategically installed in three designated underground working areas, each delineated as a separate business unit. Dynamic zero-waste baselines were developed and employed to each business unit, which factor in multiple pertinent variables to accurately determine the required water quantities.

Through the implementation of the developed method, an annual energy cost saving of approximately R19 million was achieved for Mine X. The developed method has been deemed successful through the verification and validation thereof.

Moving forward, the developed method can be used to develop an accountability methodology to ensure the appropriate stakeholders are held responsible. It is anticipated that the implementation of this accountability framework will effectively prevent the occurrence of additional costs. By establishing clear lines of responsibility and fostering a culture of accountability, the mining operations can sustainably avoid unnecessary expenses and optimise resource utilisation.

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ACCESS TO MEDICAL EVALUATION: THE DEVELOPMENT OF A COMMUNICATION TOOL APPLICATION

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ABSTRACT

Access to medical evaluation refers to the ability of individuals to receive timely and comprehensive medical assessments and evaluations for their health concerns. This process is critical for the accurate diagnosis, treatment, and management of medical conditions. However, access to medical evaluation can be affected by a range of factors. This paper aims to explore these factors by means of a systematic literature review. From this review various factors emerged, including geographic location, socioeconomic status, and the availability of healthcare resources. These factors can create disparities in access to medical evaluation, resulting in some individuals having limited or no access to medical services, which can have serious consequences for their health outcomes. By understanding these factors, future research can bridge the gaps. Thereby, ensuring that individuals have equitable access to medical evaluation is essential for promoting good health and improving health outcomes for all members of society.

Keywords: Access, medical evaluation, healthcare, innovative healthcare technology, improving health

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1 INTRODUCTION

South Africa has a complex and fragmented public healthcare system, which faces numerous challenges. According to a study by Erasmus et. al [1], access to healthcare services in South Africa is impeded by various factors, including socio-economic factors, a shortage of healthcare providers, inadequate infrastructure, and the burden of communicable and non-communicable diseases.

The country's healthcare system is divided into two main sectors: the public sector, which is funded and managed by the government, and the private sector, which is funded by private health insurance schemes and out-of-pocket payments. However, most of the population relies on the public sector for healthcare services.

Several studies have highlighted the challenges facing the public healthcare sector in South Africa. For instance, a study by Hasumi and Jacobsen [2] found that poor quality of care and long waiting times were common complaints among patients in public healthcare facilities. Additionally, the shortage of healthcare workers, including doctors, nurses, and pharmacists, has been identified as a major challenge in the public healthcare sector [3].

Overall, the public healthcare industry in South Africa faces significant challenges, but there are ongoing efforts to address these challenges through policy interventions and innovative healthcare service delivery models.

The purpose of this paper is to investigate the factors that influence access to medical evaluation, specifically focusing on the South African healthcare context. By conducting a systematic literature review, the paper aims to identify and analyse the various factors that hinder individuals from receiving timely and comprehensive medical assessments and evaluations for their health concerns.

2 RESEARCH METHOD

To achieve the research aim, a systematic literature review (SLR) was conducted using a scoping approach to explore the scopes and purpose of various studies and frameworks. The study used Albliwi et. al.'s [4] proposed SLR method, which involved the following steps: Bullets:

- **Step 1**: Developing research purpose.
- **Step 2**: Creating research protocol.
- **Step 3:** Establishing relevance criteria.
- **Step 4:** Searching and retrieving literature.
- **Step 5:** Selecting studies using inclusion and exclusion criteria.
- **Step 6:** Assessing the quality of relevant studies.
- **Step 7:** Extracting relevant information from the papers.
- **Step 8:** Analyse and synthesize the data to identify themes and patterns.
- **Step 9:** Report the review in detailed results.
- **Step 10:** Disseminate the SLR by publishing a research paper.

Steps 1 to 6 outcomes are discussed in the sub-sections, while the findings of the study are documented under the findings section. Steps 9 and 10 are addressed by publishing the research paper.

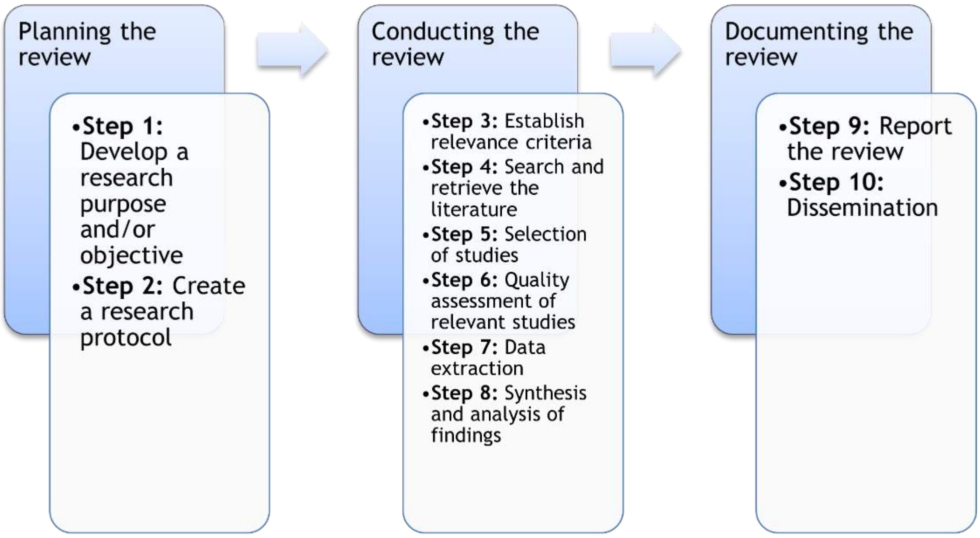

Figure 1: Research method (Adapted from [4])

2.1 Step 1: Develop a research purpose and/or objective

The purpose is to investigate the various factors that hinder individuals from receiving timely and comprehensive medical assessments and evaluations for their health concerns.

2.2 Step 2: Create a research protocol

Table 1 captures the research protocol with specific detail on the purpose, selection criteria, databases, keywords, and quality assessment criteria.

Table 1: Research review protocol (Structure adapted from [5])

Purpose of the study	To investigate the issues of poor healthcare access in South Africa
Inclusion Criteria	▪ South African based literature ▪ Literature discussing "medical evaluation", "diagnosis" and "access issues" ▪ Literature between the years 2012 – 2022
Exclusion Criteria	▪ Literature discussing private healthcare. ▪ Non-English literature ▪ Literature based in other countries (not in SA) ▪ Books, magazines, and reports
Search Databases	▪ Science Direct ▪ Scopus ▪ IEEE Explore ▪ Web of Science ▪ Emerald Insight Journals
Keywords	"South Africa" AND "Healthcare" AND "Issues"
Quality assessment criteria	• All duplicate literature must be removed. • Recovered literature checked for relevance. • Unjustifiably small sample size

	• Lack of supporting resources • Unclear scope and context • Unanswered research question • Lack of credibility, reliability, and validity

2.3 Step 3: Establish relevance criteria

When establishing the relevance criteria, it was important to be specific, but to leave room for as many studies to be included as possible [4] [5]. Thus, the following relevance criteria was developed by which studies were included:

- Literature that contained "Healthcare" and "Access" and "Issues" in the title, keywords or abstract of the study.
- Studies that are based in South Africa
- Discuss issues around access to medical evaluation.
- Literature between the years 2012 – 2022

2.4 Step 4: Search and retrieve the literature

The searching and retrieving of the literature were initially done using the databases stated in section 2.2. To initiate the search, the keywords were used to capture literature that addresses the issues of poor healthcare access in South Africa.

The search was conducted in selected databases and these databases were chosen due to their extensive coverage of scholarly literature and their relevance to the research topic. The keywords were applied in the title, keywords, and abstract fields of the literature to narrow down the search results.

The search was limited to studies published between the years 2012 and 2022 to ensure the inclusion of recent and relevant literature. This time frame allowed for an assessment of healthcare access issues in South Africa over the past decade.

Upon executing the search, the results from each database were recorded, noting the number of resources found in each database. These resources were retrieved in the form of articles or documents, which were saved for further evaluation in the subsequent steps of the SLR. This yielded a total of 9 900 studies.

The retrieved 9 900 resources then underwent a thorough screening process based on predefined inclusion and exclusion criteria. The inclusion criteria involved studies that were South African based, discussed healthcare access issues, and focused on medical evaluation. Conversely, literature discussing private healthcare, non-English literature, studies conducted in countries other than South Africa, and books were excluded from the review.

During the screening process, each paper underwent a rigorous evaluation of its title and abstract to assess its potential relevance to the research objectives. Papers that did not align with the criteria were excluded. A substantial portion of the excluded papers focused on general issues in South Africa's healthcare system without specifically addressing the issues surrounding access to medical evaluation. These papers explored topics such as economic factors influencing healthcare and strategies for improving overall healthcare quality. While valuable in their own right, they did not directly address the targeted focus of the systematic literature review on healthcare access issues.

The screening process involved reviewing titles, abstracts, and full texts of the resources to determine their eligibility for inclusion in the SLR, of which 22 resources met the criteria.

Duplicate resources were identified and removed to ensure that each study was considered only once in the subsequent analysis.

After completing the screening process, 20 remaining resources met the inclusion criteria were selected for the systematic literature review.

2.5 Step 5: Selection of studies

After applying the protocol outlined in step 1, a total of 22 studies were chosen from the initial screening process. These selected studies underwent further evaluation to eliminate any duplicate entries, resulting in 21 studies that met the criteria for inclusion. The selection process and its results are depicted in Figure 2, specifically in the "Screening" and "Eligibility" sections, which provide an overview of the search results for each database. Following the study selection, relevant information for each study, including author names, study titles, and publication years, was recorded.

2.6 Step 6: Quality assessment of relevant studies

Once the removal of duplicates was completed, a thorough assessment of the studies' quality was conducted by examining their full texts. The evaluation criteria included factors such as sample size, availability of supporting resources, scope and content of the studies, research questions addressed, as well as their reliability, credibility, and validity. Remarkably, all 21 papers met the criteria for inclusion and were deemed acceptable.

Figure 2 comprehensively documents steps 4 to 6 of the selection process, as outlined in sections 2.4 to 2.6. The figure depicts the various stages of the search on the left side and provides a clear distinction between the number of studies initially found and the number ultimately selected from each database.

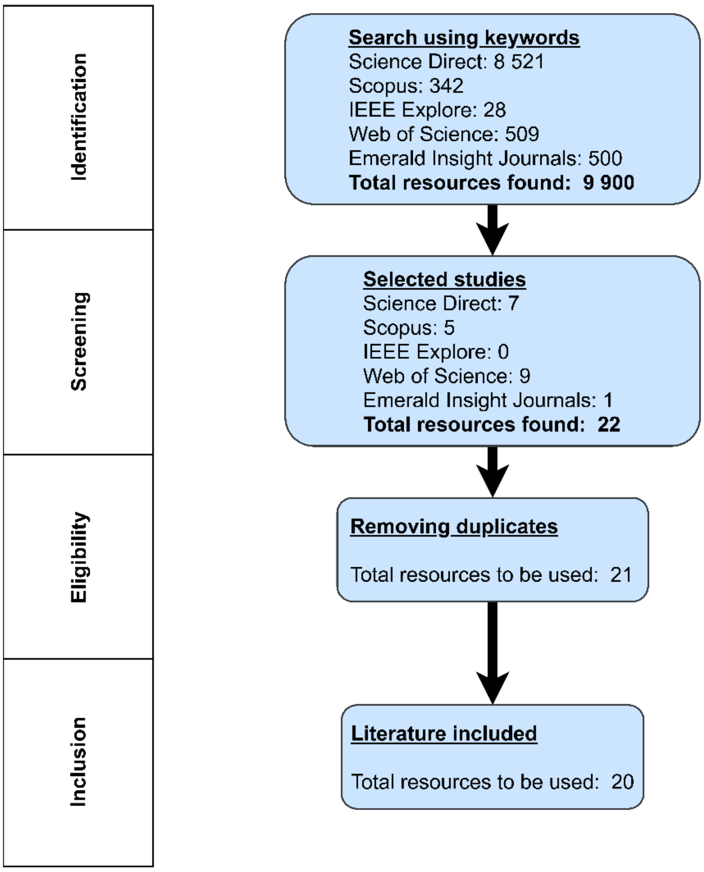

Figure 2: Selection Process

3 FINDINGS

3.1 Step 7: Data Extraction

After selecting the studies and reviewing their full texts, a summary was compiled to outline the healthcare access issues addressed in each study. This summary is presented in Table 2, which provides information such as (1) the provincial location of each study, (2) the factors influencing healthcare access, (3) the primary barriers identified, and (4) the population group affected. Additionally, Table 2 includes details about the authors, year of publication, and research titles to provide a complete overview of the included studies.

#	Author(s)	Year	Research Title	Issue addressed	Provincial Location	Affecting Factors	Main barrier to healthcare access	Population group	Ref
1	Lubuzo, B., Ginindza, T., Hlongwana, K.	2019	Exploring barriers to lung cancer patient access, diagnosis, referral and treatment in Kwazulu-Natal, South Africa: The health providers' perspectives	Barriers to lung cancer care in South Africa, particularly from the perspectives of healthcare professionals.	KwaZulu-Natal	Limited access to healthcare facilities. Lack of resources and infrastructure. Delayed diagnosis and inadequate management	Availability of healthcare resources	Diagnosed disease or illness	[6]
2	Kapwata, T., Manda, S.	2018	Geographic assessment of access to health care in patients with cardiovascular disease in South Africa	The lack of accessible healthcare facilities for people diagnosed with cardiovascular diseases in South Africa, which can lead to delayed diagnosis and inadequate management.	All Provinces	Limited access to healthcare facilities. Delayed diagnosis. Inadequate management.	Geographical location	Diagnosed disease or illness	[7]
3	Mhimbira, F.A., Cuevas, L.E., Dacombe, R., Mkopi, A., Sinclair, D.	2017	Interventions to increase tuberculosis case detection at primary healthcare or community-level services	High number of undiagnosed cases of tuberculosis, prompting researchers to assess different strategies aimed at improving access to tuberculosis diagnosis and increasing case detection.	All Provinces	Limited access to tuberculosis diagnosis. Lack of awareness and education. Barriers to case detection.	Socioeconomic status	Low-income group	[8]
4	Vergunst, R., Swartz, L., Hem, K.-G., Eide, A.H., Mannan, H., MacLachlan, M., Mji, G., Braathen, S.H., Schneider, M.	2017	Access to health care for persons with disabilities in rural South Africa	People with disabilities in impoverished rural areas of South Africa face challenges in accessing healthcare, and there is a need to address these barriers to ensure their inclusion and well-being.	Eastern Cape	Limited access to healthcare services. Transportation difficulties. Economic factors.	Transportation	People with disabilities.	[9]
5	Magadzire, B.P., Budden, A., Ward, K., Jeffery, R., Sanders, D.	2014	Frontline health workers as brokers: Provider perceptions, experiences, and mitigating strategies to improve access	Barriers to access medicines from the perspective of front-line health providers in South Africa	Eastern Cape	Limited availability and affordability of medicines. Logistical challenges.	Availability of healthcare resources	Health workforce	[10]

#	Author(s)	Year	Research Title	Issue addressed	Provincial Location	Affecting Factors	Main barrier to healthcare access	Population group	Ref
			to essential medicines in South Africa						
6	Kariuki, P.,Goyayi, M.L., and Ofusori, L.O.	2022	COVID-19, migration, and inclusive cities through e-governance: strategies to manage asylum seekers in Durban, South Africa	The limited access of asylum seekers to public services in the city of Durban, South Africa, particularly during the COVID-19 pandemic, and the potential role of electronic governance (e-governance) in improving their access.	KwaZulu-Natal	Inadequate access to public services. Impact of COVID-19. Potential role of e-governance.	Cultural barrier	Marginalized group	[11]
7	Abraham, V; Meyer, JC; Godman, B; Helberg, E	2022	Perceptions of managerial staff on the patient safety culture at a tertiary hospital in South Africa	The patient safety culture within a tertiary academic hospital in South Africa and the perceptions of managerial staff regarding it	South Africa	Perception of managerial staff. Limited resources. Constraints in providing optimal care	Availability of healthcare resources	Health workforce	[12]
8	Katzen, LS; Skeen, S; Dippenaar, E; Laurenzi, C; Notholi, V; le Roux, K; Rotheram-Borus, MJ; le Roux, I; Mbewu, N; Tomlinson, M	2022	Are we listening to community health workers? Experiences of the community health worker journey in rural South Africa	The experiences of community health workers (CHWs) in a government-run program in South Africa's rural Eastern Cape Province.	Eastern Cape	Challenges in reaching rural communities. Limited resources. Need for support and resources.	Availability of healthcare resources	Rural	[13]
9	Rattine-Flaherty, E; Burton, S	2021	The role of pharmacy personnel in promoting adherence to antiretroviral therapy in the Eastern Cape: communication barriers and breakthroughs	The potential role of South African pharmacists and pharmacy support personnel in improving medication adherence among people living with HIV	Eastern Cape	Enhancing medication adherence. Strengthening pharmacy services.	Discrimination and Stigma	Health workforce	[14]

#	Author(s)	Year	Research Title	Issue addressed	Provincial Location	Affecting Factors	Main barrier to healthcare access	Population group	Ref
10	de Villiers, K	2021	Bridging the health inequality gap: an examination of South Africa's social innovation in health landscape	The need for social innovation in the South African healthcare system to address issues of health equity and improve accessibility, affordability, and acceptability of healthcare services.	All Provinces	Addressing health equity. Improving accessibility, affordability, and acceptance of healthcare services.	Availability of healthcare resources	Low-income group	[15]
11	Benatar, S; Gill, S	2021	Universal Access to Healthcare: The Case of South Africa in the Comparative Global Context of the Late Anthropocene Era	The erosion of equitable access to healthcare and the challenges faced in achieving universal healthcare, particularly in low- and middle-income countries like South Africa, where disparities between private and public healthcare sectors are significant	South Africa	Disparities between private and public healthcare sectors. Limited resources. Historical and economic factors	Socioeconomic status	Health workforce	[16]
12	Ramathuba, DU; Ndou, H	2020	Ethical conflicts experienced by intensive care unit health professionals in a regional hospital, Limpopo province, South Africa	The ethical conflicts experienced by healthcare professionals in an ICU of a regional hospital in South Africa due to limited resources and constraints in providing optimal care to critically ill patients	Limpopo	Limited resources. Constraints in providing optimal care. Ethical dilemmas	Availability of healthcare resources	Low-income group	[17]
13	Mohr-Holland, E; Apolisi, I; Reuter, A; de Azevedo, V; Hill, J; Matthee, S; Seddon, JA; Isaakidis, P; Furin, J; Trivino-Duran, L	2019	Barriers and solutions to finding rifampicin-resistant tuberculosis cases in older children and adolescents	The barriers to post-exposure management of rifampicin-resistant tuberculosis (RR-TB) in older children and adolescents.	Western Cape	Limited access to management services. Lack of awareness and education.	Socioeconomic status	Older children and adolescents	[18]
14	Winchester, M.S; King, B	2018	Decentralization, healthcare access, and inequality in Mpumalanga, South Africa	Historical spatial manipulation and inequities in healthcare access persist in rural areas of South	Mpumalanga	Limited resources. Transportation	Transportation	Rural	[19]

#	Author(s)	Year	Research Title	Issue addressed	Provincial Location	Affecting Factors	Main barrier to healthcare access	Population group	Ref
				Africa, despite efforts to decentralize healthcare and improve access.		difficulties. Historical and economic factors.			
15	Liautaud, A; Adu, P.A; Yassi, A; Zungu, M; Spiegel, J.M; Rawat, A; Bryce, E.A; Engelbrecht, M.C	2018	Strengthening Human Immunodeficiency Virus and Tuberculosis Prevention Capacity among South African Healthcare Workers: A Mixed Methods Study of a Collaborative Occupational Health Program	Healthcare personnel in countries with high HIV and TB burdens lack sufficient training in infection control and occupational health.	Free State	Lack of training resources. Limited awareness and education. Inadequate infection control measures.	Discrimination and Stigma	Health workforce	[20]
16	Mutwali, R.; Ross, E.	2019	Disparities in physical access and healthcare utilization among adults with and without disabilities in South Africa	In South Africa, people with disabilities face challenges in accessing healthcare services due to the strained public healthcare system, highlighting the need for equal access to healthcare for all citizens.	South Africa	Limited access to healthcare services. Strained public healthcare system.	Availability of healthcare resources	People with disabilities.	[21]
17	Sommerland, N; Masquillier, C; Rau, A; Engelbrecht, M; Kigozi, G; Pliakasc, T; Janse van Rensburg, A; Wouters, E	2020	Reducing HIV- and TB-Stigma among healthcare co-workers in South Africa: Results of a cluster randomised trial	Stigma from healthcare workers towards colleagues with HIV and TB in South Africa harms the well-being of healthcare workers and the healthcare system.	South Africa	Discrimination and stigma. Impact on well-being and healthcare system.	Discrimination and Stigma	Health workforce	[22]
18	Neely, A.H; Ponshunmugam, A	2019	A qualitative approach to examining health care access in rural South Africa	People in rural areas of South Africa face challenges in accessing healthcare due to limited resources, transportation	KwaZulu-Natal	Limited resources. Transportation difficulties. Historical and economic factors.	Transportation. Availability of healthcare resources	Rural	[23]

#	Author(s)	Year	Research Title	Issue addressed	Provincial Location	Affecting Factors	Main barrier to healthcare access	Population group	Ref
				difficulties, and historical and economic factors					
19	Lynch, A; Sobuwa, S; Castle, N	2020	Barriers to the implementation of prehospital thrombolysis in the treatment of ST-segment elevation myocardial infarction in South Africa: An exploratory inquiry	The implementation of prehospital thrombolysis (PHT) for treating heart attacks in South Africa is hindered by various barriers, such as cost, logistics, collaboration among healthcare professionals, leadership involvement, and doubts or scepticism about PHT	South Africa	Logistics. Costs. Scepticism. Leadership involvement	Availability of healthcare resources	Health workforce	[24]
20	Winchester, M. S; King, B; Rishworth, A	2021	"It's not enough:" Local experiences of social grants, economic precarity, and health inequity in Mpumalanga, South Africa	Although South Africa has a social grant program to alleviate poverty, households still depend on strategies like remittances and migration to manage their income and access healthcare.	Mpumalanga	Economic factors. Poverty alleviation programs. Limited access to resources and healthcare.	Socioeconomic status	Low-income group	[25]

3.2 Step 8: Synthesis and Analysis

3.2.1 Provincial Location

From the analysis, the studies were evaluated based on their geographical location within South Africa. Figure 3 illustrates the data distribution of various provinces in South Africa, with a notable emphasis on the Eastern Cape, KwaZulu-Natal, and Mpumalanga provinces. Notably, the provinces of Eastern Cape and KwaZulu-Natal emerged as areas with a significant representation of studies. These provinces are known to have higher levels of poverty and socio-economic challenges compared to other regions in the country. The graph includes a category labelled "South Africa" to represent the studies that did not specify a specific province where they were conducted. This distribution provides a diverse and comprehensive view of healthcare access issues in different regions of the country, contributing to a more comprehensive understanding of the overall landscape of poor healthcare access in South Africa.

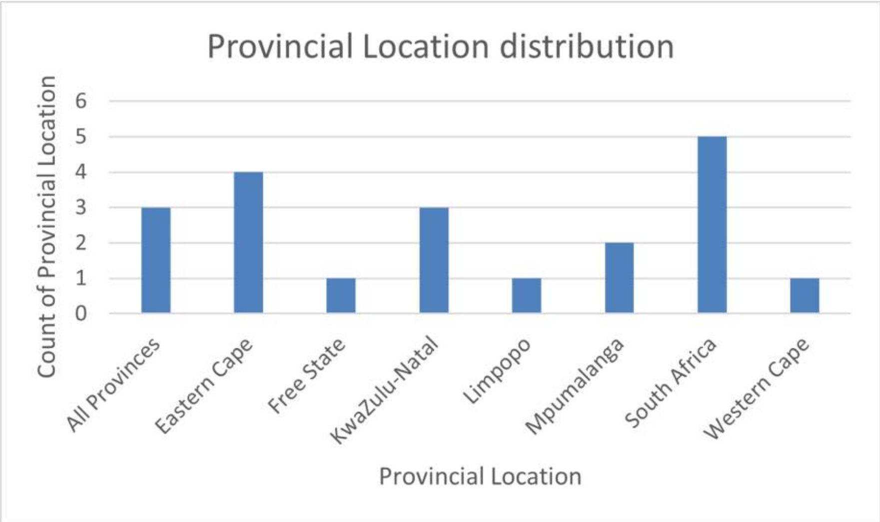

Figure 3: Bar graph of Provincial Location distribution

3.2.2 Population Groups

The data indicates the distribution of studies included in the review based on the population groups they focused on. The population groups considered include diagnosed disease or illness, health workforce, low-income group, marginalized group, older children and adolescents, people with disabilities, and rural populations. The number of studies conducted on each population group is provided in Figure 4.

The inclusion of two studies on individuals with diagnosed diseases or illnesses indicates a focus on understanding the healthcare access challenges faced by individuals already diagnosed with specific medical conditions. The seven studies on the health workforce shed light on the barriers and challenges encountered by healthcare providers, including healthcare professionals, workers, and support personnel, in accessing and delivering healthcare services.

Furthermore, the SLR included four studies dedicated to exploring healthcare access issues faced by low-income groups, highlighting the challenges experienced by individuals with limited financial resources. One study specifically focused on marginalized populations, aiming to understand the healthcare access issues faced by socially, economically, or politically marginalized groups.

Additionally, the SLR addressed the healthcare access issues experienced by older children and adolescents through one study. Two studies focused on people with disabilities, aiming to identify the barriers and challenges they encounter in accessing healthcare services. Lastly, three studies investigated healthcare access issues in rural areas, highlighting the unique challenges faced by individuals residing in remote or underserved rural communities.

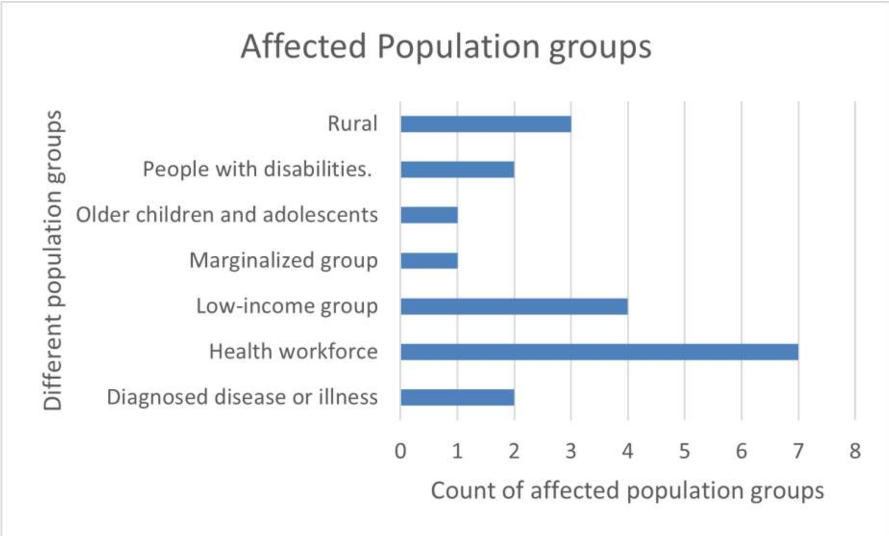

Figure 4: Affected Population groups distribution

3.2.3 Barriers to healthcare access

The barriers represent key factors that impede individuals from accessing healthcare services. Understanding and analysing these barriers is crucial for identifying gaps and challenges in healthcare access.

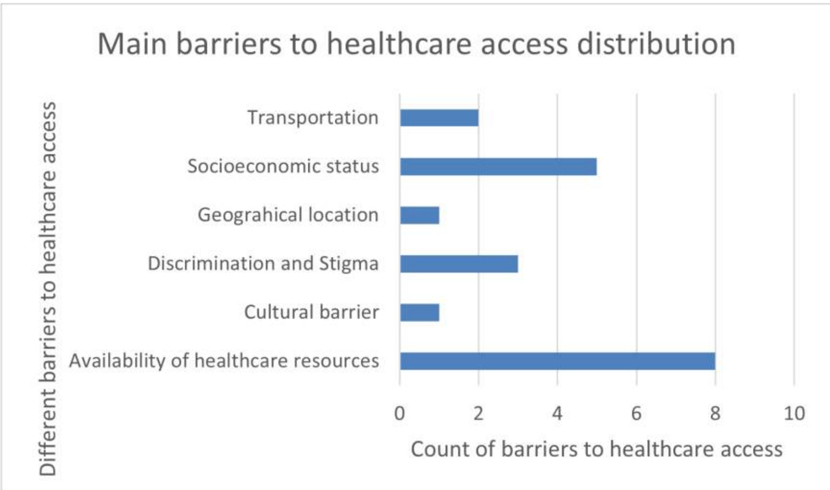

Figure 5: Barriers to healthcare access distribution

As illustrated in Figure 5, the most prevalent barrier identified in the data is the availability of healthcare resources. This suggests that inadequate availability of healthcare facilities, medical equipment, and healthcare professionals poses a significant challenge to accessing healthcare services. This finding emphasizes the need to address resource limitations and ensure sufficient healthcare infrastructure.

The presence of cultural barriers, exemplified by the resistance of certain communities to provide assistance to asylum seekers, highlights the influence of cultural attitudes and prejudices on healthcare access. This finding underscores the importance of addressing misconceptions and promoting inclusivity and empathy within society.

Discrimination and stigma emerge as barriers to healthcare access. This suggests that discrimination based on factors such as race, ethnicity, gender, or health conditions, as well as the stigma associated with certain illnesses, can deter individuals from seeking and receiving adequate healthcare. Recognizing and addressing discrimination and stigma are crucial steps towards fostering equitable and inclusive healthcare systems.

Geographical location points to the impact of physical distance and remote locations on healthcare access. It underscores the challenges faced by individuals residing in geographically isolated areas, where accessing healthcare services may be hindered by limited infrastructure, transportation options, or healthcare providers.

Socioeconomic status emphasizes the influence of economic factors on healthcare access. Individuals with lower socioeconomic status may face financial constraints, lack of health insurance, or limited resources, making it difficult for them to access necessary healthcare services. Addressing socioeconomic disparities is essential for promoting equitable access to healthcare.

Transportation signifies the role of transportation barriers in healthcare access. Difficulties in reaching healthcare facilities due to limited transportation options, especially in rural or underserved areas, can impede timely access to care. This is particularly relevant in South Africa, where a majority of the population relies on public transportation as their primary mode of commuting.

4 REPRESENTATION OF FINDINGS

The outcome the SLR illustrates the wide array of challenges that South African's face when it comes to accessing medical care. Figure 6 captures the summary of these challenges.

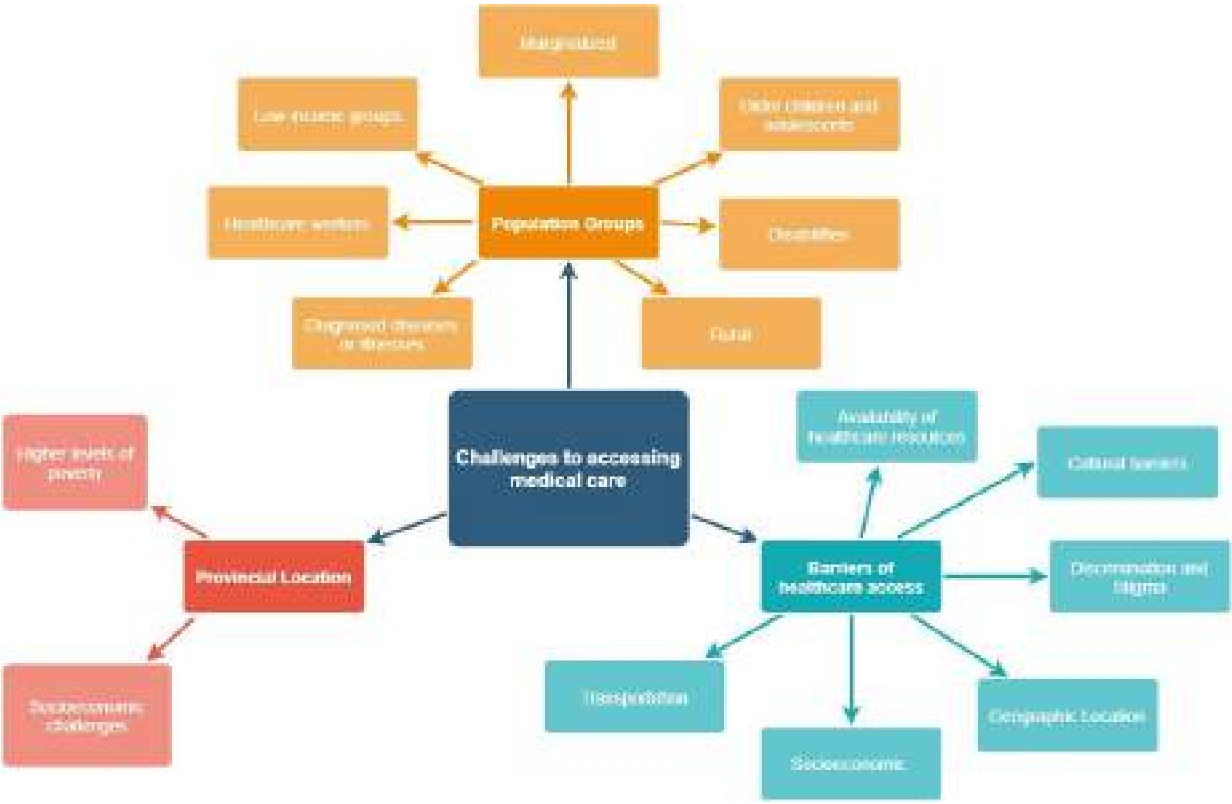

Figure 6: Representation of findings

5 CONCLUSIONS AND RECOMMENDATIONS

This study sought to look into the problems of South Africa's limited access to healthcare. The outcomes were displayed in tabulated analysis.

Using an approach adopted from Albliwi et al. [4], a systematic literature review was conducted to achieve the goal. The investigations were based on the review process, and the findings may help researchers comprehend the problems relating to South Africa's limited access to healthcare.

Based on the findings of the literature review, a few recommendations can be made to improve the situation. Firstly, it is crucial to address the availability of healthcare resources. Increasing the number of healthcare facilities, ensuring adequate staffing, and equipping them with the necessary resources will help meet the healthcare demands of the population.

Another important recommendation is to enhance cultural competency among healthcare providers. Implementing cultural competency training programs will enable them to better understand and respect diverse cultural norms, beliefs, and practices. Discrimination and stigma were identified as significant barriers to healthcare access. To address this, it is recommended to implement anti-discrimination policies and raise awareness through campaigns. Creating an environment that promotes equitable access to healthcare without fear of discrimination or judgment is essential. Socioeconomic disparities have a considerable impact on healthcare access. Strategies should be developed to address financial constraints, lack of health insurance, and limited resources.

Transportation barriers, especially in rural and underserved areas, pose challenges in accessing healthcare services. It is recommended to enhance transportation options by improving infrastructure and services. Strengthening primary healthcare will bring comprehensive and accessible healthcare closer to where people live, reducing the need for long-distance travel.

While this study provided a fulsome analysis of the challenges available in literature, it is recommended that future research work on addressing some of these challenges in a comprehensive way.

By designing a comprehensive mobile application, this design idea leverages the widespread use of smartphones to provide accessible and convenient healthcare services. The application addresses key challenges identified in the study, including resource availability, cultural sensitivity, discrimination, socioeconomic disparities, transportation barriers, and the promotion of primary healthcare. It aims to bridge the gap between individuals and healthcare services, facilitating better access to healthcare and ultimately improving healthcare outcomes in South Africa.

In conclusion, the outcomes of this study shed light on the complex issues surrounding limited healthcare access in South Africa. While the presented recommendations provide valuable insights, they represent just the beginning of a journey towards equitable healthcare for all. It is evident that further research is needed to delve deeper into these challenges, develop innovative solutions, and create strategies for implementation.

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EXPLORING THE FUTURE OF PRECISION FARMING: A SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

The primary sector includes the agricultural, forestry, and fishing industries. For South Africa's economy, these industries are considered key sectors as StatsSA indicates a joint increase of 15.9% through the 3rd and 4th Quarters of 2022. In a similar vein, Statista explained that the market value of precision farming is expected to grow from approximately 7 billion to 14.5 billion U.S. dollars from 2021 to 2027. Despite the success of precision farming, there is limited research on farm management support systems in Sub-Saharan Africa, suggesting a major research gap. Therefore, this paper aims to conduct a systematic literature review (SLR) to investigate studies that pertain to precision agriculture applied in the swine industry. This research showcases themes such as the affiliated countries of identified studies, the distribution of studies, technologies and strategies used by researchers, and experienced enablers and barriers of implemented precision agriculture solutions.

Keywords: Precision farming, Swine industry, systematic literature review

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1 INTRODUCTION

The primary sector includes the agricultural, forestry, and fishing industries that involve the production and trade of farmed crops, livestock, fish or food, and wood. For South Africa's economy, these industries are considered as key sectors as there was a joint increase of 15.9% through the 3rd and 4th Quarters of 2022 [1, 2]. In a similar vein, Statista explained that the market value of precision farming is expected to grow from approximately 7 billion to 14.5 billion U.S. dollars from 2021 to 2027 [3].

As agriculture has evolved over the past 50 years, recent use of techniques such as precision agriculture has emerged. Fuglie [4] defines precision agriculture as "the application of modern information technologies to provide, process and analyse multisource data of high spatial temporal resolution for decision making and operations in the management of crop production." This has been noted in various industries, which include agriculture, forestry, and fishing. In South Africa, the aforementioned industries planned to make use of precision agriculture. Buchana et al., [5] shows that, between 2016-2018, 52.9% of the agriculture industry, 18.3% of the forestry industry and 0% of the fishery industry makes use of precision agriculture.

Agriculture is considered as the largest industry in South Africa compared to forestry, and fishery industries. In 2017, animals and animal products made up 52% of the total South African agricultural income of which pigs were the third most sold animals [6].

Despite the success of precision agriculture, there is limited research on farm livestock management support systems in Sub-Saharan Africa, suggesting a major research gap [7]. This suggestion motivates the research to cast a larger initial focus by expanding to a global search before contextualizing the findings to Sub-Saharan Africa. Therefore, the aim of this paper is to conduct a systematic literature review (SLR) to investigate studies that pertain to precision agriculture applied in the swine industry.

This paper comprises of an overview on the methodology (section 2), followed by the results (found in Appendix A), findings (Section 3), and conclusions and recommendations (Section 4).

2 RESEARCH METHOD

For this study a systematic literature review (SLR) is conducted [8].Furthermore, this took the form of a scoping SLR, to allow for the investigation of available literature to scope and understand the current state of precision agriculture applied in the swine industry.

The sequence and grouping of the steps into research phases are captured in Figure 1, while the detail of each step is as follows:

- Step 1: Develop a research purpose and/or objective – Clearly state the goal of the SLR.
- Step 2: Develop research protocol – Create a research protocol that includes the purpose, inclusion criteria, exclusion criteria, databases, keywords and quality assessment criteria.
- Step 3: Establish relevance criteria – State the reasoning for if a resource is relevant to this study.
- Step 4: Search and retrieve the literature – Conduct searches on applicable scientific databases to find literature.
- Step 5: Selection of studies – Use the inclusion and exclusion criteria to select studies.
- Step 6: Quality assessment for relevant studies – Assess the quality of each paper.
- Step 7: Data extraction – Extract relevant information from the papers.
- Step 8: Analysis and synthesis of findings – Analyse and synthesise the data from the papers in order to find themes and patterns.

- Step 9: Report – Report the review in detailed results.
- Step 10: Dissemination – Publish the SLR

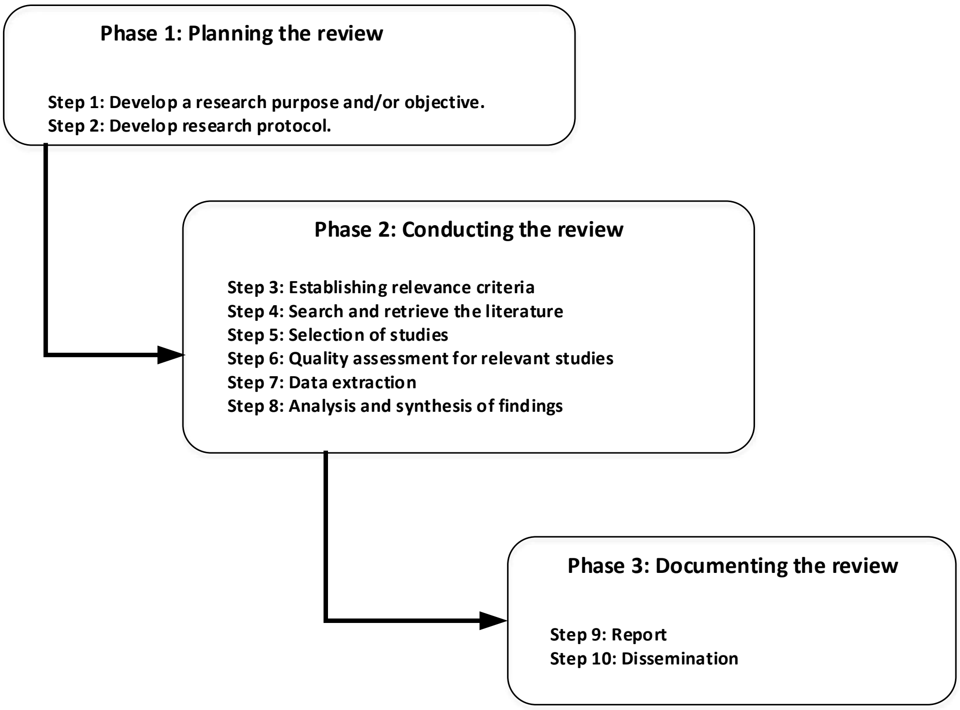

Figure 1: Research method for SLR (Adapted from [8])

2.1 Step 1: Develop a research purpose

The purpose of this research is to investigate studies on precision agriculture applied in the swine industry.

2.2 Step 2: Develop research protocol

The research protocol was developed and is shown in Table 1. The protocol breaks down the purpose, criteria, databases, keywords and quality assessment criteria.

Table 1. Research protocol

Purpose of the Study	To investigate studies on precision agriculture applied in the swine industry.
Inclusion Criteria	• Literature that contains "Precision", "farming", "agriculture", "Pig". • Time period for searched literature 2019-2023 • The explanation of techniques, tools, method, concepts in precision farming or agriculture is provided. • Information and communication management systems (ICM)
Exclusion Criteria	• Literature referring to other types farming. • Precision technology used in industries other than agriculture. • Non-English literature • Literature that relates to the advancement of technology

Search Databases	• Science Direct • Scopus • IEEE Explore • Web of Science • Emerald Insight Journals
Keywords	"Precision farming" OR "Precision agriculture" AND "Pig"
Quality assessment criteria	• All duplicate literature must be removed. • Negative results/findings are presented. • The conclusions are reliable and relate to the purpose of the study. • The aim or purpose of the study is clearly stated. • The overall methodology used is described in such a manner that the study can be replicated.

2.3 Step 3: Establish relevance criteria

The following relevance criteria was developed in order to screen studies for inclusion and exclusion:

- Inclusion criteria:
    - Literature that contains "Precision", "farming", "agriculture", "Pig".
    - Time period for searched literature 2019-2023
    - The explanation of techniques, tools, method, concepts in precision farming or agriculture is provided.
    - Information and communication management systems (ICM)
- Exclusion criteria:
    - Literature referring to other types farming.
    - Precision technology used in industries other than agriculture.
    - Non-English literature
    - Literature that relates to the advancement of technology

2.4 Step 4: Search and retrieve the literature

The search and retrieval of the literature was done on the databases captured in Table 1. The initial search yielded 431 studies. The search and retrieval process that was followed, is documented in the “Identification” section of Figure 2.

2.5 Step 5: Selection of studies

After reviewing the abstracts and titles of the studies 34 studies were deemed eligible for inclusion using the criteria stated in table 1. The outcome of the selection process is captured in the “Screening” and “Eligibility” sections of Figure 2.

2.6 Step 6: Quality assessment for relevant studies

After all duplicates were removed, the quality of the studies were assessed using the assessment criteria outlined in Table 1. Studies were selected for inclusion. A total of 34 studies were finally used. Figure 2 captures step 4 through to 6 of the selection process, as discussed in section 2.4 – 2.6 (refer to Figure 1).

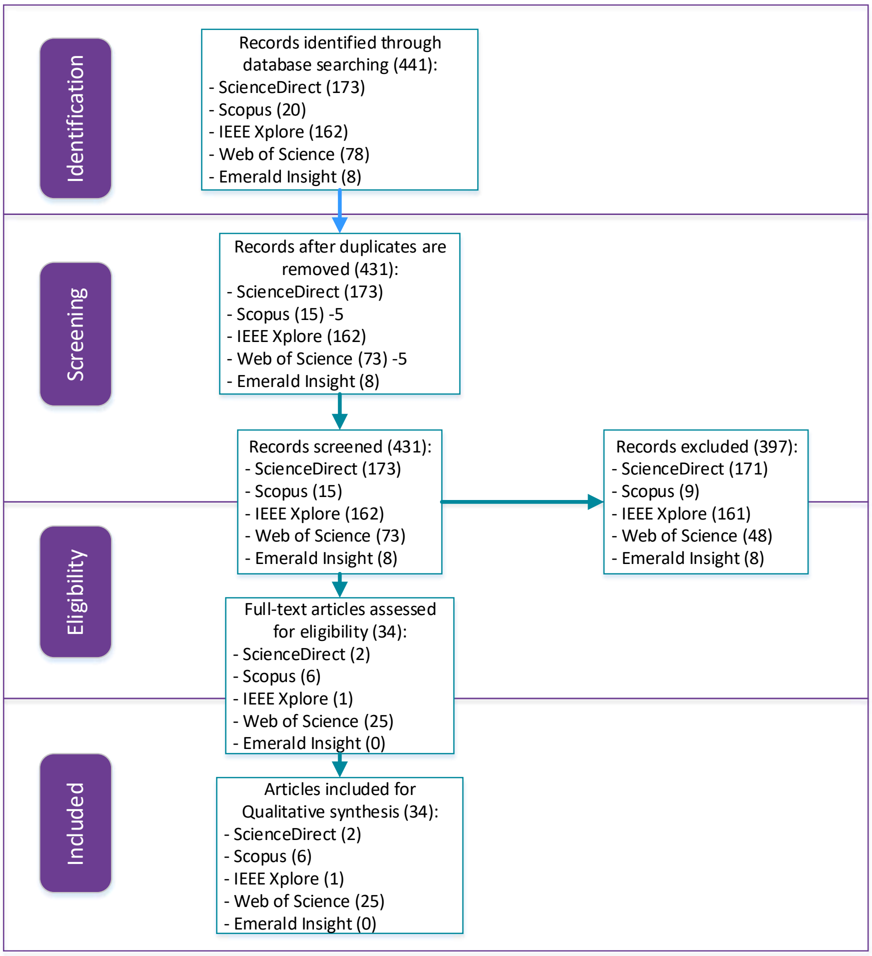

Figure 2. Systematic Literature Review (SLR) selection process chart

3 FINDINGS

The findings (step 7 and 8 in Figure 1) from the SLR methodology are discussed in the following sub-sections.

3.1 Step 7: Data extraction

After reviewing the literature a table was completed to capture and summarize technologies used, strategies/tools/techniques/methods/concepts, enablers and barriers to the implementation and use of the technology, as well as the core findings of the studies (Refer to Table 4 in Appendix A).

3.2 Step 8: Analysis and synthesis of findings

Using the research protocol described in Table 1, 34 publications were identified and used for analysis and synthesis. Findings include themes such as authors affiliated countries, distribution of publications per year, identified technologies, identified strategies, enablers, and barriers.

3.2.1 Authors affiliated countries of publication

Figure 3 illustrates a map distribution of authors' affiliated countries publications. Per continent, it was found that 10 studies are affiliated to North America, 10 to Europe, 17 to Asia, and 1 to Australia. More specifically, 13 studies are affiliated to China and 7 to the United States of America (USA). This suggests that China and USA are leaders in researching pig precision farming. Interestingly, no pig precision farming research has been found that is affiliated with Africa.

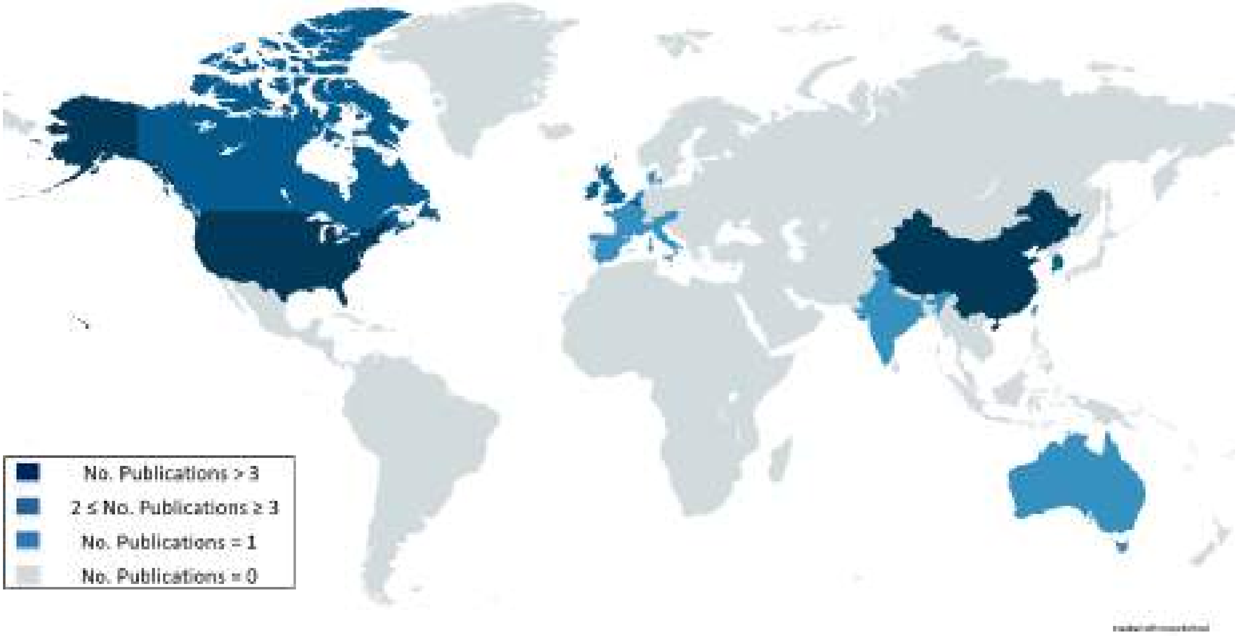

Figure 3: Map distribution of authors' affiliated countries of publication

China, The European Union, and USA are the top 3 global pork producers in 2022 and 2023 [9], which correlates with the map distribution of published research in pig precision agriculture techniques illustrated in Figure 3. It is important to note that given the research protocol (refer to Table 1), no studies were found within the South African context, specifically.

3.2.1.1 Distribution of Studies

Figure 4 illustrates the distribution of publications per year. Figure 4 illustrates that there is an increase of research in pig precision agriculture under the research protocol deployed the past 5 years. It is important to note that the low number of publications for 2023 is attributable to study being conducted in this year.

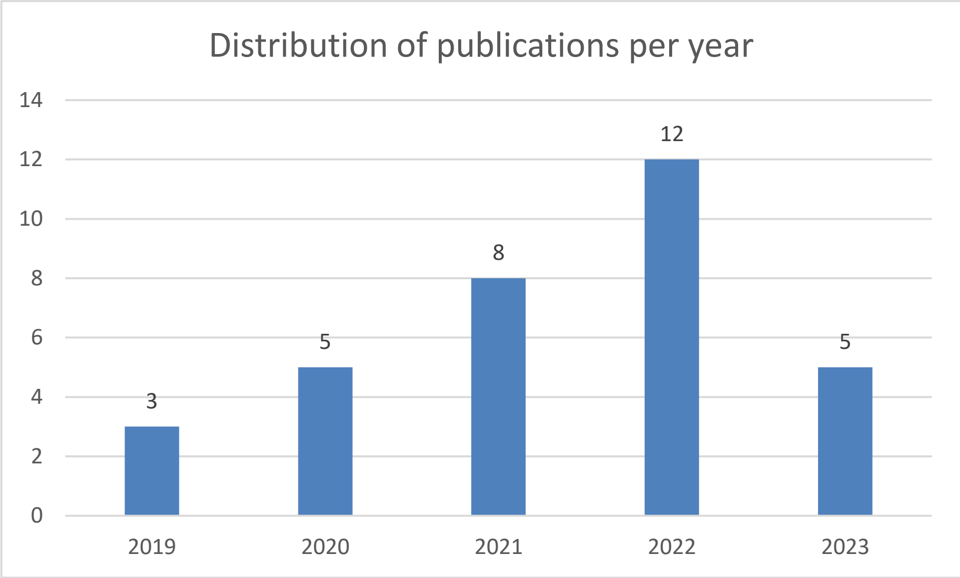

Figure 4. Studies published per year

This increase may suggest that there is an increase of interest in applying precision agriculture in the pig farming industry.

3.2.1.2 Identified Technologies

Table 2 includes brief descriptions of identified technologies. In general, the technologies involve the acquisition, processing, and analysis of data.

Table 2. Brief descriptions of identified technologies

Technologies	Brief Description
Thermal/infrared imagery	Infrared imagery is used to indicate pig growth efficiency, health and to improve pig identification.
Precision feed stations	Precision feed stations are used to indicate pig growth efficiency and to acquire data for relevant feed consumption indicators.
IoT systems	This technology involves the acquisition, management, and visualization of data for effective decision-making purposes.
Artificial Intelligence (AI)	AI is used for data analysis purposes and to improve pig detection.
Computer Vision systems (CVS)	CVS involves remote pig weighing and body weight prediction using camera recordings.
Deep learning software	Deep learning is a machine learning method that improves pig detection by analysing acquired data.
Coding Software	Coding software are platforms for development of data acquisition, and processing i.e., Matlab, RStudio, Visual Studio.

Sensors and Scanners	Several sensors and scanners are found in the SLR and are used to acquire data relevant to the purpose of the study i.e., humidity, temperature, motion, pressure, photoelectricity etc.
Cameras	Similar to sensors, cameras are used to acquire data that pertains to pig behaviour, health, and growth.
Qualtrics	In one of the studies, Qualtrics is used as a survey system,

Table 2 includes cutting edge technologies which suggests that precision agriculture gives rise to data driven farming. The implementation strategy of these technologies is discussed in Section 3.2.1.3. Furthermore, the enablers and barriers of implemented technologies are discussed in Section 3.2.1.4.

3.2.1.3 Strategies/tools/techniques/methods/concepts

Various strategies, tools, techniques, methods and concepts emerged from the literature. Table 3 includes a brief description of identified strategies.

Table 3. Brief description of identified strategies

Strategy	Brief description
Implementation of data acquisition technologies (Sensors, cameras etc.)	This involves the installation of software, sensors, cameras, and other equipment or technology used for the capturing of data. In some studies, specific pigs breeds and pig sizes were selected that meets the capacity of the technology used
The acquisition of data	The process of acquiring data occurs over a set period of time where pigs interact with technologies. This process presents the opportunity to determine the durability, effectivity, usability, and accuracy of the technology used
Pre-processing of data (i.e., data enhancement)	Pre-processing of data occurs when large sets of data have been acquired and requires filtering or, in the case of images, enhancement for algorithms or efficient datasets
Processing of data (i.e., Dataset creation)	The processing of data involves the dataset creation wherein pre-processed data is stored. The structure of the set is important as it determines the efficiency of the processing of the data.
Analysis of data (Using deep learning, AI, or other algorithms)	Data analysis involves analysing the acquired data to communicate a finding depending on the purpose of the research. Some studies analysed data using algorithms to determine which algorithm is considered more accurate, where some studies used deep learning to improve the technology's detection ability.
Visualization of analysed data	Visualization of analysed data involves graphs and tables with the purpose of conveying a finding of the methods or algorithms used.

Results of different scenarios are used for comparison and verification	Several studies applied a method in different scenarios and compared findings for verification purposes.

It is worth noting, a study's strategy involved infrared technology applied to four different pig age groups to determine if there is a differentiation in results [10]. Where a different study developed a CVS for the prediction of measurement variables and compared several algorithms to identify the most accurate predictor [11]. One study's strategy involved the processing of acquired data as an input for a nutritional model. The output of this nutritional model determines the nutrient requirements of an individual pig and instructions are communicated to automatic feeders [12].

These findings indicate the various utilization of techniques and technologies, coupled with the generalized strategy included in Table 3, to improve pig growth, behaviour, and health.

3.2.1.4 Enablers and barriers for the successful use of precision agriculture in Pig farming

Figure 5 illustrates identified enablers and barriers affecting pig precision agriculture. In summary, identified enablers involve utilizing technology to acquire, manage, and report data effectively and in a manner that is useful for decision making purposes. However, data inaccuracies, the impracticability of precision technologies, and farmer scepticism act as barriers to the adoption of pig precision agriculture. These barriers are further detailed in Appendix A relevant to the study.

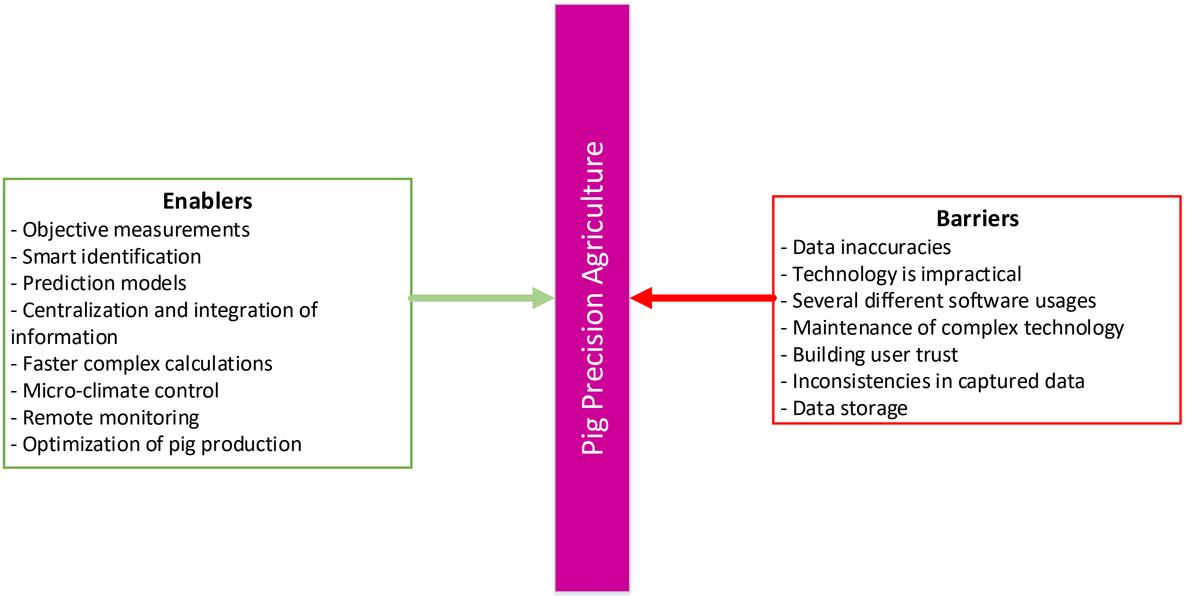

Figure 5. Identified Enalers and Barries for Pig precision agriculture

One study found that developed countries have the ability to invest in agricultural research and development projects where developing countries do not. This barrier for developing countries may serve as a reason for lack of published research in Africa (refer to Section 0).

4 CONCLUSIONS AND RECOMMENDATIONS

This paper conducted a systematic literature review (SLR) to investigate studies that pertain to precision agriculture applied in the swine industry. It was found that China, the Europe, and the USA are leaders in researching pig precision farming which is understandable as these leaders are the top 3 global pork producers. Moreover, there is a growing interest of research in pig precision agriculture the past five years which suggests the increase of pig precision agriculture technique applications.

The SLR finds numerous technologies that are used for acquiring, processing, and analysing data. The technologies integrate with strategies used by researchers which involves the implementation of these technologies, the management and analysis of acquired data, and visualization of analysed data for discussion purposes. Discussions included enablers and barriers experienced by researchers where it was found that precision agriculture technologies assist farm operations to be done remotely, and automatically. However, failure of adoption remains a barrier due to events such as data inaccuracies, impractical technology, farmer scepticism and more.

Although IoT technologies bear several benefits for pig farmers, to mitigate the barrier of failed adoption, further research in technology usability and data accuracy is required in the technological development space of IoT to implement and realise benefits in pig farming operations.

The research synthesis shows that there is a growing interest in pig precision agriculture which agrees with the trend of the growing precision agriculture market. However, this study did not find relevant published articles that are affiliated to South Africa, or Africa, indicating a research gap in the research of pig precision farming. Yet, a barrier that South Africa may face is the lack of investment in agricultural research and development projects. Pig precision agriculture can be seen as valuable for South Africa due to the growing pork production market due to the benefits it has, but for efficient implementation further research, and investment in research and development projects may be needed.

It is recommended that investigation into the application of IoT in the administrative space of pig precision agriculture is explored. In addition, it is recommended to investigate the impact of IoT on the pig value chain.

This study highlighted the growing global interest of pig precision agriculture and the research involved in the implementation of IoT systems on pig farms. Pig farmers consider several variables that influence decision making and IoT enables the integration of these puzzle pieces to build the larger narrative. Effective decision making will have a ripple effect, improving the larger and more complex puzzle of an inefficient value chain. The study contributes one piece to the puzzle of the implementation of precision agriculture techniques.

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APPENDIX A

Table 4. Data extracted from applicable studies

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
1	Shi Shuaia, Yin Linga, Liang Shihao, Zhong Haojie, Tian Xuhong, Liu Caixing, Sun Aidong, Liu Hanxing	2020	China	Research on 3D surface reconstruction and body size measurement of pigs based on multi-view RGB-D cameras	Thermal imaging	Measuring of pig size using a low-cost depth camera. 3D point cloud acquisition. Point clouds pre-processing and registration. Feature extraction and body size measurement.	Provides a method for objective measurement of pig size.	Data acquisition had missing data due to environmental conditions i.e., railings and pig behaviour. The technology is unfriendly to ordinary workers and needs a specialized worker for installation and maintenance.	The method used improves registration precision and increases the accuracy in the curve-fitting.	[13]
2	A.L.Schaefer , O. Iheshiulor, H. von Gaza, P. Charagu, G. Simpson, A. Huisman	2023	Canada	Thermal Profiles: Novel phenotypic measurements of animal growth and metabolic efficiency	Infrared thermography Infrared thermal scanner Nedap feed station technology Google cloud Microsoft Access MedCalc	Feed station technology and infrared thermography are used to indicate pig growth efficiency in a controlled environment.	The technological results present a correlation between animal performance and thermal biometrics. Assists in identifying top performing pigs thus channelling feed costs effectively.	The method is not useful for mid test weights for removing animals from feed stations is disruptive and stressful for the animal, negatively affecting their growth.	The results indicate that the tool is useful for reducing cost of production and greenhouse gas impact.	[14]
3	Stephan Rosengart,	2022	Germany	Characteristics of thermal	Infrared thermography	Infrared thermography of the mammary gland	The technology used does help	Using the warmest pixel	Infrared thermography	[10]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
	Bussarakam Chuppava, Lea-Sophie Trost, Hubert Henne, Jens Tetens, Imke Traulsen, Ansgar Deermann, Michael Wendt and Christian Visscher			images of the mammary gland and of performance in sows differing in health status and parity	Artificial Intelligence	is used to identify diseased sows with poor milk production. The method is applied to four different parities to determine whether there would be differentiation between PDS-affected and non PDS-affected sows or not.	identifying diseased sows.	offers a risk of inaccuracies.	coupled with precision livestock farming and smart farming can provide the tool to detect old diseased sows earlier which will assist in better piglet feeding and improved animal health.	
4	Arthur F. A. Fernandes, João R. R. Dórea, Bruno Doura do Valente, Robert Fitzgerald, William Herring, and Guilherme J. M. Rosa	2020	United States of America	Comparison of data analytics strategies in computer vision systems to predict pig body composition traits from 3D images	Computer vision systems (CVS) Elastic networks Artificial neural networks Deep learning image encoder Matlab, R, EziWeigh5i, Python, TensorFlow,	The approach involves firstly, the development of CVS for prediction of body weight, muscle depth, and back fat from top view 3D images of pigs. Secondly, the comparison of predictive approaches such as multiple linear regression, partial least squares, and machine learning techniques.	3D imaging enables easier image processing and removal of background. Results show that CVS improves the prediction of body composition in live finishing pigs.	At least three different predictive models would need to be deployed to apply the study's models in the field.	The study demonstrates the possibility to predict muscle depth and back fat with CVS in an automated setting using 3D images from farm conditions, without needing to pre-process images.	[11]
5	Zhiwei Hu, Hua Yang, Tiantian Lou, Hongwen Yan	2023	China	Concurrent channel and spatial attention in Fully Convolutional Network for individual pig image segmentation	Ubuntu 16.04, 16GB Tesla V100 GPU, Adam, ImageNet, MobileNetV2, VGC16, ResNet50, ResNext50, UNet, LinkNet, FPN, PSPNet	The most suitable encoder-decoder combination is identified through evaluating several encoder and decoder structures. A novel model that combines channel with	The method used improves the distinguishing of the pig area from the background and the outline of the pig is clearer in captured images.	While the study was conducted, it was found that debris, light intensity, and grouped pigs provide challenges for accurate segmentation.	The study shows that concurrent channel and spatial attention can capture contextual information effectively resulting in	[15]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
						spatial attention information is proposed. The model is implemented on an individual animal and then to a grouped pig environment. The results of implementation in different scenarios is used as verification.			performance gains. The study found that spatial attention is more effective than channel attention. The study's model can be moved to complex scenarios	
6	Rachel Schambow, Yoder Colin, Wright Dave, Daniella N. Schettino, and Andres M. Perez	2022	United States of America	Enhancing passive surveillance for African swine fever detection on U.S. swine farms	Qualtrics	The study characterized regularly collected swine data and disease surveillance activities. It then explored how characterized activities can be used for ASF surveillance. Lastly, it identified how advancing swine industry technologies and initiatives for disease preparation could be used to improve ASF surveillance.	The study found that management software usage is high across all farm types in the U.S which can facilitate API connections, smart phone devices, and the uploading of a centralized management software.	Software usage varied greatly which may hinder the development of a uniform, data-monitoring EPS protocol.	Results from the study demonstrate the potential role for enhanced passive surveillance (EPS) to improve African Swine Fever detection in the United States.	[16]
7	Eduarda M. Bortoluzzi, Mikayla J. Goering, Sara J. Ochoa, Aaron J.	2023	United States of America	Evaluation of Precision Livestock Technology and Human Scoring of Nursery Pigs in a	NUtrack system, Dell-Alienware GPU, RStudio	The sensitivity, specificity, and area under the curve (AUC) of the curve of skilled technicians to correctly identify induced sick pigs from control pigs	The study discusses that the precision technology had less false positive and negative identifications	The technology does not facilitate a moderate disruption of pig behaviours hinders the	The introduced technology in combination with timepoint human observations may act as an optimum system for semi-	[17]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
	Holliday, Jared M. Mumm, Catherine E. Nelson, Hui Wu, Benny E. Mote, Eric T. Psota, Ty B. Schmidt, Majid Jaberi-Douraki, and Lindsey E. Hulbert			Controlled Immune Challenge Experiment		using time point sampling was established. Furthermore, the evaluation of the sensitivity, specificity, AUC, and cut-off values of behavioural outputs that were continuously collected by visually based precision technology.	than human observations.	technology's identification ability.	real time sick pig identification.	
8	Giovani Trevisan, Kent J. Schwartz, Eric R. Burrough, Bailey Arruda, Rachel J. Derscheid, Michael C. Rahe, Edison de Souza Magalhães, Marcelo N. Almeida, Rodger G. Main, Daniel C. L. Linhares	2021	United States of America	Visualization and application of disease diagnosis codes for population health management using porcine diseases as a model	SAS, R, Power BI	Data to capture was first structured and then captured. This captured data was then prepared for visualization. A connection was established between prepared dataset and the visualization platform where reports were visualized.	Visualization and coding tools have flexibility which is helpful for users.	Visualization tools should be user friendly so that meaningful visualizations can be developed for decision-making purposes.	Insights made from data visualizations can be used to optimize the diagnostic process and help guide and monitor interventions for improved animal health.	[18]
9	S.A. Shaik Mazhar, G. Suseendran	2021	India	Precision Pig Farming Image Analysis Using Random	Kinect sensor, Camera, R, Python	The study followed a process of Image input which involves the acquisition of images, acquired images are	A neural network and big data makes the process of calculating pig weight	Picture images were shallow on numerous pigs which caused errors with	The study increased the robustness of predicting pig	[19]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
				Forest and Boruta Predictive Big Data Analysis Using Neural Network and K- Nearest Neighbor		then processed, data captured from processed images are analysed which results in the opportunity of decision making.	estimation, captured from images, quicker.	statistical results.	weight and growth.	
10	Alessia Dianaa, Lenn Carpentierc, Deborah Piettec, Laura Ann Boylea, Daniel Berckmansc, Tomas Nortonc	2019	Ireland, Belgium	An ethogram of biter and bitten pigs during an ear biting event: first step in the development of a Precision Livestock Farming tool	2 Panasonic camera's	The study developed an ethogram of ear biting behaviour. Through observing the developed ethogram, researchers sought for behavioural features for the development of an algorithm to monitor ear biting behaviour continuously.	The technology shows the potential development of an intervention strategy that monitors ear biting behaviour and escalation prevention.	A third of ear biting instances were incompletely identified by an ethologist because the bitten pig did not react, or the action of ear-to-mouth did not occur. This suggests that future technologies may encounter similar problems.	A combination of biter behaviours and bitten pig responses can be used as variables in an algorithm. Furthermore, the duration of non-vocal behaviour is explored to automatically extract mentioned variables from video recordings.	[20]
11	Nicholas J. Black, Luis E. Moraes, Andreia G. Arruda	2021	United States of America	Association between different types of within-farm worker movements and number of pigs weaned per sow in U.S. Swine farms	Pig Champ Pro Europa, STATA 15	The study utilized an internal movement monitoring system beacon sensor technology to describe farm-worker movements. From the data captured, the study investigated the association of farm-worker movements and	The monitoring technologies have shown the impact of internal biosecurity on farm-worker movements which may affect measures of productivity.	Sensor inoperability may have caused bias in the study. Moreover, the lack of direct oversight of compliance to the internal movement monitoring system may have	Internal movement monitoring technologies can be successfully applied in the field.	[21]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
						number of pigs weaned per sow.		introduced misclassification bias.		
12	Ali Alameer, Stephanie Buijs, Niamh O'Connell, Luke Dalton, Mona Larsen, Lene Pedersen, Ilias Kyriazakis	2022	United Kingdom, Ireland, Denmark, Belgium	Automated detection and quantification of contact behaviour in pigs using deep learning	GoPro cameras, Adobe Premier Pro., Monacar infrared surveillance cameras, Microsoft video codec, YOLO detector, Matlab R2021a, Ubuntu 20.04.2 LTS	The study developed an automated system that quantifies frequency of pig head-to-rear contacts. Furthermore, it proposes a system that identifies complex body parts.	The method provides a means for timely intervention of behavioural changes that occur due to health and welfare compromises.	The method shows a higher rate of incorrect classification for pens with higher pig interaction rates which is due to pig-to-pig occlusions.	The study's method enables quantifying interactions between group housed pigs by using machine learning, image processing, deep learning, and video surveillance.	[22]
13	AliAlameer, Ilias Kyriazakis & Jaume Bacardit	2020	United Kingdom	Automated recognition of postures and drinking behaviour for the detection of compromised health in pigs	RBG cameras, YOLO, Faster R-CNN, MatlabR2019b, ResNet-50	A whole encompassing system was developed to detect postures. From this system Pig behaviours were obtained from images. Individual pig profiles were generated from obtained pig behaviours.	Subtle changes are identified by the method used which a person observing from pen side will not be able to detect.	The proposed system does not account for the pig's head, but instead the structural features of the pig. Detection is limited to the camera field view.	Methods presented in the study automatically detect change in posture and drinking behaviours.	[23]
14	Kuan-Ying Ho, Yu-Jung Tsai, Yan-Fu Kuo	2021	Taiwan	Automatic monitoring of lactation frequency of sows and movement quantification of new-born piglets in farrowing	EfficientNet, LSTM, RetinaNet, SORT, wide-angle USB camera, Pytorch toolbox, ResNet101	The study built embedded systems to acquire the videos. These videos were then transmitted to a cloud server. Videos on the server were converted to images. Software was trained to recognize the	The proposed method is objective and automatic making observation quicker and less labour-intensive.	Some Piglets were partially occluded by metal railing or heat lamps.	The proposed automated method recognizes the lactation behaviour of sows. Moreover, it tracks and quantifies the movements of	[24]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
				houses using convolutional neural networks		behaviour of lactation sows and localize piglets. Once, training was complete, piglets were then tracked.			individual piglets in complex videos.	
15	Hengyi Ji, Jionghua Yu, Fengdan Lao, Yanrong Zhuang, Yanbin Wen and Guanghui Teng	2022	China	Automatic Position Detection and Posture Recognition of Grouped Pigs Based on Deep Learning	YOLOX, YOLOv5, Hikvision 2D camera, LabelImg, SimOTA,	The study established a human annotated dataset captured by a 2D camera. Data captured was processed to mitigate the problem of class imbalance. Processed data was used to create an automatic recognition algorithm for pig posture and behaviour.	The lack of a class in a dataset was improved resulting in better recognition of pig sitting postures therefore improving data quality.	The learning ability of technology used may be insufficient if more pigs than accounted for in the study are in camera view.	The proposed method meets the needs of pig position detection and posture recognition in pig production farms. Moreover, it addresses the challenge of automatic recognition of sitting postures among grouped pigs.	[25]
16	Santosh Pandey, Upender Kalwa , Taejoon Kong , Baoqing Guo , Phillip C. Gauger, David J. Peters and Kyoung-Jin Yoon	2021	United States of America, Korea	Behavioral Monitoring Tool for Pig Farmers: Ear Tag Sensors, Machine Intelligence, and Technology Adoption Roadmap	Infrared temperature sensor, 3-axis accelerometer, gyroscope, sound sensor, Bluetooth low energy module	The study built an electronic sensor board. Tests were conducted on the built sensor boards both in the laboratory and on farm. Lastly, an investigation in possible machine learning methodologies were conducted to identify attributes of normal versus abnormal pig behaviour and behavioural pigs' well-being indicators.	Automation and integration of various swine activities in swine production.	The collection and analysis of massive qualities of field data with cross validation by farm animal caretakers is a challenge. There is also a risk of damage to the sensory board. Lastly, winning the trust of users is a highlighted challenge for technology adoption.	A electronic sensor board concept that attaches to the ear tags of individual pigs was developed to record pig activities.	[26]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
17	Maciej Oczak, Florian Bayer, Sebastian Vetter, Kristina Maschat, Johannes Baumgartner	2021	Austria	Comparison of the automated monitoring of the sow activity in farrowing pens using video and accelerometer data	IP camera, infrared spotlights, Multicam Surveillance system, SMARTBOW system, Interact and Boris labelling software, RetinaNet, Computer Vision Annotation Tool, PyTorch, ResNet-152	The study applied a state-of-the art object detection algorithm of sow activity. Accumulated data were stored in a dataset which involved data processing and data labelling. Evaluation of data was then conducted to compare measurements of sow activity between ear tag, tri-axial accelerometer, gold standard based on human observation, and automated camera-based method.	The object detection technology allows to directly measure the movement of different body parts where an accelerometer is limited to the movement of an ear.	Part of the sow's body are occluded because of the farrowing pen structure. Lighting and the position of camera's determine image quality.	Ear tag accelerometer and object detection of body and head of sows provide similar information on activity levels of animals.	[27]
18	Miguel Garrido-Izard, Eva-Cristina Correa, José-María Requejo and Belén Diezma	2019	Spain, The Netherlands	Continuous Monitoring of Pigs in Fattening Using a Multi-Sensor System: Behavior Patterns	iButton DS1922E loggers, OneWireViewer, Matlab R2018b, Compident MLB	The study distributed pigs accordingly in pens. Temperature measurements and electronic feeding stations were implemented. Captured data was then analysed	The study shows the possibility of establishing a connection between thermal parameters and intake parameters which may be useful for precision phenotyping and animal management	Results show that the rate of pig feed intake is not consistent requiring further data processing to make meaningful visualizations.	The study found that registering the high frequency of animal temperatures in a complete fattening period makes it possibles to identify individuals with different thermal patterns.	[28]
19	Kaidong Lei, Chao Zong, Ting Yang, Shanshan Peng, Pengfei Zhu,	2022	China	Detection and Analysis of Sow Targets Based on Image Vision	Azure Kinect DK, Pytorch, Ubuntu16.04,	The study first developed a sow target detection method that is based on deep learning algorithms. An assessment of two	The use of the study's method enables users to efficiently and accurately identify	Markings on the pig, the pen railing, and the drinking trough affect image segmentation	Sows in a pen can be detected through image segmentation. Moreover, identification of	[29]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
	Hao Wang Guanghui Teng and Xiaodong Du					algorithms was conducted to evaluate the algorithm segmentation and recognition performances in sow detection. Lastly, from the results of implementation of algorithms, identity and analysis of sows' behaviours, based on segmentation, was conducted.	physiological behaviours of the sow.	performance negatively.	the sow's behaviour of eating, drinking, and lying is possible.	
20	Chen Shi, Jianlong Zhang and Guanghui Teng	2020	China	Division of Pig Growth Stages According to Body Component Variation using Computer Vision	RFID tags, ground scale with pressure sensors, serial port server, binocular stereo vision acquisition system, photoelectric sensors, Embedded Vision System, relay output model, Laboratory Virtual Instrumentation Engineering Workbench Environment.	The study involved the selection and housing of pigs to be experimented on. Weight scales and relevant sensors were used to capture data. Data captured was analysed using several methods.	The system could enable automatic grouping of pigs based on data analysis results. In addition, it is a simple, low manufacturing cost structure which could be combined with precision feeding systems.	Results show that grower stages ended at different kilograms requiring further data processing to better understand the data.	The study introduces a system that monitors and manages individual pigs which collects data accurately.	[30]
21	Wim Gorssen, CarmenWint	2022	Belgium	Estimating genetics of body	DeepLabCut, Python-based Graphical User	The study combined traditional pig weighing with video analysis.	The study expands pig weighing with a	The study found that defining and scoring	Pigs' body dimensions and activity traits	[31]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
	ers, Roel Meyermans, Rudi D'Hooge, Steven Janssens & Nadine Buys			dimensions and activity levels in pigs using automated pose estimation, RFID, ground scale platform, camera	Interface, markerless pose estimation Convolutional Neural Network-based technology		computer vision system, which is able to accurately phenotype pigs body dimensions and activity traits.	behavioural read-outs in pigs is challenging to do on a large scale for application in breeding programs.	were estimated using automated pose estimation and recorded videos	
22	Charlotte Gaillard, Nathalie Quiniou, Raphaël Gauthier, Laetitia Cloutier and Jean-Yves Dourmad	2020	France, Canada	Evaluation of a decision support system for precision feeding of gestating sows	Python, automatic feeder	Farmers and Sensors collect data and store it in a database. Captured data is processed and serves as an input for a nutritional model. The outputs of the nutritional model determines the individual pig's daily nutrient requirements. Requirement instructions are communicated to the automatic feeders.	The decision support system has the potential to integrate several real-time data collections by making use of different sensors which are installed on-farm to characterize housing conditions and animal behaviour. This enables better nutrient supply and requirement decision making.	Information availability is dependent on the equipment available on the farm and the type of data collected.	The developed decision support system allows for the adaptation of the quantity and quality of daily ration's given to sows throughout gestation according to a set criterion.	[12]
23	Harry Wooseuk Ryu, Joo Ho Tai	2022	Korea, Canada	Object detection and tracking using a high-performance artificial intelligence-based 3D depth camera:	AI-based 3D depth camera, Direct X, Unity, ZED software development kit	AI-based 3D depth cameras were used to acquire 3D depth data. The captured data is processed and integrated with AI models. Results after integration are then analysed to formulate a conclusion.	AI will enable farms to detect African Swine Flu symptoms as early as possible remotely and automatically.	Object detection is generally incapable of differentiating individual objects of the same classification.	Prepared custom data sets in an appropriate model farm can train AI models for proper 3D detection. This will be critically important in operating object tracking.	[32]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
				towards early detection of African swine fever						
24	Christian Taylor, Jonathan Guy, Jaume Bacardit	2022	United Kingdom	Prediction of growth in grower-finisher pigs using recurrent neural networks	Nedap feeding station, environment control system, temperature sensors	Relevant data was captured and processed. Processed data was used to generate a dataset and served as an input for various machine learning models. Results were then analysed to formulate conclusions.	The study shows all developed models were able to predict the length of time it would take for grower pigs to reach the target finished weight.	Presented results in the paper may have limited use in the global pork industry because of the limited data available to researchers. In addition, few commercial farms can facilitate the collection of individualised daily data on pig liveweight and food consumption.	The study found that an ensemble of long short-term memory models proved the best predictor of pig growth as it utilised average daily temperatures and full daily temperature.	[33]
25	Zhixiong Zeng, Fanguo Zeng, Xiaoteng Han, Hamza Elkhouchlaa, Qiaodong Yu and Enli Lü	2021	China	Real-Time Monitoring of Environmental Parameters in a Commercial Gestating Sow House Using a ZigBee-Based Wireless Sensor Network	Sensors, Mobile devices, Wireless Sensor Network, wireless communication technology, Internet of Things, transmitting terminals	Mobile devices, Cloud servers, and transmitting terminals are installed in a gestation sow house. Sensors capture relevant data which is then processed. Processed data is communicated to the transmitting terminals which is then displayed on a web page.	The system practically contributes to monitoring the microclimate from spatial and temporal perspectives. By deploying the system, real-time monitoring and timely intervention could take place	Wired communication technology encounters problems such as difficult wiring, complex maintenance, and high costs. The capturing of data encounters null entries and requires further processing.	The proposed system, applied in a commercial gestating sow confinement building, proves to be helpful with microclimate management accurately and effectively by real-time monitoring of four environmental parameters.	[34]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
							resulting in the possibility of providing effective climactic adjustment and human labour adaptation suggestions.			
26	Yuanqin Zhanga, Jiahao Caia, Deqin Xiaoa, Zesen Lia, Benhai Xiong	2019	China	Real-time sow behavior detection based on deep learning	Infrared network camera, webcam, NVR device, MobileNet classification network, single shot multibox detection network,	Once the video of sows is taken, irrelevant features in the video are removed manually. The image undergoes further pre-processing i.e., data enhancement. Finally the image is processed and undergoes MobileNet classification and single shot multibox detection network for further image refinement.	Monitoring of sow behaviours can be done remotely.	Redundant computation and storage, which makes the extraction process tedious.	The study proposes a real-time video of sows drinking, urination, and mounting are detected by using an object detection method based on deep learning.	[35]
27	Yue Gao, Kai Yan, Baisheng Dai, Hongmin Sun, Yanling Yin, Runze Liu, Weizheng Shen	2023	China	Recognition of aggressive behavior of group-housed pigs based on CNN-GRU hybrid model with spatio-temporal attention mechanism	Hikvision camera, conv-block, Gated Recurrent Unit,	A behaviour video dataset including aggressive and non-aggressive behaviours was built and used for model training and testing. A novel model was proposed to undergo training and testing. This model's results were evaluated to determine effectivity.	Because the designed model presents a means of identifying aggressive behaviour, it enables the ability of strategic assignment of aggressive behaving pigs.	Misclassification of behaviour due to camera vie limits, lighting, and angles.	The study designed a hybrid model that consists of the spatial feature extractor module with a special feature mechanism. This model recognizes aggressive behaviour of group housed pigs	[36]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
									accurately (94.8% accurate)	
28	Qi-an Ding, Longshen Liu, Mingzhou Lu, Kang Liu, Jia Chen, Mingxia Shen	2022	China	Social density detection for suckling piglets based on convolutional neural network combined with local outlier factor algorithm	camera, network hard disk recorder, switch, local server, Python 3.7, PyTorch 1.7, OpenCV 4.1, YOLOv5	A system of data acquisition is implemented at each farrowing pen. Acquired data undergoes pre-processing and dataset creation. A piglet detector is developed that makes use of the created dataset for functionality.	The method enables the analysis of piglet distribution and the relationship between piglet growth and social status.	The method encountered false detections which influences the accuracy of detection. Data has inaccuracies due to piglet deviations which makes social density detection inaccurate.	The study quantified social density of piglets which achieved detection of piglet clusters, non-clusters, and outlier piglets.	[37]
29	Jinxin Chen, Jie Zhou, Longshen Liu, Cuini Shu , Mingxia Shen and Wen Yao	2023	China	Sow Farrowing Early Warning and Supervision for Embedded Board Implementations	cameras, a network hard disk video recorder (NVR), a switch, and a local server, Power over Ethernet, Python, OpenCV, YOLOv5s-6.0, Jetson Nano, TensorRT,	Cameras are installed over farrowing pens. Recorded video are transmitted to an Ethernet switch and stores videos on a network video recorder. The videos are manually screened and processed into image data. Image data undergoes data labelling and data enhancement. Enhanced data is used as a dataset for an Object-Detection algorithm	The method is low cost, low latency, high in efficiency, is easy to implement, and enables breeders to transition to intelligent pig breeding. The detection of new-born piglets and the communication thereof increases the survival rate of piglets.	Missed and false detection sow postures is affected by the change of light.	The study proposed a method that automatically predicts and detects of sow farrowing duration using an embedded development board which includes and early warning of approaching farrowing and farrowing behaviour supervision.	[38]
30	Haiming Gan, Chengguo Xu, Wenhao Hou,	2022	China	Spatiotemporal graph convolutional network for	Camera, Labelme, Pytorch	Piglets are first detected and tracked using software in the authors' previous study. A convolutional	The method incorporates different types of social behaviours associated with	It was found that piglets that engage in playing behaviours move	The study shows a positive detection performance detecting body part associated	[39]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
	Jingfeng Guo, Kai Liu, Yueju Xue			automated detection and analysis of social behaviours among pre-weaning piglets		neural network node detector is used to precisely detect piglet body nodes. Acquired data undergoes classification of suspected behaviour. Experiments are conducted to validate the feasibility of classification.	different body parts which enables piglet behaviour analysis.	their bodies rapidly resulting in image problems such as motion blur.	social behaviour in piglets using graph convolutional networks which also demonstrates the feasibility of the method used.	
31	Elanchezhian Arulmozhi, Anil Bhujel, Byeong-Eun Moon and Hyeon-Tae Kim	2021	Korea	The Application of Cameras in Precision Pig Farming: An Overview for Swine-Keeping Professionals		A literature review is conducted.	Technological developments provide a solution to the food insecurity challenge in developing countries. The review suggests that solving multiple issues in one system, fewer sensors, affordable price, reliability, and easy handling increases the adoption rate ,and improves production and quality.	The review found that there are significant differences between models and ground level occurrences. Models also do not account for regional-level genetics which could have a user apply an incorrect algorithm affecting results. Data captured from video recordings produces large amounts of data points making it expensive. Integrated technological	The review finds that in the future, Artificial Intelligence algorithms for automatic monitoring, control, and overall management will be depended on by farmers. Furthermore, developed countries have the ability to invest agricultural R&D, but developing countries do not.	[40]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
								systems cannot solve multiple issues.		
32	Shunli Wang, Honghua Jiang, Yongliang Qiao, Shuzhen Jiang, Huaiqin Lin and Qian Sun	2022	China, Australia	The Research Progress of Vision-Based Artificial Intelligence in Smart Pig Farming		The study summarizes summarises research progress of Artificial intelligence in pig farming.	Intelligent analysis systems transforms data of animal response characteristics into key indicator information and can analyse transformed data using AI and machine learning for farm management decision making. These systems enable pig farmers to optimize production/reproduction processes to avoid over-feeding, waste reduction, cost reduction, and make livestock farming more sustainable economically, socially, and environmentally.	Technology reliability, ease of maintenance, and use of intelligent devices remain a challenge. In practice, lack of large high-quality datasets and data standards are a challenge due to pig farms growing and increases of data captured.	Modern farming utilizes sensors for temperature, weighing, and tracking pigs to capture data about the pig environment or pig. Moreover, for the same purpose 2D and 3D cameras are used.	[41]
33	Chun-Peng J. Chen, Gota Morota, Kiho Lee, Zhiwu	2022	United States of	VTag: a semi-supervised pipeline for	Python OpenCV, laptop controlled camera, Intel	Data acquisition is done with video cameras. Successful tracking algorithms are	The Vtag does not require laborious work in setting up the training	Trackers lost tracking the correct pig due to frequent	The study proposes a semi-supervised pipeline, VTag,	[42]

#	Author(s)	Year	Country	Title	Technologies	Strategies/tools/techniques/methods/concepts	Enablers (success)	Barriers (failure)	Core finding	ref
	Zhang and Hao Cheng		America	tracking pig activity with a single top-view camera	RealSense Viewer, YOLOv5, Mask R-CNN, Sparse Optical Flow, multiple instance learning, channel and spatial reliability	implemented that learn representatives from the object of interest and find the similar image region in the next input video frame. Results are evaluated.	system. The system enables individual-level activity per unit time and walking speed measurements. In addition, it enables the monitoring of tail biting behaviour.	interactions between two pigs in a short period. Moreover, video quality adds to this problem.	that can track pigs in video recordings. Minimal human supervision is needed for adequate precision.	
34	Chong Chen, and Xingqiao Liu	2019	China	An intelligent monitoring system for a pig breeding environment based on a wireless sensor network	Wireless Sensor Network, Sensors, ASP.NET, Matlab, Visual Studio 2012	Sensors are implemented that acquire relevant data. Acquired data is stored and managed. Managed data is communicated to users and analysed for decision making purposes.	The system provides high quality and efficient control of environment temperature and humidity.	The system endures long calculation times, consumes a lot of computer memory, and has difficulty in modifying control rules.	An intelligent control system for livestock was developed which improved piggery environmental quality, and pig welfare.	[43]

MOO-VING TOWARDS OPERATIONAL EFFICIENCY: A VENN DIAGRAM APPROACH TO FACILITY LAYOUT DESIGN AND CATTLE HANDLING PRINCIPLES

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ABSTRACT

In today's fast-paced and highly competitive industrial landscape, achieving optimal efficiency is the key to success. This review compares the fundamental facility layout design principles of industrial engineering with those of cattle handling facilities. This comparison is achieved through an integrative literature study on facility layout design principles, consisting of 1) a narrative literature review on industrial engineering principles and 2) a rapid systematic review of cattle handling facility design principles. By examining these principles side by side, we aim to identify the correlations and variations that exist and unearth opportunities for mutual enrichment and interaction between these seemingly disparate fields, to enhance both operational efficiency and improved production. A Venn diagram has been constructed to illustrate the relationship between these principles. This review offers valuable insights for industrial engineers, livestock managers, and researchers seeking innovative approaches to optimise operational performance and improve facility layout designs in diverse industrial and agricultural settings.

Keywords: cattle handling, facility, layout, design, principles, industrial engineering

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1 INTRODUCTION

The pursuit of operational excellence and efficiency is a constant challenge. Organisations are continually seeking innovative ways to streamline their operations and enhance productivity [1]. While many factors contribute to overall efficiency, one aspect with significant implications is the facility layout of such organisations. The importance of a well-designed facility layout cannot be overstated as it directly impacts the overall functioning of a physical workspace. This holds true not only in industrial settings but also in the intricate world of agriculture. It goes beyond mere aesthetics and holds the power to reshape workflows, reduce bottlenecks, and maximise resource utilisation [2].

Cattle feedlots are a specialised type of agriculture operation focusing on managing, raising, growing, and fattening cattle until they reach slaughter weight for meat production [3]. The advantage of feedlots is raising a large number of cattle on less land with fewer inputs, which results in maximum production at minimum cost. Feedlots strive for better productivity to drive profitability while ensuring animal welfare. Handling facilities are needed at feedlots to guide cattle in the desired direction for sorting, feeding, and handling. Cattle handling facilities demand a specialised set of design principles focussing on animal behaviour to ensure animal welfare, worker safety, optimised handling processes, and minimised stress on the cattle [4].

The heavier the cattle in weight, the better income they will receive if cattle are sold as beef. Thus, proper design, maintenance, and operation of these facilities can help minimise stress injury and improve the overall productivity and profitability of the livestock producers [5]. Therefore, it becomes imperative for feedlot operators to carefully consider the design and layout of their facilities, taking into consideration the unique needs of the cattle they handle.

Unfortunately, sometimes feedlot facilities fall short of meeting these objectives resulting in an inefficient facility layout that inhibits the flow of cattle. A poor facility layout causes bottlenecks to form in the corrals and cattle chutes leading to unnecessary stress on cattle. Elevated stress levels of cattle lead to increased rates of injury and a reduction in production (growth), leading to economic losses [6]. Furthermore, a poor facility layout will increase labour costs and increase the risk of potential safety hazards to workers [4].

In a similar vein, industrial engineering facility layout principles revolve around strategically organising machinery, workstations, people, and resources to achieve maximum operational efficiency. By applying these principles, industries have successfully improved workflows, reduced operational bottlenecks, and enhanced overall productivity [7].

Both the manufacturing industry and feedlots require proper facility layout to achieve operational excellence. However, there is a significant gap in research regarding the integration of industrial engineering and cattle-handling facility design principles.

By elucidating the parallels, industrial engineers can gain new perspectives on facility layout design by embracing the unique challenges and principles of cattle handling. The specialised considerations in cattle handling can offer novel insights into the design and optimisation of facility layouts in industrial settings. Simultaneously, it can demonstrate how the application of industrial engineering facility layout design principles can enhance cattle handling practices at feedlots.

The aim of this study is to investigate the relationship between industrial engineering facility design principles and cattle handling facility design principles. By comparing these principles, we can uncover the potential synergies, determining how they can mutually reinforce and contribute to one another, in the pursuit of better production and increased profitability.

The next section explains the method that was followed, while section 3 and 4 provide the findings and discussions. The review is concluded in section 5, with future research recommendations stated in section 6.

2 METHOD

An integrative literature review was utilised for this study as it is a method that seeks to summarise and synthesise existing knowledge and theories across literature to provide a comprehensive understanding of a topic [8]. It allows for generating new perspectives on a topic and resolving inconsistencies in literature by combining different literature review studies [9].

This method was followed to establish the possible correlations and variations between cattle handling and industrial engineering facility design principles. The findings of a 1) rapid systematic literature review and 2) a narrative literature review, were integrated to identify relationships concerning the respective principles.

2.1 Integrative literature review

The integrative literature review followed the 5-stage framework by Whittemore and Knafl [8] and is illustrated in Figure 1.

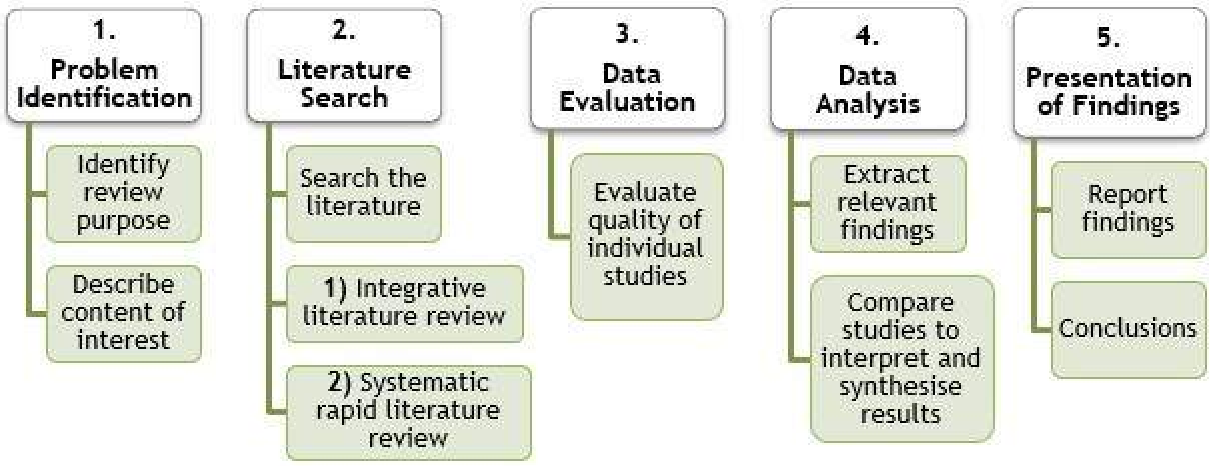

Figure 1:Integrative review methodology framework (Adapted from Whittemore and Knafl [8])

2.1.1 Stage 1: Problem identification

An integrative literature review was done to acquire practical insights into industrial engineering and cattle handling facility design principles. This review aimed to bridge the gap between these facility layout design principles. It has uncovered the correlations, explored the variations, and harnessed the collective wisdom of these domains to pave the way for a more efficient, sustainable, productive, and harmonious future.

2.1.2 Stage 2: Literature search

The literature review consisted of two separate literature reviews the findings of which were compared:

1) Since abundant information is available, a narrative literature review was conducted on Industrial Engineering facility design principles. (Detail of the method followed is discussed in Section 2.2)

2) A more specific systematic rapid literature review on cattle handling facility design principles was conducted. (Details of the method followed are discussed in Section 2.3.)

2.1.3 Stage 3: Data evaluation

Data evaluation entails the evaluation of the literature from each review based on their respective evaluation criteria, which can be found in Section 2.2 and Section 2.3.

2.1.4 Stage 4: Data analysis

Data analysis requires the extraction of key information from each study and comparison of the reviews to synthesise the results [9]. This will allow for the identification of the relationship between both reviews' findings where areas correlate and vary.

2.1.5 Stage 5: Presentation of findings

The key insights derived from the findings are effectively summarised and communicated. A Venn diagram allows for the representation of the research gaps and how the findings complement one another.

2.2 Narrative literature review - Engineering facility design principles

A general narrative literature review was conducted to extract information regarding facility layout design principles within the industrial engineering field. The purpose of this review was to synthesise and analyse a wide range of literature by combining various sources to construct a coherent narrative that highlights the current body of knowledge about industrial engineering facility layout design principles [10]. The following method of Green *et al.* [10] was adapted and followed for the review.

2.2.1 Objective

The industrial engineering facility design principles applicable to various industries were identified and established. The aim was to provide a comprehensive overview of the key principles contributing to efficient facility design and optimisation.

2.2.2 Search Strategy

Various electronic databases and books were searched to explore existing research that provided a comprehensive understanding of the topic [10]. The search terms used to obtain data were "industrial engineering" AND "facility layout design principles".

2.2.3 Inclusion and Exclusion Criteria

Sources were screened based on their relevance to industrial engineering facility design principles. Relevance refers to the degree to which the information provided by the source aligns with the research topic being investigated. Inclusion criteria included sources directly addressing these principles in an industrial engineering context. Sources that did not meet these criteria or were not specific to facility design principles were excluded.

2.2.4 Selection Process

Sources were reviewed to identify relevant studies. The full texts of the selected sources were thoroughly examined to extract pertinent information related to industrial engineering facility design principles.

2.2.5 Data Extraction

Relevant data were extracted from the selected sources. The information was organised in a structured manner to facilitate further analysis.

2.2.6 Synthesis of Findings

Recurring data and key findings were highlighted to provide a comprehensive overview of the principles. The findings are summarised and analysed in section 3.1 to compare them to the findings of the rapid systematic literature review (SLR).

2.2.7 Critical Evaluation

The findings were compared with existing knowledge to ensure a comprehensive and reliable representation of industrial engineering facility design principles.

2.3 Rapid systematic literature review - cattle handling facility design principles

A rapid SLR was conducted to explore cattle handling facility design principles. The review was accomplished by searching a specific database using predetermined keywords.

The reason for the rapid SLR is to extract as much information as was available on cattle handling facility design principles in a timely and comprehensive manner while still adhering to the rigorous methodology of a traditional systematic literature review [11].

Xiao and Watson [12] provide a methodological framework for conducting systematic reviews which is embedded with verification and validation within the steps to ensure rigour throughout the process. This framework was followed for the rapid SLR and is illustrated in Figure 2.

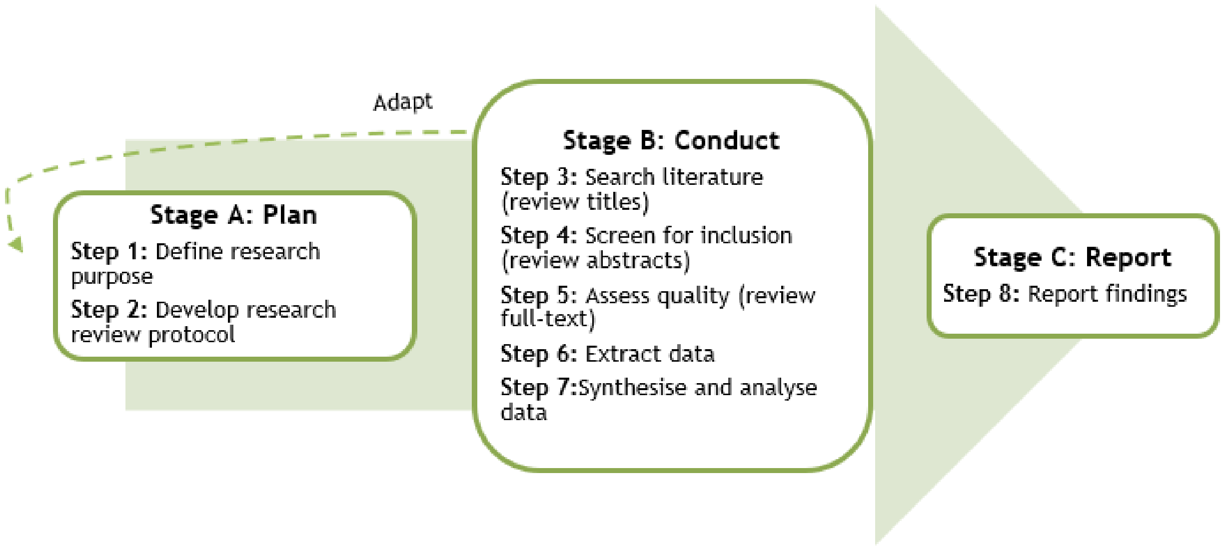

Figure 2: Method of Systematic Literature Review (Adapted from Xiao & Watson [12])

2.3.1 <u>Step 1:</u> Define research purpose

The purpose of the rapid SLR is to investigate the available literature on cattle handling facility layout design principles.

2.3.2 <u>Step 2:</u> Develop research protocol

Table 1 represents the research review protocol followed to guide the search and assess its quality. Following the protocol inclusion and exclusion criteria will remove research bias. For the rapid SLR only one scientific database will be utilised - Scopus.

Table 1: Research review protocol

Purpose of the study	To establish cattle handling facility layout design principles
Keywords	"Cattle handling" AND "facility" OR "layout" AND "design" OR "principles"
Inclusion criteria	• Literature on design principles for cattle handling facilities. • Literature on behaviour principles affecting design principles. • Literature on cattle handling facility layouts.
Exclusion criteria	• Literature that is not in English. • Cattle handling facility design literature about transportation or slaughter/abattoir. • Literature on Edu game. • Literature on dairy cattle handling. • Literature on diseases and reproductive performance. • Literature related to the biology of animals. • Literature on nutrients in animal feed.
Search databases	• Scopus
Quality assessment criteria	• Literature that provides reliable and valid information related to cattle handling principles. • The use of correct scientific methods during the research study.

2.3.3 Steps 3 to 5: Selection process

The search yielded 57 sources using the database and keywords mentioned in the review protocol. The titles of the sources were reviewed, and the inclusion and exclusion protocols were applied.

Thereafter, the abstracts of the sources were screened for inclusion using the criteria stated in the review protocol. It was determined that ten sources met the criteria after the screening of the abstracts. It was assessed based on the sources' correct interpretation of the keywords and checking the sources against the exclusion criteria. The literature that was discarded had no relevance relating to the design of cattle handling facilities. The focus of these studies relates to factors affecting bruises on carcasses, cattle behaviour during transport and slaughter and dairy cattle handling practices.

The full text of the ten sources was reviewed to determine the quality and reliability of the literature. Finally, seven sources were deemed eligible for use after quality assessment. The excluded literature was invalid and not related to cattle handling facility design principles. The literature was on an experiment conducted on designing and assessing animal welfare rather than focussing on facility layout design principles. Moreover, the literature was about the effect of stockperson handling on cattle behaviour. The process for selecting relevant sources on cattle handling facility design principles is depicted in Figure 3. It displays the different processes of the search, the number of sources found, and how this number decreased through the different selection processes.

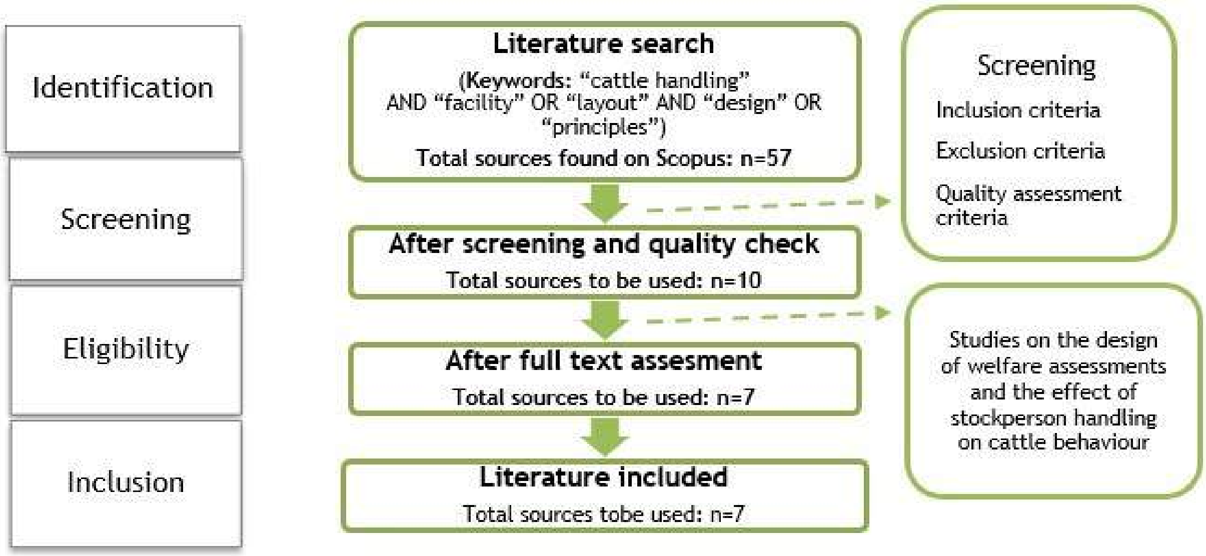

Figure 3: Selection process chart

2.3.4 *<u>Step 6:</u> Data extraction*

After the selection process, seven sources met the criteria and were eligible to be included in the study. The applicable literature on cattle handling facility design principles is presented in Table 2.

Table 2: Data extracted from applicable literature

#	Author(s)	Year	Title	Type	Ref
1	T. Grandin	1997	The design and construction of facilities for handling cattle	Journal article	[13]
2	T. Grandin	1977	Cattle handling systems for ranches, feedlots, meat packaging plants and auction yards, utilising curved and diagonal lanes	Journal article	[14]
3	D. Scott-Harp, C. Peek-Asa, D. S. Rohlman, B. Janssen	2019	More than time and money: A mixed-method study of the barriers to safer cattle handling practices	Journal article	[15]
4	T. Grandin	2014	A whole systems approach to assessing animal welfare during handling and restraint	Book chapter	[16]
5	T. Grandin	2018	Cattle welfare and principles of handling facility design	Book chapter	[17]
6	T Grandin	1980	Observations of cattle behaviour applied to the design of cattle-handling facilities	Journal article	[18]
7	T. Grandin	1998	Reducing Handling Stress Improves Both Productivity and Welfare	Journal article	[19]

2.3.5 *<u>Steps 7 to 8:</u> Data analysis and report findings*

The findings of the sources listed in Table 2 are analysed and summarised in section 3.2 so that they can be compared to the findings of the narrative literature review.

3 FINDINGS

The findings from each literature review are represented in separate tables to provide a summary and overview of the literature extracted from 1) the narrative literature review on industrial engineering facility design principles and 2) the rapid systematic literature review on cattle handling facility design principles.

3.1 Narrative literature review

Table 3 presents the findings of the narrative literature review conducted on industrial engineering facility design principles. It provides a summary of each principle, highlighting the core focus and objectives within the context of facility design.

Table 3: Industrial engineering facility design principles

Design Principles	Summary
Workflow optimisation	Optimising the flow of materials, information, and people within the facility. Designed to avoid bottlenecks and interruptions. Emphasises minimising waste and maximising productivity [20].
Operation efficiency	Related processes, inventory and equipment should be located near each other to minimise movement but also to facilitate material handling and process efficiency [20].
Lean manufacturing	Incorporate lean manufacturing principles. Focus on minimising inventory storage, creating clear visual cues, and facilitating smooth material flow [21].
Ergonomics	Considers the design of workstations and equipment to ensure optimal human performance and safety. Emphasises ergonomic principles to reduce strain and enhance worker comfort [22].
Space utilisation	Maximises the efficient utilisation of available space within the facility, ensuring optimal placement of equipment and resources. Aims to minimise empty or unused spaces and maximise storage capacity [20].
Safety	Incorporates safety measures to create a secure working environment, preventing accidents and promoting employee well-being [22].
Management	Apply supply chain principles to optimise the flow of materials, information, and resources across the facility and its external partners [21].
Flexibility	Enables easy modifications. Changes should be made with minimal interruption to production. Allows for future expansion or reconfiguration to accommodate evolving needs [20].
Accessibility	Considers the ease of movement and accessibility for personnel, equipment, and materials. Ensures efficient flow and reduces travel distances within the facility [22].

Design Principles	Summary
Visibility	Focuses on adequate ability for supervision with clear lines of sight, foot access and visibility across the facility to enhance monitoring and control [22].
Sustainability	Consider energy-efficient design principles to minimise environmental impact and reduce operating costs [22].
Economic feasibility	Finding the right balance between cost and efficiency that will contribute to overall profitability and long-term sustainability [22].
Technology utilisation	Incorporates advanced technologies, automation, and digital systems to enhance operational efficiency and streamline processes [20].
Regulatory Compliance	Adhere to industry regulations, safety standards, and building codes [22].

3.2 Rapid systematic literature review

Table 4 presents the findings of the rapid systematic review on cattle handling facility layout design principles. It summarises each principle, outlining its focus and objectives within the context of cattle handling.

Table 4: Facility design principles for cattle handling

Principles	Summary
Reduce distractions	Design facility with solid walls and floors, avoiding bright lights and shadows, helps maintain their focus and reduces anxiety during handling [13].
Reduce obstructions	Ensuring that the facility design does not include sharp edges, protrusions, or objects that could potentially harm cattle. Clear path with minimal obstructions ensures the safety of cattle [13].
Cattle flow	Visual barriers, non-slip flooring, and gradual slopes to facilitate smooth and efficient movement of cattle for handling operations. Minimises congestion, reduces handling time, and optimises the overall workflow [18].
Prioritise animal welfare	Gentle handling to reduce stress and improve the overall well-being, safety, and comfort of the cattle. It includes investing in the necessary infrastructure and resources. Providing shaded areas, proper ventilation, and non-slip flooring can further enhance animal welfare [17].
Sufficient Space	Providing enough space for cattle to move freely to allow cattle to move comfortably and avoid overcrowding, which can lead to stress and injury [14].
Adequate infrastructure	Ensure a robust and durable system capable of efficiently handling a large number of cattle, minimising the risk of breakdowns or frequent

Principles	Summary
	replacements, thereby maximising productivity and reducing long-term maintenance costs [15].
Efficient handling operations	Selection and placement of equipment. Enables efficient and safe handling, sorting, and containment of cattle. Consider resource placement to optimise the flow of handling operations while minimising unnecessary movement and resource wastage [19].
Safety	Use safety measures and protocols to minimise risks and injuries to both cattle and handlers. Ensure secure and controlled handling environments to prevent accidents or escapes [15].
Worker efficiency	Optimise layout to enhance worker efficiency during cattle handling tasks, reduce fatigue, and streamline processes. Consider factors like access to tools and clear communication [19].
Ease of cleaning	Facilitate easy cleaning and maintenance of the facility to maintain hygiene and reduce the risk of diseases. Efficient removal of waste to promote a healthy environment for cattle [14].
Low-Stress Handling Techniques	Implementing low-stress handling methods, adopting modern, humane handling practices such as calm and patient approaches, minimising loud noises, and avoiding abrupt movements helps maintain a relaxed environment for the cattle and encourages cooperative behaviour [19].
Cattle Behaviour	Incorporating an understanding of cattle behaviour into the facility design, considering their natural instincts, social hierarchy, and movement patterns [16].
Flexibility	Design for adaptability to accommodate different sizes and various types of cattle [13].
Accessibility & visibility	Workstations, equipment, and pathways designed to provide clear visibility and easy access for personnel, allowing for efficient monitoring and handling of the cattle [18].
Welfare regulations	Comply with animal welfare regulations and guidelines [16].
Training workers	Train workers to handle livestock, considering cattle flight zones, thereby minimising stress effectively and ensuring the safety of the cattle and maximising operational efficiency [19].

4 DISCUSSION

The exploration of cattle handling and industrial engineering facility design principles reveals an overlap and shared principles between the two domains. A closer examination reveals that both domains recognise the importance of layout optimisation, workflow analysis, and safety considerations.

There are notable similarities between these design principles. However, there are also variations since industrial engineering principles provide a more comprehensive approach to facility design across various industries, while cattle handling principles offer specialised insights specific to the unique challenges and requirements of handling livestock, which may not be fully captured by general industrial engineering design principles.

A visual representation of the correlations and variations amongst the respective principles is depicted in a Venn diagram (Fig 4). The correlations are further discussed in Section 4.1 and the variations in Section 4.2.

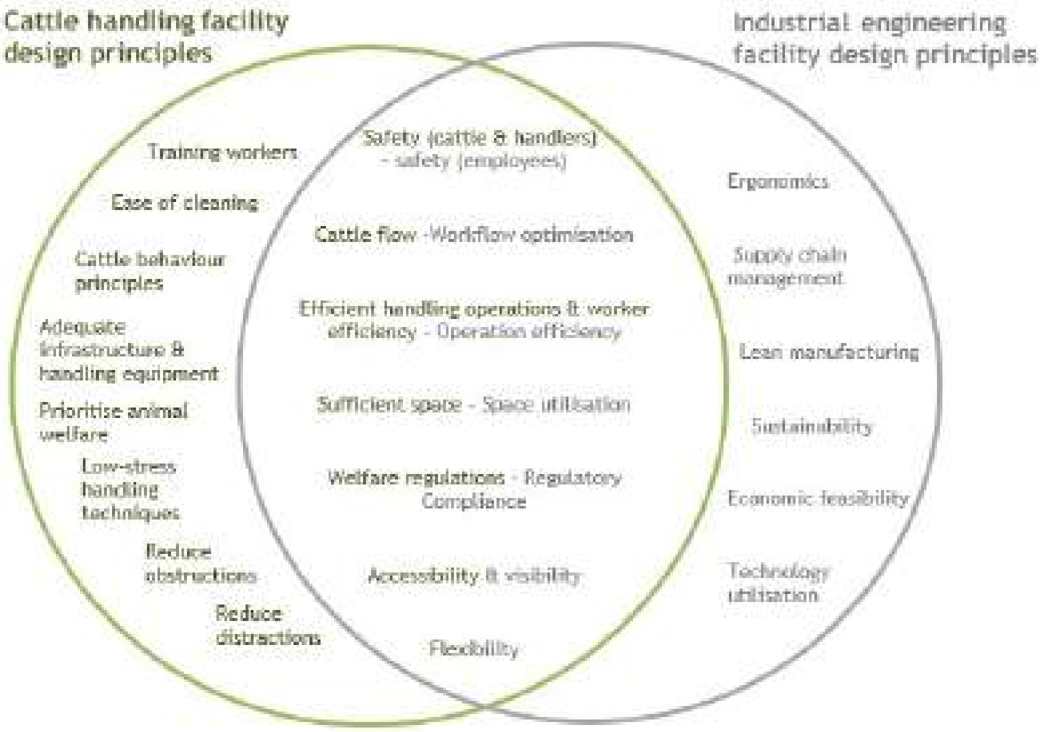

Figure 4: Venn diagram of correlations and variations between industrial engineering- and cattle handling facility design principles

4.1 Correlations

The correlations between cattle handling facility design principles and industrial engineering design principles are captured in a comparison table (Table 5). These correlations highlight the distinct objectives and considerations that shape the design principles in cattle handling facilities and industrial engineering, reflecting the specific needs and challenges of each industry.

Table 5: Correlation between facility layout design principles in Industrial Engineering and Cattle handling

Principle	Cattle handling	Industrial engineering
Safety	Incorporation of safety measures and low-stress animal handling techniques to minimise injury of both cattle and workers. Ensuring a safe working environment.	Implementing ergonomic workstations and safety measures to create a safe and comfortable working environment for employees.
Flow	*Cattle flow* - Attention to animal behaviour, cattle movement and	*Workflow* - Analysing material flow and movement patterns to minimise

Principle	Cattle handling	Industrial engineering
	designing chutes, gates, and alleys to facilitate smooth and controlled movement of livestock. (Minimise stress and congestion).	bottlenecks and streamline workflow. (Optimise process and remove waste).
Efficiency	*Handling and worker operations* - Appropriate equipment and resource placement to optimise the flow of handling operations while minimising unnecessary movement and resource wastage. (Improve livestock handling efficiency)	*Operation efficiency* - Related processes, inventory and equipment should be located near each other to minimise movement but also to facilitate material handling and process efficiency.
Space	Sufficient space - Provide enough space for cattle to move freely and comfortably to avoid overcrowding, which can lead to stress and injury.	Space utilisation - Efficiently utilise space to optimise workflow and productivity.
Regulations	Compliance with animal welfare regulations and guidelines to ensure humane treatment.	Compliance with relevant industry regulations, safety standards, and building codes.
Accessibility & visibility	Proper positioning of the equipment, infrastructure, and pathways to maximise operator visibility and accessibility while minimising distractions for livestock. (Efficient monitoring and handling of the cattle).	Considers the ease of movement and accessibility for personnel, equipment, and materials. Consideration of operator visibility to maximise productivity and minimise errors.
Flexibility	Design facilities that can handle different sizes and types of cattle.	Design for adaptability to accommodate changes in production demands.

4.2 Variations

The variations between cattle handling - and industrial engineering facility layout design principles occur due to the nature of the industries they serve and the specific objectives they aim to achieve. While both share the goal of improving operational efficiency, they differ in their primary focus areas. Cattle handling principles strongly stress the importance of animal welfare, cattle behaviour and the reduction of stress (for the animal) during handling processes. On the other hand, industrial engineering principles prioritise factors such as worker (human) ergonomics, automation and technology integration, and lean manufacturing within industrial settings. These differences stem from the distinct challenges and requirements of each industry, revealing the need for tailored approaches to facility design to meet specific objectives effectively.

4.2.1 Cattle handling principles

The literature reviews showed that cattle handling facilities employ principles in their layout design that are distinct from industrial engineering design principles. However, industries can learn from these principles:

4.2.1.1 Training Workers:

Providing proper training programmes to handlers will ensure that they have the necessary skills and knowledge to handle cattle safely and effectively. The training includes teaching workers proper handling techniques, understanding cattle behaviour, and promoting gentle and humane handling practices.

Implementing training programmes for workers in industrial settings can enhance safety protocols, reduce the risk of accidents or injuries, and improve overall operational efficiency. Well-trained workers are better equipped to handle machinery, follow procedures accurately, and make informed decisions, thereby reducing human error and optimising productivity. Moreover, training programs can foster a culture of continuous improvement, where workers are encouraged to share their knowledge, learn from each other's experiences, and contribute to the overall growth and success of the organisation. Investing in worker training in an industrial setting will enhance employee morale.

4.2.1.2 Ease of Cleaning:

The principle will permit the maintenance of hygiene and prevent disease transmission. The design includes easy access to all areas, including chutes, pens and alleys, to facilitate thorough cleaning and disinfection. Proper drainage systems and smooth surfaces will also aid in efficient cleaning processes.

The principle can be applied to various industries by ensuring hygienic and easily maintainable environments. Industries can improve cleanliness standards and maintain a safe and healthy working environment for employees.

4.2.1.3 Cattle behaviour principles:

Feedlots showcase a diverse range of physical and behavioural variations among cattle, reflecting differences in breeds, growth rates, temperaments and responses to the feedlot environment. Therefore, it is imperative to understand and account for cattle behaviour. The facility layout should align with natural cattle movement patterns to facilitate smooth flow and minimise sudden visual barriers that may cause distress to the animals.

Industries can leverage insights from cattle behaviour principles observed at feedlots to implement efficient processes within their own operations.

4.2.1.4 Adequate Handling Equipment and Infrastructure:

In cattle handling facilities, well-designed chutes, gates, and pens are necessary to facilitate smooth movement and sorting of cattle. Sturdy infrastructure is needed to ensure the safety of both animals and handlers, reducing the risk of accidents or injuries during handling.

Having adequate infrastructure and equipment in an industrial organisation is crucial to ensure the safety of employees by providing them with reliable and well-maintained machinery and facilities. It enables efficient and smooth operations, reducing downtime and maximising productivity.

4.2.1.5 Prioritise Animal Welfare:

Gentle handling is utilised to reduce stress and improve the overall well-being, safety, and comfort of the cattle. Providing shaded areas, proper ventilation and non-slip flooring can further enhance animal welfare.

Industries can learn from the animal handling environment by prioritising human welfare in an organisation. Prioritising the safety and comfort of workers will lead to improved operational efficiency and worker satisfaction.

4.2.1.6 Low-Stress Handling Techniques:

Gentle handling methods will minimise stress in cattle and encourage calm and cooperative behaviour. Minimising loud noises, sudden movements and other potential stressors are also important to keep cattle calm during handling operations.

Cattle handling principles offer unique insights into promoting animal welfare and ensuring safe and stress-free handling procedures. Industries can learn from these techniques and apply them to enhance worker safety and reduce stress in the workplace.

4.2.1.7 Reduce Obstructions:

Clear pathways, well-placed gates, and adequately designed alleys in cattle handling facilities ensure smooth and unobstructed cattle flow and the safety of cattle.

4.2.1.8 Reduce Distractions:

Avoiding visual distractions and reducing noise levels in cattle handling facilities will maintain cattle cooperation and focus during handling. Minimal distractions will result in stress free handling operations.

Creating layouts in the industry that align with natural movement patterns, minimal distractions, and obstructions can lead to improved operational efficiency.

4.2.2 Industrial engineering principles

Industrial engineers utilise principles that are distinct from cattle handling principles when designing facilities. However, these principles could be used to improve cattle handling facilities:

4.2.2.1 Principles of Ergonomics:

Ergonomics refers to designing workstations and equipment layouts that promote worker safety, comfort, and productivity. The principles of ergonomics involve accounting for factors such as proper lighting, ventilation, noise control, and ergonomic design of tools and equipment.

In the feedlot environment, cattle handlers would compromise their own comfort to prioritise the welfare of the cattle. This contrast underscores the intricate balance that must be struck between human comfort and animal welfare within the context of cattle feedlots, to ensure both human and animal needs are met effectively.

Principles of ergonomics can be adapted to design layouts that also prioritise the comfort of workers (not just animals) during handling operations. Applying ergonomic principles to cattle handling systems could reduce fatigue, injury and improve production efficiency.

4.2.2.2 Supply chain management principles:

Supply chain management principles optimise the flow of materials, information, and resources across the facility and its external partners. The principles include inventory management, supplier collaboration, and demand forecasting to enhance overall supply chain efficiency.

These principles can be applied at cattle feedlots by implementing effective inventory management systems, collaborating with suppliers to ensure timely delivery of feed and other resources, and utilising demand forecasting techniques to enhance overall efficiency and minimise disruptions.

4.2.2.3 Principles of lean manufacturing:

Lean manufacturing requires eliminating waste, reducing variability, and streamlining processes. Lean manufacturing involves techniques such as value stream mapping, just-in-time production, and continuous improvement to maximise efficiency.

In the feedlot environment these principles could be utilised to optimise workflow and minimise unnecessary movement of cattle and workers.

4.2.2.4 Sustainability and environmental factors:

Sustainability and environmental factors incorporate energy efficiency and waste reduction measures into facility designs. It involves implementing energy-saving measures, recycling programmes, and sustainable material selection.

These factors can be integrated into the design of feedlot facilities to minimise the environmental impact of livestock operations.

4.2.2.5 Principles of economic feasibility:

Economic feasibility studies focus on balancing cost-effectiveness with operational efficiency by considering factors such as resource utilisation, space optimisation, equipment selection, and labour allocation. The aim is to create facility layouts that minimise unnecessary expenses while maximising productivity and profitability and to create sustainable and financially viable solutions that optimise resource utilisation and contribute to long-term success.

These principles can be applied in the feedlot environment by optimising resource utilisation and minimising unnecessary expenses. Feedlots could invest in durable equipment and infrastructure to reduce maintenance costs and the need for frequent replacements. By making this investment, feedlots could save money in the long run and improve their overall financial stability. An economical and efficient facility layout can contribute to cost savings by optimising labour utilisation and maximising the output per worker.

4.2.2.6 Automation and technology integration:

Integrating automation and technology improves productivity and efficiency and reduces human error. The integration can include the use of robotics, automated material handling systems, and data-driven decision-making tools.

In the feedlot environment, utilising technology and automation will improve productivity. Implementing robotics and automated material handling systems could enhance the speed and precision of cattle movement and sorting. Additionally, technology integration for tracking, identification and data analysis could optimise handling processes.

5 CONCLUSIONS

This review has examined the fundamental design principles of industrial engineering facility layouts and compared them with the design principles applied in cattle handling facilities. The intricate puzzle of merging these distinct fields, emphasises the comforting truth that solutions exist even in complex integrations. This review visually mirrors the convergence through a Venn diagram, elucidating the overlapping puzzle pieces where these principles offer potential mutual enrichment and interaction. Furthermore, to the researcher's knowledge at the time of publication, it is believed that this study is the first comparison concerning these distinct facility design principles.

The overlap between industrial engineering principles and cattle handling principles lies in the shared goals of operation efficiency, productivity and safety. Both fields recognise the importance of eliminating waste, reducing variability and streamlining processes. Integrating best practices from both domains will enhance facility layout designs, improve production, and increase profitability in both industry and agriculture settings.

The similarities between these principles underscore the critical importance of a well-designed facility layout. The shared emphasis on creating efficient and effective facility layouts highlights the universal need for thoughtful design considerations and their influence on overall operational success.

The divide between industrial engineering facility design principles and cattle handling facility design principles is rooted in the distinct nature of these domains. The disparity is particularly evident in the realm of ergonomics, where a notable contradiction arises. Industrial ergonomics is primarily driven by optimising human comfort, while cattle handlers compromise their own comfort to prioritise the well-being of the cattle.

Despite their apparent differences, there exists a connection that remains largely unexplored. The knowledge and insights to be gained from this exploration can lead to transformative advances in operational efficiency and hold value for professionals in both industry and livestock sectors.

6 FUTURE RESEARCH

Future research should explore the potential for further integration between industrial engineering principles and cattle handling principles to continue to explore relationships between these principles, facilitate knowledge exchange, and foster collaboration to unlock new possibilities for operational excellence.

By leveraging these design principles, it will become possible to enhance cattle handling facility layouts through insights and strategies derived from industrial engineering, ultimately leading to improved productivity, safety, and economic feasibility.

Further research should also address the specific challenges faced by different sectors within the livestock industry and explore tailored solutions to optimise operational performance and animal welfare.

Additionally, there is a need to bridge the gap in research between theoretical principles and practical implementation. Future research could conduct field studies to assess the real-world effectiveness of different facility layout designs. By closely examining how these designs function in practical scenarios, researchers can gain valuable insights into their actual performance and identify areas for improvement. Moreover, future research could conduct field studies to evaluate real-world challenges. This would entail observing and analysing the current issues and obstacles encountered at feedlots, enabling researchers to develop more informed and effective solutions that align theory with practical application.

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INVESTIGATING THE CONTRIBUTION OF ORGANISATIONAL STRUCTURE AND CULTURE FACTORS IN THE ADOPTION OF AGILE METHODOLOGY IN FINANCIAL INSTITUTIONS

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ABSTRACT

Financial institutions are rapidly adopting Agile to speed up the development of products and services. In such a highly regulated industry the adoption of a Software Development Life Cycle (SDLC) is hampered by the organisation's existing structure and culture. This paper investigates how a financial institution's organisational structure and culture influence its SDLC decision-making process to ensure that Agile is accepted by the organisation. A survey of 80 project practitioners in various South African financial institutions and hypothesis testing revealed that the organisational structure factors of management style and work ways and the organisational culture factor of work style have a significant positive influence on SDLC decision-making in a financial institution. The research indicates that the way the organisation approaches decision-making influences the perceived acceptance of agile. Financial institutions are encouraged to regularly review their organisational structure, culture, and decision-making to ensure that it is aligned with their development strategy.

Keywords: Organisational culture, organisational structure, agile, financial institutions, South Africa

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1. INTRODUCTION

Financial institutions operate in a very competitive environment to produce innovative products and services for their customers [1]. In South Africa, financial institutions are known for being very innovative and providing solutions that cater to their customers' needs. South African banks are ranked amongst the top 15 banks on the African continent with Standard Bank, First National Bank (FNB), Amalgamated Bank of South Africa (Absa), and Nedbank holding the Top 4 positions [2]. The solutions financial institutions develop are dependent on information technology (IT) infrastructure and require a software development approach. The rapid evolution of technology is forcing the financial industry to embrace digitisation, which requires this industry to align its business with information technology (IT). Various competitive factors have created a strategic need for financial institutions to be more agile, so that they can respond quickly and adapt faster while delivering greater value and keeping their existing market share [1]. This is the reason why most financial institutions are transitioning from a traditional waterfall methodology to an agile methodology as their preferred Software Development Life Cycle (SDLC). An SDLC is the framework that is used to plan, manage, and control the process of developing an information system (Bassil, 2012). There are seven different SDLC methodologies namely agile, lean, waterfall, iterative, spiral and dev-ops. This paper investigates how an organisation goes about adopting a new SDLC methodology such as agile based on its existing organisational culture and structure.

Agile methodology is based on the agile manifesto, which is a set of guiding principles of practice. The agile manifesto promotes values of collaboration over contract negotiations, adapting to change over following a specific plan, having a working solution over comprehensive documentation, and finally, human interactions over tools and processes [3]. These values speak to an organisation's culture and structure.

Many studies have investigated agile and agile adoption in organisations [4]. However there has been a much more limited focus on agile studies in financial institutions [5]. Financial institutions differ from the software development industry, where agile is very prevalent. Financial institutions are more traditional and have a lot more regulations, policies, and procedures that they need to comply with. This highly regulated environment provides a level of complexity when implementing an agile methodology. Failing to adhere to these regulations can result in (a) the institutions being fined; (b) reputational damage, and the most serious consequence which is (c) having their financial license revoked. It is due to operating in such a highly regulated environment that financial institutions seemingly have stringent and bureaucratic decision-making processes and have taken a conservative approach to adopting agile [6]. It is therefore important to investigate the factors/dimensions that are unique to the financial industry that determine the successful adoption of agile.

It has been shown that an agile methodology provides a workable solution much faster than when a traditional methodology is used, although organisations often struggle to adapt to agile [7]. Past research shows that software development process changes trigger complex organisational changes and that these changes cannot be accomplished by merely replacing current tools and technologies with new ones [8]. When an organisation decides to adopt an agile methodology it should review its entire structure, management practice, and culture.

The aim of this study is to investigate the organisational structure and culture factors that contribute to a financial institution successfully adopting an agile methodology for its projects.

The objective is to identify the factors relating to an organisation's structure and culture that contribute to the successful adoption of agile methodology in the financial industry.

Given the objectives, the research questions are:

1. How does the organisational structure in the financial industry play a role in the acceptance of an agile methodology?

2. What organisational culture factors ensure a perfect culture for agile adoption in the financial industry?

2. LITERATURE REVIEW

2.1. Organisational culture

Organisational culture is a shared belief system that infuses an organisation or sub-unit and ultimately influences the actions of people and workgroups [9]. Understanding the culture of an organisation ensures that an organisation and its project office choose a software development method that suits the organisational culture irrespective of software development evolution [10]. The culture of an organisation can be categorised according to various typologies. Burns [11] uses the Hofstede dimension framework to measure the culture in an organisation. Organisational culture studies tend to evaluate individualism vs collectivism; power distance; uncertainty avoidance; and masculinity vs. femininity in the organisation [11]. In contrast, Livari and Huisman [12] use a competing value framework (CVM) to determine the organisational culture based on the organisation's value system. The culture types that be identified based on the CVM framework [12] include:

- The group culture - This culture is concerned with morale and human relations. This type of culture values collaboration and the distribution of decision making.
- The development culture – Describes a culture that emphasises growth and the willingness to adapt. This type of culture values communication that is horizontal, and informal coordination.
- The rational culture – This culture focuses on efficiency, productivity, and the achievement of goals. The culture prefers centralised decision making with formal control systems.
- The hierarchical culture - This culture is concerned with control, stability, and efficiency by following formal rules and regulations.

Each culture type mentioned above has its drawbacks which highlights the inherent dilemmas an organisation might have. An organisation may consist of more than one type of culture based on the size and structure of the organisation.

Although organisational culture may be interpreted in various ways, previous studies emphasize that organisational culture influences the adoption of a software development methodology [13], [14].

Moreover, organisational culture or the organisational climate has a significant impact on the work style exhibited by individuals in an organisation [15]. Work style is defined as the appropriate skills and abilities that an individual possesses to be able to do their job [15]. The literature states that work style, management style, communication, and knowledge sharing processes are all important cultural factors that influence the implementation of agile in an organisation [9].

By knowing which factors are indicative of the organisational culture and therefore determine the different culture types, the study aims to establish the organisational culture factors that can influence the acceptance of an agile methodology.

2.2. Agile culture

Agile is defined as "a network of teams within a people-centred culture that operates in rapid learning and fast decision cycles which are enabled by technology, and that is guided by a powerful common purpose to co-create value for all stakeholders" [14]. To determine the quality of agile, one needs to understand agile development from a human and cultural perspective [13]. By knowing the type of culture inherent in an organisation one can gain insight into how that organisation will embrace an agile culture which is part and parcel of adopting an agile methodology. An agile culture encompasses factors that influence the decision-making process in an organisation. Depending on how decision-making power is distributed in the organisation, the organisation and its management can either empower their employees to be self-sufficient and creative or the employees can be disempowered which results in them doing just the bare minimum of what is required. The latter will limit the benefits of adopting an agile methodology in an organisation.

An agile culture changes the way employees coordinate, communicate, and collaborate [16]. Furthermore, there should be alignment between product and project decision making and the organisation's business strategy to ensure the success of the agile strategy in the organisation [16]. An agile culture requires a shared decision-making model to empower the team to not be confined to a specialised role. This implies that decision-making power should not only be vested in the project managers and management of the organisation but also in the team [16]. Moreover, the involvement of team members in the decision-making process may even change based on the phase of the development cycle the team finds itself in. An example of this is that when the team is collaborating, the decision making process should include the input of various stakeholders even though they may have different goals and backgrounds [16].

2.3. Organisational Structure

Organisational structure is defined "as the formal system of task and reporting relationships that controls, coordinates, and motivates employees so that they cooperate to achieve an organisation's goal" [Ajagbe (2017) in 17]. The structure of the organisation determines how tasks are executed which in turn has implications for the performance of that organisation.

Karpik [14] describes the functional structure as a "hierarchical structure where each department consist of employees who report to the functional manager and where the functional manager reports to the head of department who oversees the overall performance of the department" [14].

One of the oldest organisational structures is the hierarchical structure also commonly known as the traditional organisational structure. Burns [18] describes the hierarchical structure as a structure where decision making power is centralised towards the top of the organisation and cascades down. This provides managers with the confidence that they have the authority to manage their units [18]. Funminiyi [19] found that the decision-making process in a hierarchical structure may have a negative impact on the organisation if management is ineffective in motivating employees and providing them with training [19].

A second type of organisational structure is the matrix structure where the organisation is more project-oriented and where teamwork between departments is required. The matrix structure tends to be flexible, but it requires interactions and communication amongst the employees. The level of authority in the matrix structure may not be equally shared between the functional and project managers as it depends on the balance of power in the organisation [14]. One of the organisational benefits of the matrix structure is motivated employees. Motivated employees perform at a high level as they have some sense of autonomy and don't always need to wait for top management to make decisions. The mindset of people working in the matrix structure tends to be more strategic and receptive to new ideas [20].

The third organisational structure is called the flat structure. This type of structure is the opposite of the hierarchical structure in that it typically has few to no management levels [21]. The organisation of the flat structure can be based on projects, production, geography, or division. Funminiyi [19] suggests that the flat structure allows employees to be more creative which increases their productivity as they are more satisfied with their work [19].This is because decision making power is distributed to the employees and everyone is seen as equals.

Based on the literature above how managers manage and direct their employees and how these employees respond to their manager's direction is an important factor that determines the organisation's structure. Olmedo-Cifuentes and Martínez-León [22] named this factor management style. They further suggest that management style can assist in the organisation's brand identity. Management style is described as the manner in which managers of an organisation control and manage their employees [22]. The management style of an organisation also influences how the employees respond to the method of management which then determines employees' work ways.

The literature review indicates that an institution's organisational culture and structure may influence its SDLC decision-making and adoption process with reference to the adoption of agile. However, few studies have investigated these factors in the financial institution context, this is the gap we hope to address with this study.

3. CONCEPTUAL MODEL

The conceptual model shown in Figure 1 below is derived from Chan and Thong's [23] framework for studying agile adoption by reviewing various factors in an organisation that contribute to knowledge management outcomes which will in turn ensure that an agile methodology is successful in an organisation. The conceptual model indicates the organisational structure and culture factors that will be covered in this study. This study will be make use of the organisational culture types identified by Iivari and Huisman [12] namely group culture, developmental culture, hierarchical culture, and rational culture. By identifying the existing culture type(s) in a financial institution one can determine if that culture supports an agile culture which the institution requires to be able to successfully adopt agile.

To identify the organisational structure of a financial institution we will be using the structures identified by Funminiyi, Taylor and Karpik [14], [19], [21] namely the functional, hierarchical, flat and matrix structure.

3.1. Organisational structure factors

The organisational structure factors (See Figure 1) refer to how the organisation is structured in terms of the level and type of hierarchy and the decision-making authority. The management style is indicative of the style of the management that is followed. The style will either be one of mentor and leader where the employees are provided with autonomy and support, or the style can be authoritative and dictating. The work ways factor refers to how the employees perform their duties in relation to management giving them more accountability and responsibility to make decisions and carry out work. These factors have been derived from the literature and are based on studies that determine how the structure of an organisation impacts how decisions are made in an organisation [14], [19], [21].

3.2. Organisational culture factors

Organisation culture factors (see Figure 1) refer to the employees' behaviour in the organisation. These factors provide insight on how the employees perform their duties and to what extent they are involved in decision making in the organisation. Work style refers to the extent to which the organisation encourages teamwork and collaboration from their employees. How the organisation reacts to uncertainty and the distribution of power (power distance) provides more insight on the flexibility of the organisation.

3.3. Agile culture factors

Agile culture factors refer to those factors that need to be considered when an organisation wants to adopt an agile SDLC to be able to deal more effectively with change and uncertainty. Agile culture factors take into consideration the structure that is necessary to be able to follow an agile methodology as well as the culture that needs to be in place for these practices to be successful. The decision-making variable for agile is given to employees as it is not a 'top management only' function. The team is provided with autonomy and flexibility to deliver what is required without the need to get approval from management [14]. By using decision making as an agile culture factor, it becomes apparent that the management style suited for agile is one of mentoring and leadership instead of demand and control [9]. Communication methods focuses on collaboration, cooperation, and consultation to ensure that the team is working towards a common goal and sharing knowledge [24]. By doing a comparison between the existing organisational structure, culture factors and agile culture factors it will become clear whether the organisation is ready to embark on an agile transformation journey and what changes will be required to make the adoption successful.

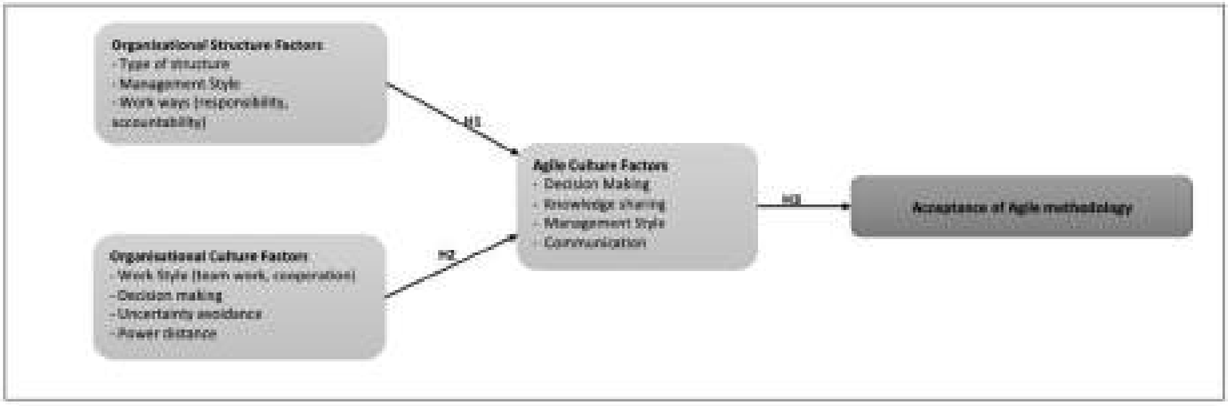

Figure 1: Research Conceptual Framework derived from [23]

The hypotheses derived from the conceptual model, to be tested in this study are set out below:

H1: Organisational structure has an influence on decision-making regarding the choice of the software development life cycle methodology used in the financial industry.

H2: Organisational culture has an influence on decision-making regarding the choice of the software development life cycle methodology used in the financial industry.

H3: The approach towards decision-making regarding the choice of the software development life cycle methodology has an influence on the acceptance of an agile methodology in the financial industry.

4. RESEARCH DESIGN AND METHODOLOGY

A quantitative method was used to gather data for this study and to test the hypotheses that were derived from the conceptual model. A questionnaire containing both open and closed, likert type questions, was distributed amongst a purposive sample of participants working in a project environment.

4.1. Population and sample

Respondents from all four major commercial banks and the central bank of South Africa participated in the study. The participants were selected because of their involvement in the Business Analysis Book Of Work (BABOK) and/or the Project Management Office (PMO) community in the financial institutions. Using these communities of practice in the financial sector ensured that the participants provided accurate information regarding the decision-making process which is used to choose the software development life cycle methodology for their financial institution. Incomplete responses and responses from participants that did not work in the financial industry were excluded. Eighty complete responses were received and analysed as part of the study. Statistical methods were used to analyse the data derived from the survey. Descriptive statistics were used to summarise the data and to be able to perform complex analysis [25]. Inferential statistics consisting of scatter plots, regression analysis, and Pearson correlation analysis were done to test the study hypotheses.

4.2. Data collection

Out of the 82 responses received for the questionnaire, only 80 were found to be suitable for data analysis as 2 participants did not work for a financial institution, so these responses were excluded. Due to limitations imposed by the COVID19 pandemic the low number of responses and limited data was insufficient to measure all the factors contained in the original conceptual model. The conceptual model was revised to accommodate this limitation. The conceptual model shown in Figure 2 was used to test the hypotheses.

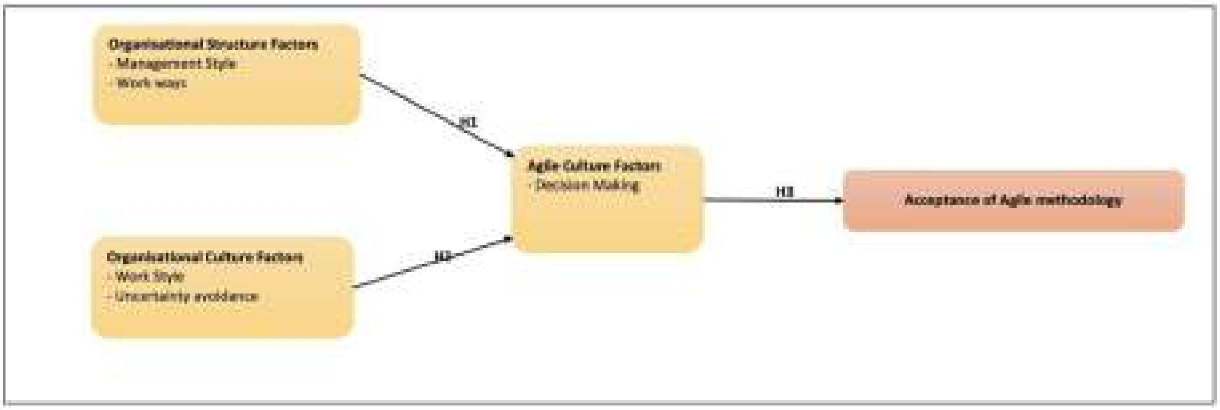

Figure 2: Revised conceptual model

4.3. Data analysis and reliability

The 23 likert scale questions items were analysed to determine the measure of internal consistency. Internal consistency was measured using the Cronbach alpha coefficient, where the overall reliability of α = 0.91 is regarded to be very good [26], [27]. All the dimensions (agile methodology, decision making, work ways, management style, work style) were reliable except uncertainty avoidance with a Cronbach alpha coefficient higher than 0.6, the rest were all within the range α = 0.636 – 0.865. These alpha values are within the acceptable range of 0.6 – 0.7 and very good reliability levels of greater than 0.8 [26]. As the reliability of uncertainty avoidance was questionable, this dimension was removed from the study.

Table 1: Reliability of the dimensions

Dimension	Number of items in a scale	Items	Cronbach alpha (α)
Agile methodology	3	Q10, Q18, Q19	0.8654
Decision making	4	Q13, Q26, Q27, Q28	0.6404
Work ways	4	Q14, Q20, Q31, Q32	0.6364
Management style	4	Q11, Q12, Q29, Q30	0.7139
Uncertainty avoidance	2	Q15, Q21	0,4227
Work style	6	Q16, Q17, Q22, Q23, Q24, Q5	0.6573
Overall	23		0.9118

4.4. Hypothesis testing

To test the hypothesis, scatter plots, correlation, and regression analysis were used. The scatter plot was used to determine the extent of the correlation between variables for organisational structure factors [28]. The Pearson correlation analysis was used to determine the statistical significance between the variables whilst regression analysis was used to determine the impact of the variables. Further tests were done to determine the regression model correlation using multicollinearity [29] along with the variability of variables using the heteroskedasticity method with the variables [30].

5. RESULTS & DISCUSSION

5.1. Methodology used in the respondent institutions.

Results from the survey showed that the South African financial institutions use several SDLC methodologies. The dominant methodology was agile (53%) followed by waterfall/predictive/traditional (36%) and then hybrid (12%). Of the 38 respondents who indicated that their organisations were using other SDLC methodologies, 92% indicated that their organisation was thinking about using an agile methodology. This meant that more than 95% of the organisations were either using the agile methodology or were thinking of migrating to agile methodology. For the organisations that were using agile, 5% indicated that it was not working, while most respondents did not answer this question (84%). We speculate that this could be because the respondents were unsure of how to determine if agile was working or not working in their organisation.

5.1.1 Organisational structure factors

Organisational structure is a formal system that contributes to the performance of an organisation and how tasks can be performed. The organisation’s structure promotes a management style which influences the work ways of the employees. Most financial institutions still use the functional structure (44.3%) followed by the hierarchical (26.6%), matrix(20.3%) and flat(5.1%) structure. The financial industry with its mainly functional structure may not be a good fit for agile based on the literature [14]. The reason for this is that the decision-making authority is centralised at the top of the organisation which can result in silos in an organisation and its departments. However, when taking a closer look at the factors within organisational structure, the results contradict the literature.

The first hypothesis consisted of:

H10: Organisational structure has no influence on decision-making regarding the choice of the software development life cycle methodology used in the financial industry.

H1A: Organisational structure has an influence on decision-making regarding the choice of the software development life cycle methodology used in the financial industry.

Table 2: Correlation between organisational structure variables and decision making.

	Decision making	Management style	Work ways
Decision making	1		
Management style	0.604***	1	
Work ways	0.553***	0.560***	1

* $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

The results show that an organisational structure with management style and work ways as variables has an influence on the decision making of which software development life cycle to use. The results showed a positive correlation of r = 0.604, p < 0.001 between management style and decision making, and positive correlation of r = 0.553, p < 0.001 between work ways and decision making as shown in Table 2. The regression results also revealed positive relationship with ß = 0.307 (3.00), p < 0.001 with good r-squared value of 0.4318 indicating that management style and work ways are predictors of decision making in an agile culture.

The management style of the financial institutions in terms of decision-making show that the financial industry still has high levels of bureaucracy (54.3%). This corresponds with the nature of the organisation, as financial institutions are risk averse, burdened by regulations, policy driven and conservative. Therefore, the management style tends to be concerned with reducing any uncertainty and job security [22]. Upon assessing the productivity and quality of work within the financial institution, the results showed a high level of productivity and quality with 74.1% and 81.5% respectively. This shows that the management style in the financial industry is also one that fosters productivity and innovation although the decision making might not be shared at all levels and at all times, amongst the employees.

Results pertaining to the work ways of the financial institutions revealed that 76.5% of these institutions ways of work is still driven from top management downwards, which correlates with the existing organisational structures ie. functional. The respondents indicated that financial institutions value their clients (82.7%) and focus on their clients' needs (71.6%). With 70.7% stating that the chosen methodology fosters a focus on client requirements. This client centric approach supports an agile culture as the purpose of agile is to co-create value and be people centred [14]. Organisational structure factors form part of the organisational identity and the way in which the organisation chooses to distribute the decision-making power. It should be aligned to the structure of the organisation especially when adopting an agile methodology.

All the three factors that were used to measure the organisational structure and agile culture yielded a positive relationship, therefore accepting the alternative hypothesis being that the organisational structure with management style and work ways as variables has an influence on the decision making of software development life cycle used in the financial industry.

5.1.2 Organisational culture factors

The respondents were also asked to describe the culture of their organisation. These questions analysed the shared belief and practice systems that inform all team members' actions. The most dominant culture within these organisations was group culture (46.8%), which is characterised by collaboration and the distribution of decision-making[12]. This was followed by the hierarchical culture (26.6%), which is concerned with control, stability and efficiency by following rules and regulations. The least dominant culture in the SA financial industry was the development culture (15.2%) and rational culture (11.4%), which prefers centralised decision-making with formal control systems. This means that the dominant culture in financial institutions (group culture) supports the findings of Siakas and Siakas [13]. This culture is suitable for agile since the employees' values collaboration and management also values distribution of decision making with their employees. However, there are still some financial institutions that are still conservative and prefers formal decision-making processes and regulations which is why there is still centralised decision making and formal control systems in place[12].

The second hypothesis was that organisational culture has an influence on the decision-making regarding the choice of the software development life cycle methodology used in the financial industry. The variable of organisational culture was work style. Where work style describes employees working attributes, based on their environmental exposure [15]. The second hypothesis can be recapped as follows:

H20: Organisational Culture has no influence on the decision-making regarding the choice of the software development life cycle methodology used in the financial industry.

H2A: Organisational Culture has an influence regarding the decision-making regarding the choice of the software development life cycle methodology used in the financial industry.

Table 3: Correlation between organisational culture variables and decision making

	Decision making	Work style
Decision making	1	
Work style	0.543^{***}	1

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

The results show that organisational culture has an influence on the decision making of software development life cycle. A positive correlation of $r = 0.543$, $p < 0.001$ between work style and decision making is shown in Table 3. The regression results also reveal a positive relationship with $\beta = 0.528$ (5,67), $p < 0.001$ with r-squared value of 0.295 indicating that work style is regarded as a predictor of decision making in agile culture.

The working style factor for financial institutions in projects show that the team members collaborate to execute project related work though they also have a sense of individual accountability in the delivery. 58% Of the respondents say that they are solely responsible for the deliverable and with 95.1% of respondents say that they work together with their team members to execute project work. This finding supports a group culture which is characterised by collaboration [12].

56.8% Of the respondents indicated that there is a knowledge management process in place in the financial institutions. Only 43.2% say that the knowledge management process in place is effective and 31% feel that the knowledge management process can be improved. These results suggest that there is room for improvement when it comes to the work style factor in the financial institutions though the culture has facets of agile culture in place. When the work style factor was compared to the decision-making factor for an agile culture, the findings revealed a strong relationship with a correlation of 0.543. Based on these results, it can be concluded that the null hypothesis is rejected, and the alternative hypothesis is accepted. As such, organisational culture has an influence on the decision-making of software development life cycle methodology in the financial industry.

5.1.3 Agile culture factors

The results showed that 64.1% of the participants are using agile methodology in their organisation and 35.9% uses waterfall methodology. The respondents indicated that there was no dominant group that makes project-related decisions in the organisation within the financial industry. 34.2% Indicated that it was the project sponsor, 32.9% the project team and 30.4% the project owner, respectively that made project related decisions. This data highlights the divergence in terms of where the decision making resides in financial organisations. An agile methodology requires an agile culture that has shared decision-making power to empower their employees [14] [16] whilst the findings of this study shows that only 32.9% are allowed to make decisions as a project team.

The third hypothesis focused on the influence of the approach to decision-making on the acceptance of agile methodology. This hypothesis can be recapped as follows:

H30: The approach to the decision-making regarding the choice of the software development life cycle methodology has an influence on acceptance of agile methodology in the financial industry.

H3A: The approach to the decision-making regarding the choice of the software development life cycle methodology has an influence on acceptance of agile methodology in the financial industry.

Table 4: Correlation between decision making and acceptance of agile methodology.

	Agile methodology	Decision making
Agile methodology	1	
Decision making	0.5221^{***}	1

$^{*}p < 0.05$, $^{**}p < 0.01$, $^{***}p < 0.001$

The results show that the approach to decision making of software development life cycle has an influence on the acceptance of agile methodology in the financial industry. The results showed a strong and positive correlation of r = 0.5221, p < 0.001 between agile methodology and decision making as shown in Table 4. The regression results also reveal a positive relationship with ß = 0.590 (5,37), p < 0.001with r-squared value of 0.272. indicating that the approach to decision making is a statistically significant positive predictor of acceptance of agile methodology for projects undertaken in the financial industry. Based on these results, it can be concluded that the null hypothesis is rejected, and the alternative hypothesis is accepted. As such, the approach to decision-making of software development life cycle methodology has an influence on the acceptance of agile methodology in the financial industry.

When reviewing the factor of agile culture in terms of collaborative work in the financial institution, the findings showed that 84% perform collaborative work in their financial organisations which would support an agile culture [13].

When determining the level of understanding of agile in the financial institution, 51.85% agreed that the entire organisation knows what agile involves, while 25.93% disagree with this statement. When determining the suitability of agile in the organisation, 49.4% agreed with the agile approach while 25.9% disagreed with the statement. Finally, when determining the success of agile in the organisation, 55.6% believed that agile is a success while 21% disagreed.

These results indicate that financial institutions are moving towards an agile culture with shared decision making though this is still in the early stages as only 32.91% of respondents stated that decision making is shared amongst the project team.

6. CONCLUSIONS AND RECOMMENDATIONS

This paper investigates how a financial institution's organisational structure and culture influence its SDLC decision-making process to ensure that Agile is accepted by the organisation. Most organisations adopt an agile methodology by migrating from the traditional methodology i.e., moving from waterfall to agile. This migration tends to introduce various people related challenges [8]. Identifying and addressing those challenges should theoretically increase the adoption of agile in an organisation. From the literature it was evident that amongst others, organisational structure and culture are key factors that contribute to an organisation successfully adopting an agile methodology.

The results of a survey with 80 respondents showed that there is a positive relationship between organisational structure and agile culture in terms of decision making. As well as a positive relationship between organisational culture and agile culture in terms of decision making. The research also found that management style and work ways as organisational structure factors; and work style as organisational culture factor do have an influence on the decision of which SDLC is used in the financial industry. Moreover, the research indicates that in the financial industry the way an organisation approaches decision making can influence the acceptance of agile methodology.

Financial institutions need to review their structures and align it to their business and information strategy. This means that an organisation should change their structure to fit their strategy. An agile methodology requires a structure that is flexible and quick to adapt therefore, having a functional structure or hierarchical structure adds a level of complexity in the acceptance of the agile methodology.

The second recommendation involves the decision-making process within a financial institution's organisational structure. Adoption of an agile methodology requires a management style that motivates, builds a positive team, and most importantly empowers employees to make work-related decisions. When looking at the organisational structure factors of management style and work ways, it was found that the financial industry still has high levels (54.3%) of bureaucracy and 76.5% of the 'way of work' in this industry is still driven by top management. By addressing these issues organisations will ensure the acceptance of agile increases, as it will empower the employees to self-manage and be more accountable for their work output without the need to get approval from top management.

Organisational culture forms part of the organisation's identity. Having a culture that is conducive to creativity, and high productivity requires financial institutions to occasionally assess their culture to ensure that it is aligned to what the organisation is trying to achieve. An agile culture is centred on decision making and people. Therefore, having a culture that allows for shared decision making and transparency in the knowledge sharing process will ensure that the success of the methodology is not short lived. The findings showed that there are employees who are still undecided regarding the adoption of agile in the SA financial industry. It is important that organisations address these findings if they desire to effectively implement agile and build an agile culture in the organisation.

6.1. Theoretical contribution and managerial implications

The findings of the study contribute to the limited research on software development life cycle selection in the financial institution industry. The results indicate that financial institutions are different from the typical software industries that use agile methodology and decision making is important to ensure agile adoption is successful. The relevance of the organisational factors suggests that financial institutions need to perform due diligence before deciding on a development methodology to ensure that the entire organisation is on board with the change and is equipped to exploit the methodology.

6.2. Limitations and recommendations

The study was limited to South African financial institutions. The scope of this study was limited to a few selected organisational factors and this list was reduced further based on the low number of complete responses received. Therefore, it is recommended that future studies include the agile culture factors of knowledge sharing, management style and communication that could not be investigated in detail this study. Finally, the respondents were not distributed equally across the financial institutions therefore the findings may not be consistent across the financial institutions investigated.

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EXPLORING THE TANGIBLE AND INTANGIBLE RESOURCES OF THE SOUTH AFRICAN SAWMILLS: A RESOURCE-BASED VIEW APPROACH

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ABSTRACT

In the era of globalised trade, abundant forest resources are no longer the primary source of sustainable competitiveness for sawmills but rather a primary resource owned by most sawmills. Strategies applied in sawmilling firms have been approached generally, whereas the role of intangible and tangible resources in constructing firm-level success has received less concentration in the literature. Although vital insights can be derived from the business economic literature on other industries, comprehensive research is required to explain the resource-based view of the firm and identify resources that can contribute to sustainable competitive advantage in sawmills. The resource-based view was used as the base theory to examine the South African sawmill industry firms in this study. A desktop study on the available resources was conducted to determine the resources within the sawmills. The results will help guide what resources have benefits to firms.

Keywords: resources, resource-based view, strategy, sustainable competitive advantage, sawmill industry

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1 INTRODUCTION

The sawmill industry is a significant source of employment and is vital for sustaining global economic development [1]. Establishing a competitive advantage in this industry can be seen as a challenging puzzle worth solving to promote environmental and social sustainability. In the era of globalised trade and increased trade, ample forest resources are no longer the primary source of sustainable competitiveness [2]; however, the raw material (logs) is crucial and can be regarded as a primary resource for all sawmills [3], [4]. Past research on forestry prioritised the influence of external factors compared to internal factors when evaluating a sawmill's ability to establish a sustainable competitive advantage [2]. According to Lähtinen [2], there is a lot of technology study being done on the sawmilling sector, but not much business economics research. Though important knowledge may be gained from the business and economic literature on other sectors, it is essential to examine South African enterprises' competitiveness and the variables that influence their competitive advantages in light of their resources. Extensive study is needed to explain the resource-based vision of the company and discover resources that might help it achieve sustained competitive advantage in the sawmilling industry. [1]. An official investigation of the physical characteristics and geographic location of land is necessary for the study of manufacturing economics. [5]. The study's objective is to evaluate the resources that lead to competitive advantage in the sawmilling industry internationally and locally by applying the resource-based view of the firm theory. The results will be used to understand the overall available resources in the South African sawmill industry and how they compare with resources in global sawmill industries.

2 LITERATURE REVIEW

2.1 Strategy

Strategic decisions inside sawmills have been essential to maintain competitiveness in the rapidly evolving business environment [3]. Its history and strategy determine any company's resource mix and how well the resources integrate with the external business environment [2], [6]. Strategic decisions significantly influence the value of a company's resources and capabilities with the opportunities present in the market [3]. The structural strategy of a company is based on its assets, capacities, core competencies, and interactions with the external business environment [2]. Core competencies refer to what a firm does particularly well compared to competitors [7]. Business performance measures are pointers for a firm's success in reaching its strategies, goals, and key performance indicators [3]. For example, a strength, weaknesses, opportunity and threats (SWOT) analysis could produce valuable knowledge [8]. Resource-based theorists believe a sustainable strategy should be based on the firm's resources and competencies [7]. Resources are strengths that may be leveraged to implement corporate plans by managing valuable, scarce, and unique resources to obtain a sustained competitive advantage [9].

2.2 Resource-Based

The resource-based view of the firm can be used to evaluate a company's strategic resources. It suggests that company managers may develop a plan to establish a sustained competitive advantage in markets and sectors by utilising their internal resource base and core skills [4] [10]. Penrose 1959 established the resource-based viewpoint [10]. Some critics of the resource-based view argue that it places too much emphasis on firm [11]. According to the resource-based perspective, capabilities and resources must be valuable and scarce to give firms a competitive advantage. To provide a durable competitive advantage, they must be challenging to copy, substitute, and trade [1], [12]. Li [13] discussed value, rarity, imitability, and organisation within firms.

A corporation cannot adopt strategies that take advantage of environmental possibilities if the resources or capabilities it controls have no value.

Competitive parity will result through exploiting resources or talents that are valued yet in abundant supply.

A corporation will temporarily gain a competitive edge if it can use resources or talents that are valuable, scarce, and inexpensive to copy.

Exploiting precious resources, hard to come by and expensive to copy, will provide a persistent competitive edge.

From a resource-based view, each firm is a distinctive collection of resources [9], [13] that determines which external conditions offer opportunities and which cause threats [6]. The resource-based view of the firm is based on two main assumptions, which are that firms within an industry may be heterogeneous concerning the strategic resources they control, e.g., though wood is the standard input raw material used, the resources of various firms are not the same. The second assumption is that resources may not seamlessly move across firms, and heterogeneity can be permanent [1]. These assumptions signify that every firm has unique resources that others cannot easily copy.

2.3 Resources

Firms comprise resources from ongoing organisational activity and external opportunities and threats [12]. The term "resources" refers to a collection of tangible and intangible assets, capabilities, organisational processes, company characteristics, information, and knowledge [7], [8]. Firm resources must be diversified in character and permanently immobile to transition from a short-term competitive advantage to a sustained competitive advantage [14]. Large-scale forest sector enterprises have enough resources for expanding and sustaining their service offerings, according to research by Mattila [9] on the Finnish sawmill industry. According to Bonsi [1], many businesses are failing or have ceased operations due to increased international competition, partly due to a focus on external variables over which firms have little or no control instead of emphasising internal resources and capabilities. When organisations create uncommon and valuable resources due to their 'unique historical route,' they may exploit them in ways rival enterprises cannot [8].

Resources are usually categorised as either tangible or intangible. Tangible resources comprise only assets, while intangible resources include assets and capabilities [2]. According to Mattila [9], tangible and intangible resources may be classified as operand (manufacturing elements) and operant (knowledge and information). Capabilities refer to this knowledge and information. Intangible assets have no physical form and frequently exist in people's thoughts and minds. Firm resources become valuable if utilised resourcefully [1]. Firms will achieve long-term competitive advantage if the resource and capability requirements (valuable, uncommon, imperfectly imitable, and non-substitutable) are met [4]. Both assets and capabilities must be the foundation for long-term planning since they give the principal direction for a company's business strategy and financial success [2].

2.4 Competitive advantage

The competitive environment of the sawmill sector is rapidly evolving, requiring managers to seek out fresh streams of competitive advantage and develop plans that exploit their fundamental strengths [10]. Firms geared to adapt can better preserve their competitive edge than those that are not, as management can renew and alter their resources and connections as time, rivalry, and shifts within a competitive environment diminish their value [14]. The sawmill sector must develop new value-creation strategies to maintain a sustained competitive edge [4]. The firm's long-term competitive advantage is based on its abundance of specialised resources. Firms that manage a niche through reduced prices or distinguishing goods have a competitive edge [15]. Businesses that actively recognise and take advantage of environmental opportunities may experience sustainable and competitive advantages, resulting in competitive sustainability [12].

2.5 Competitiveness

A firm's capacity to acquire and use the right mix of resources determines its long-term competitiveness [4]. Tangible and intangible resources and capabilities are the foundation for competitiveness in today's fast-changing business environment [3]. In the forest products business, the capability to innovate significantly influences a firm's competitiveness. Firms in the wood products business are not uniform and might be productive depending on their own internal conditions [1]. The chance of a business maintaining its competitive edge increases with the heterogeneity of the resources on which that firm's competitiveness is built [2].

According to the resource-based theory, businesses in the sector differ in terms of competitiveness since each firm has a unique set of resources and capabilities [10]. The ability to develop value-added, make educated strategic decisions, and creatively employ intangible and tangible resources is critical for preserving sawmilling sector competitiveness in higher-cost nations [2], the capacity to produce value-added, make informed strategic decisions and creatively use intangible and tangible resources are essential to achieving sustainable competitiveness in higher-cost-level nations. Maintaining long-term competitiveness in the conventional sawmill sector has grown more complex than ever [4]. This is because competitiveness is resource-based and subject to variance [12].

3 METHODOLOGY

A systematic scoping review was selected for this study [16], [17]. This form of study ensures that the process of conducting the review is documented in enough detail to allow replicability of the study by other researchers. The scoping review framework entails establishing the research questions, sourcing relevant studies, selecting studies, mapping the data, and organising, summarising, and reporting the results [16].

3.1 Research questions

From the literature review, the following research questions were identified:

1. What tangible resources do international sawmills use to gain a competitive advantage?
2. What intangible resources do international sawmills use to gain a competitive advantage?
3. How do South African sawmills' typical tangible and intangible resources compare with international sawmills?
4. Which resources (strengths) can South African sawmills leverage to obtain a competitive advantage?
5. Which resources (weaknesses) can South African sawmills develop to increase competitiveness?

3.2 Inclusion and exclusion criteria

Scopus and Web of Science were used to find publications. The two databases were chosen since they are two of the three main bibliometric databases, along with Google Scholar [18], [19]. The initial step was to define the articles' inclusion and exclusion criteria. The search was restricted to articles:

- Published between 2002 and 2022.
- Only articles relevant to the research questions were used.

- Publications not written in English were excluded.

The search query and phrases used to search are shown in Table 1.

Table 1:Seach quarry search phrases used on Scopus and Web of Science

(TITLE-ABS-KEY (resource-based AND view AND sawmill AND industry)
OR TITLE-ABS-KEY (tangible AND intangible AND resource AND allocation)
OR TITLE-ABS-KEY (resource AND based AND view AND sawmill AND industry)
OR TITLE-ABS-KEY (resource AND utilisation AND in AND the AND sawmill AND industry)
OR TITLE-ABS-KEY (resources AND in AND sawmill)
OR TITLE-ABS-KEY (resources AND capabilities AND in AND the AND sawmill AND industry)
OR TITLE-ABS-KEY (innovation AND resources AND in AND the AND sawmill AND industry)
AND TITLE-ABS-KEY (resource)
AND TITLE-ABS-KEY (forestry)
AND TITLE-ABS-KEY (sawmill))
AND PUBYEAR > 2001 AND PUBYEAR < 2023

The number of articles obtained from applying the search query and inclusion and exclusion criteria in both Web of Science and Scopus is shown in Figure 1. The number of papers obtained from Web of Science was 617, and Scopus 161 from the search — 689 articles in total after removing duplicates. After the abstract and full-text screening, the articles relevant to the research questions were 21.

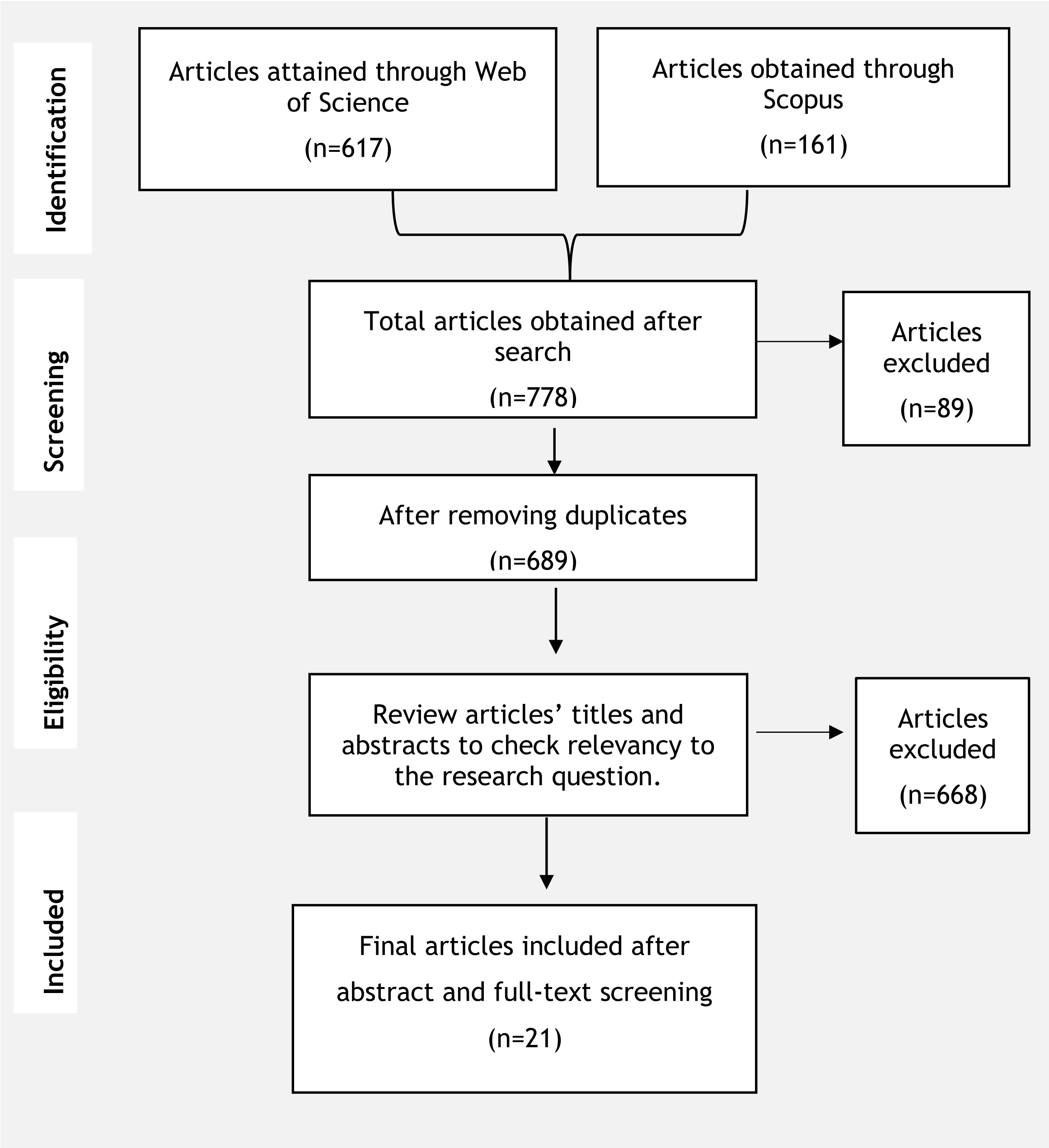

Figure 1: Steps followed to identify articles for the scoping review

3.3 Data analysis

The data was analysed using Atlas. ti, and information relevant to the research questions were extracted and used to answer the research questions. Some of the material utilised to answer the research questions was acquired through a desktop examination of published reports due to the limits of studies on resources and resource-based theory as it applies to the South African sawmill industry. Atlas.ti was used to generate a word cloud based on the most dominant topics in the identified included articles. The most occurring words were wood, forest, production, model, and resources. The highlighted words show the main themes of the articles used to answer the research questions.

Figure 2: Word cloud of the reviewed articles

4 RESULTS

The research aimed to determine which resources lead to a competitive advantage in the local and international sawmilling industries. The tangible and intangible resources in the sawmill industry, as found in the reviewed papers, are shown in Figure 3. The resources are grouped according to whether they are tangible or intangible. The tangible resources were the raw material, geographic location, finance, strategy machinery, and production technologies. The intangible resources highlighted from the studies were managerial expertise, human resources, employee know-how, operational reputation, technological know-how, organisational culture, and collaboration. Some of these resources offered competitive advantages in some international firms, while some resources still need to be fully utilised to create competitive advantages in some sawmills.

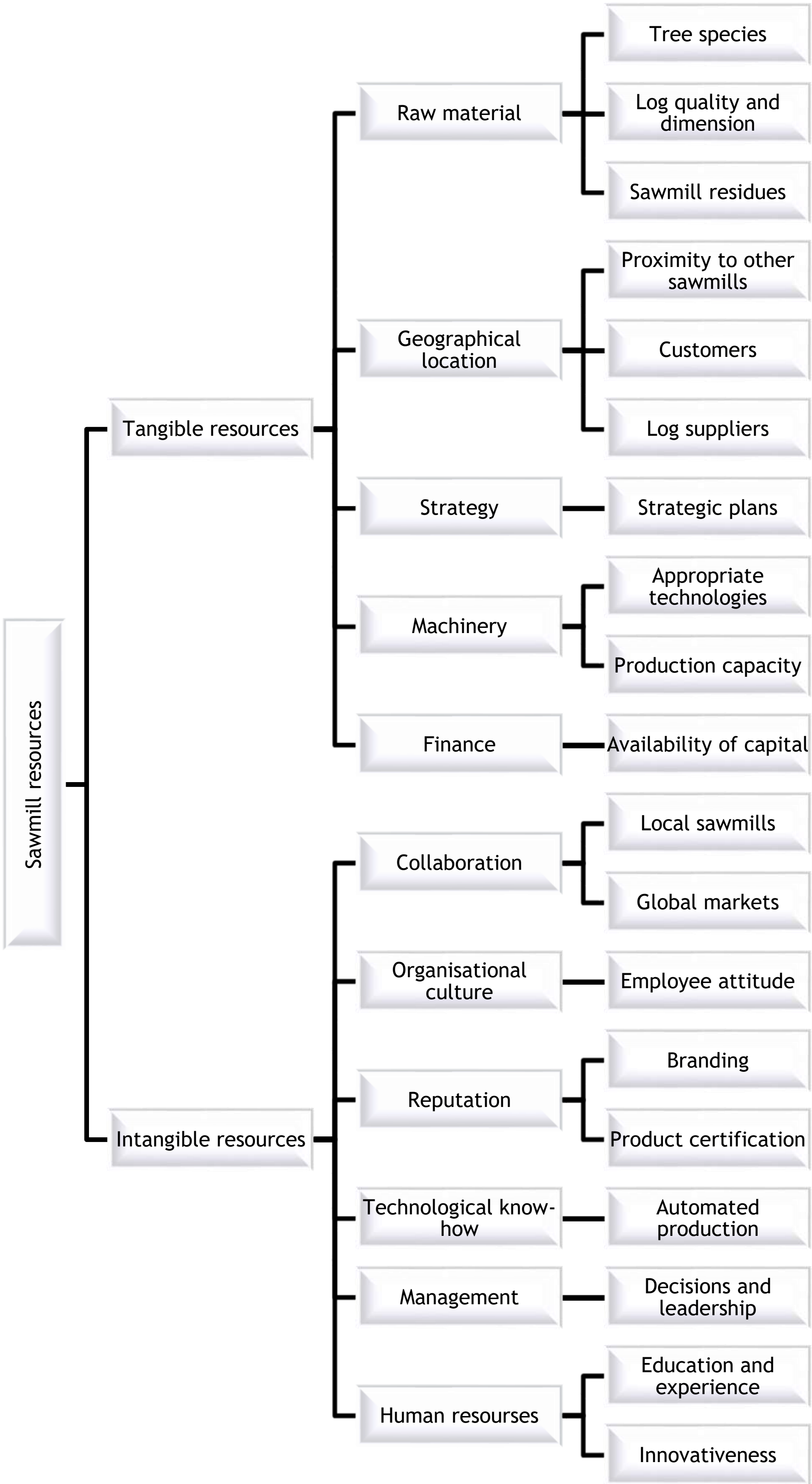

Figure3: Summary of the identified tangible and intangible resources used in the sawmill sector.

4.1 Research question 1: What tangible resources do international sawmills use to build a competitive advantage?

In their study of Finnish medium- and large-sized-sized sawmills, Lähtinen and Toppinen [20] found that finance, strategy and personnel were highly valued, whereas factory and machinery attained were less of a priority. They also emphasised that while conventional techniques for manufacturing are not a unique resource, access to investors and specialised sawmilling skills is required to acquire a competitive edge.

Some authors highlighted the availability of raw materials as key to attaining competitive advantage. Luppold and Sendak [21] said that the availability of a wood resource in Maine, USA sets in motion a series of economic and technological instruments to utilise the resource and meet a present or future demand for a specific set of goods and services. This is why there is a need to establish additional forest areas that would act as resource-feed to sawmill industries [22]. A study conducted in Vietnam showed how policies are geared towards establishing planted forests and developing the wood processing industry to increase the timber resource's availability [23]. This is due to the need for the necessary technology and raw materials to develop higher-priced products and customised services in sawmilling [24].

With the changing global needs and operating environment, resources are no longer being seen only as logs but also the residues from the forest and sawmills. Sawmills typically produce at least one of these wood residues: chips, sawdust, wood shavings, and bark. This means that mills can use this biomass to introduce a new market for bioenergy, as some mills do not use the residues to dry their timber. Holm *et al* [25] highlighted how customers may be given access to more diverse wood assortments, as the sustainable potential of wood has yet to be realised in Switzerland.

In their study, Venn *et al.* [26] highlighted the importance of strategic decisions regarding the mill's location, production capacity, and level of value-adding. This was supported by Uusitalo and Lidelow [27], who said that firms must consider supply chain structures when making future strategies. This is because sawmills that can attain logs from closer locations would be advantageous over mills that transport much longer distances, saving them time and money [22].

The development, execution and control of an entire firm strategy entail reflective data and information basis [28]. Firms are also increasingly expected to invest in resource-efficient and clean technologies [29]. When resources are limited, it is required to transition from traditional technical innovation to green innovation [30]. This allows firms to explore innovative ways to use their available resources.

4.2 Research question 2: What intangible resources do international sawmills use to build a competitive advantage?

Sawmills with brilliant workforce and research and development departments benefit from employees' knowledge, such as specific understandings about the products or production process and companies' specific know-how and their patents [31]. Other mills that lack particular expertise capitalise on their relationships with others. Network-based business models (collaboration) present a novel angle for pursuing competitive advantage by exploiting international opportunities [32]. By taking firm-level collaboration into account as one of its strategic resources, a company can assess its present or potential partners [33]. Their study also revealed valuable collaborations in the Finnish sawmilling industry. Still, the sawmill managers do not believe these collaborations can be a strategic resource. In their study, Lahtinen *et al.* [24] showed that management was regarded highly as a resource but collaboration, reputation, and organisational culture were less valued. Silva and Oliveira [34] found a strong relationship between innovation, intellectual capital, human resources, services facilities, results and procedures. Firms that advance innovation are said to promote their export visibility globally [34].

4.3 Research question 3: How do South African sawmills' typical tangible and intangible resources compare with international sawmills?

The sawmilling business in South Africa is based on timber from highly maintained plantations of exotic Pines and Eucalypts. Seventy-five per cent of those plantations are FSC certified (among the highest in the world) [35]. It is estimated that plantation areas globally will grow between 20 million and 40 million ha by 2050 [36]. Plantations cover 1.2 million hectares in South Africa [37]. This implies that South Africa has a small forested area compared to Sweden, Finland, the USA, Russia, etc.

Although some studies [33] suggested that wood raw material did not provide a foundation for long-term competitive advantage in other sawmills, having wood is vital for market share. South Africa is a predominantly dry country, and areas with sufficient rainfall for plantations are restricted to catchments in the southern (Western Cape, Eastern Cape, KwaZulu-Natal, Mpumalanga and Limpopo provinces) part of the country [37]. South African plantations mainly produce pine, eucalypt and wattle logs to be used by pulp mills, sawmills, pole treaters, mining timber manufacturers, and wattle tannin manufacturers [37]. Schwarzbauer and Stern [38] highlighted that international trade in industrial roundwood is essential to domestic supply.

A report by Crickmay and Associates [35] highlighted that Zimbabwe supplied ±85,000 m3 of sawn timber to South Africa annually. They also highlighted that geographically, Zimbabwe is the closest alternative resource if there is a shortage of wood. Charis *et al.* [39] mentioned the valorisation of biomass in Zimbabwe, specifically its residues and waste into bioenergy and engineered wood products, has been considered as a response to climate change issues; however, adoption of such practices has been limited in Zimbabwe, where most sawmills lack enough downstream industries to use waste.

According to their analysis FOA [36], engineered wood products and mass timber are the most promising wood products for replacing non-renewable resources on a broad scale. This could mean that South Africa could see an uptake in the use of wood in construction. Regarding employment, FAO [36] stated that the number of official and informal workers in the forest industry was anticipated to be 33.3 million in 2019, down from 39.5 million in 2013. According to Crickmay and Associates [35], the South African Lumber Miller's Association reported in 2001 that there were 113,000 direct employees in the sawmilling business from plantation to product. The number of direct employees continues to go down as sawmills are closing. It was reported that the number of direct employees in the industry in 2019 was 59 200 [40], a significant decrease from 113 000 in 2001.

The markets for sawn wood have seen several significant innovations in the form of improvement in glueing technology enabling exterior plywood use (the 1930s) and Oriented Strand Boards and Medium Density Fibreboard (1960s and 1970s); the emergence of pre-engineered woods (Cross Laminate Timber and glulam) and Modular prefabricated factory construction [41]. According to a study conducted in South Africa by Crafford and Wessels [42], green-glueing of eucalypt timber might enable manufacturing engineered structural lumber such as cross-laminated timber from rapidly grown pulp wood resources.

4.4 Research question 4: Which resources (strengths) can South African sawmills leverage to obtain a competitive advantage?

The balanced allocation of resources is necessary for distinctive competitive advantages, exceptional performance, and growth by reducing operation costs, improving capital utilisation efficiency, and corresponding the resource with operational needs [30]. Silva and

Oliveira [34] argue that the business climate in which companies operate is challenging, forcing managers to employ effective business tactics. This implies that South African sawmills can readjust their business strategies to respond to the changing business environment. They went on to say that to be competitive, businesses must prioritise market orientation, management expertise, and customer management relationships. South Africa's forest sector is regarded as a global pioneer in sustainable plantation forestry since it has the world's biggest area of endorsed exotic plantations and is one of the nations with the greatest FSC-certified wooded area [32]. The sawmilling industry could leverage this differentiator to gain a competitive advantage.

Coley *et al* [31] suggested that managers should strive to secure relationship-specific intangible resources partnerships, with a focus on ensuring equality in distributing intangible resources. Global demand for renewable energy sources is rising [43]. This is also evident in South Africa, which is facing a major energy crisis. Like the Contemporary Energy Policy of the European Union, which set an agenda for implementing the energy industry based on biomass [44], South Africa could follow suit by working with sawmills to generate electricity from wood biomass. Applying the solutions of biomass resource regionalisation reduces the cost of transport and energy consumption [44]. To achieve this, the industry will have to focus on innovation.

4.5 Research question 5: Which resources (weaknesses) can South African sawmills develop to increase competitiveness?

According to Silva and Oliveira [34], a particular market's crucial players are those with access to unique resources that are difficult to copy; hence, the technological boom was believed to be extremely important. This means that the sawmill industry in South Africa can work towards improving the technologies in their processing plant and investigate inventing new technologies.

The external business environment and internal strategic decisions made by a corporation are considered to impact its competitiveness [33]. One way of using strategy as a resource is for sawmills within an industry to align their overall strategy towards collaboration. South African enterprises should consider collaborating because it increases flexibility, economies of scale, effective risk management, and facilitates inter-firm learning [33].

Firms within the South African sawmill industry can also look for international partners. Hietala *et al.* [32] stressed the relevance of a firm's inter-organisational networks in producing new unique information and facilitating internationalisation in the network theory of internationalisation. Bioeconomy expansion will establish new prospects for firms functioning in the global wood marketplaces, and recognising and utilising these prospects is stressed as a key to achieving competitiveness. A study was conducted by Nwokolo *et al.* [45] to evaluate the performance of a Johansson biomass gasifier system, which utilises chunks of wood from a sawmill industry, for energy production in South Africa. This shows that the implementation of such systems can ease the energy crisis in South Africa. Still, in terms of renewable resources, there is a growing need for building goods that are environmentally friendly and have minimal embodied energy [26], [27].

5 DISCUSSIONS

Several types of resources were discussed as significant for firms to gain a competitive advantage. Each of these resources influences firm performance in its way. Employees are essential in developing and maintaining a firm’s competitive edge over rivals, as highlighted. The downside of human resources as a resource is that, unlike other organisational resources, employees can leave.

According to Mattila *et al*. [9], a customer, as a resource, develops value in collaboration with the firm that provides tangible and intangible resources for the value creation process.. They further emphasised that the firm must offer resources that enable or improve this process to add any additional weight to a client's value creation process. Technological know-how as a resource may aid in achieving a competitive advantage when combined tactically with other resources. Still, it is not a strategic resource for sawmills [3]. Strategic resources are said to be valuable, rare, inimitable and non-substitutable. Producing value-added products and improving customer service have been highlighted as critical strategic choices and vital for competitiveness.

Collaboration is a positive strategy that allows mills to expand their other resources. This is because sawmills benefit from collaborations, partnerships, and mergers by utilising each other's resources and focusing on their core strengths to grow their business. If individual sawmills would each specialise in a particular niche area in the wood value chain, it would influence other sawmills' willingness to collaborate and grow the sawmill industry as each one will be meeting a gap in the industry. This will also limit the need to compete as each mill will provide a niche product to the South African sawmill industry.

6 CONCLUSION

The assessment brought to light that a firm's resource attributes—which include tangible and intangible assets required to carry out selected strategies—determine its competitiveness. Firm resources include all assets, capacities, organisational processes, and insights within the jurisdiction of a business that enables it to carry out its strategies. Sawmill strategy ensures that the resources are acquired and allocated accordingly to carry out the mill's operations. This implies that the strategy of the individual firms on which resources to prioritise should all be geared towards attaining competitive advantage.

The study revealed that South African and international sawmills' primary tangible and intangible resources do not differ much; however, the strategies, policies and implementations differentiate them. The resource can supply logs to the sawmills; however, with the planted area's decline, the industry must look at different innovative ways to gain a competitive advantage. The industry could invest more towards using forest and mill residues in manufacturing composite products and bioenergy to maximise the value they get from the logs. International mills have demonstrated how sawmill residues are being utilised to generate energy that feeds into the grid and not just as fuel for the boilers in the mill. Sawmill managers should seek local and global strategic collaborations to achieve sustainable competitive advantage in sawmills. South Africa could look into expanding their use of timber as a construction material.

7 RECOMMENDATIONS

The study highlighted the primary resources firms and other sawmills use to gain a competitive advantage. A more in-depth analysis is necessary to understand the specific resources in the South African sawmill industry. Interviews or surveys with mill managers will highlight some of the strategies mill managers employ and the scope of resources in each sawmill.

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THE ROLE OF COMMUNICATION IN THE SYSTEMS THINKING PROCESS

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ABSTRACT

In an ideal world, life would be like a puzzle where all the pieces are in the box and fit perfectly together. In reality, life is more like a million-piece puzzle where many pieces are missing or do not fit into the correct or available place. This mental picture provides a glimpse of the complex world we live and work in daily. This complex world is characterised by many parts that interconnect via non-linear interfaces. Systems thinking is one of the ways to gain a greater understanding of this complex world. Systems thinking advocates first understanding the complex environment before intervening in it. Proper communication between the stakeholders is central to these activities. The focus of this paper is to examine the role that communication between the different stakeholders plays in the systems thinking process, from understanding the problem situation to intervening in it.

Keywords: systems thinking, complex systems, communication, stakeholder engagement

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1 INTRODUCTION

We are experiencing an increased interaction between the social or human elements in our society and created artefacts [1], [2]. The term artefact in this context is understood to mean "produced by art rather than nature"[1]. This artefact is also produced with the specific purpose of solving one or more problems [3].

This increased interaction between the social or human elements and the created artificial (including processes, tasks, and technologies) can be seen in everyday life in the form of an increase in technology adoption in various areas ranging from personal electronics to electric vehicles and, even now, the availability of artificial intelligence (AI) based tools such as ChatGPT. The direct interaction between the social or human elements and the technical artefacts creates a socio-technical system [4]–[7]. These socio-technical systems exhibit high levels of dynamic complexity or anthro-complexity resulting from the interaction between the social elements and the technology over time [8]. One consequence of the dynamic complexity is a noticeable delay between observing events and reacting to them or between deciding and implementing the decision. The net effect of these delays is to slow down the situational learning loop, thus reducing the overall improvement achieved within a complex situation with a limited time [9].

One can typify this complex, socio-technical world as multi-dimensional due to the complex interaction between the elements present [10], [11]. These elements can include physical or material elements and others that belong more to the social domain or even elements resulting from personal characteristics such as beliefs, values and fears [12]. Such a complex world can be described as seemingly resisting universal truths [13].

Solving complex or wicked problems within such a complex, socio-technical system can be daunting, and an instinctive approach by many people or researchers is to apply a reductionistic approach. A reductionist approach aims to generate an understanding of a problem by breaking the problem situation into smaller, less complex and more manageable parts [11]. This approach can often produce counter-intuitive results in the sense that instead of bringing clarity and a way to resolve the problem situation, it results in an increased unpredictability and inability to manage the problem [5], [14], [15]. These results can be attributed to our inability to provide a single or unique description of the complex, socio-technical problem.

The late biologist and essayist Lewis Thomas, as quoted by Sterman [16], remarks in an essay entitled "On Meddling" that:

> *"This realisation is one of the sore discouragements of our century . . . You cannot meddle with one part of a complex system from the outside without the almost certain risk of setting off disastrous events that you hadn't counted on in other remote parts. If you want to fix something, you are first obliged to understand . . . the whole system. . . . Intervening is a way of causing trouble."*

A further challenge that a person or researcher faces when working to solve a complex socio-technical problem is that there is no single or unique way of defining complex or wicked problems, but rather many based on the specific viewpoint or worldview of the person[17]. Since there is no single description of the problem, it is impossible to determine when a problem has been solved, or a specific research objective has been reached. Any added effort can only improve (or worsen) the situation [4], [18]. Some of the reasons that can be identified for these types of failures are that complex systems, including complex socio-technical systems, contain many interconnected parts, with the resulting relationship between the interconnected parts being more significant than the individual parts themselves [13], [14]. These relationships between the different parts of the complex, socio-technical systems also behave as non-linear and non-predictable. The situation can be compared to the problem solver attempting to building a puzzle consisting of many similar pieces without a picture on the box to judge the level of completeness of the puzzle. One may complete the puzzle, but is this the accurate picture as intended by the artist?

As described previously, the alternative to applying a reductionist approach is to approach the stated problem from a systems-thinking perspective. This approach calls for viewing the problem situation first as an investigation activity and second as an improvement activity. In both the investigation and the improvement activities, the first step is to establish a current baseline within a specific problem scenario, identify areas of improvement, make changes, and apply these improvements to the problem scenario. Once these improvements have been made, a new baseline can be determined and compared with the original baseline to see if any improvements have been realised. Proper and clear communication between stakeholders is central to successful investigative and improvement activities.

2 RESEARCH METHODOLOGY AND PAPER LAYOUT

2.1 Research methodology

Research can be defined as diligent searching, studiously enquiring, investigating, or experimenting. The main aim of the research activity is to discover new facts or findings [19]. A further function of research can be identified that is aimed at enhancing an organisation's knowledge and understanding of known phenomena, lesser-known phenomena or unknown phenomena and, by doing so, increasing its ability to meet the demands of the future [19], [20]. The objective of the research exercise is aimed at explaining and predicting the behaviour of specific observed phenomena and finding new truths or proofs [19], [21]-[24].

The research activity is not performed in isolation; the knowledge and insight gained from research should be shared with other researchers and stakeholders. In order for the knowledge and insight to be incorporated into the general body of knowledge, the research methodology must be based on recognised ontologies, boundaries, guidelines, and deliverables [23], [25], [26].

Strang [23] defined a topology of a four-layer, top-down research model, as shown in Figure 1. Based on this model, the research presented in this paper can be classified in the following way:

Table 1: Research classification

Basic belief	Description
Research Ideology	Pragmatist / Interpretivist research ideology in which the researcher interprets the results.
Axiology	Understanding
Epistemology	Subjective
Ontology	Multiple realities that are socially constructed.
Research strategy	Qualitative data analysis based on scientific and academic literature obtained via searches of relevant academic databases.
Research method	Mixed methods
Research technique	Literature reviews and inductive reasoning, together with thought experiments based on systems thinking principles and more than 30 years of practical experience as a researcher in the field of complexity and complex socio-technical systems

The research approach produces Mode 2 research knowledge [27].

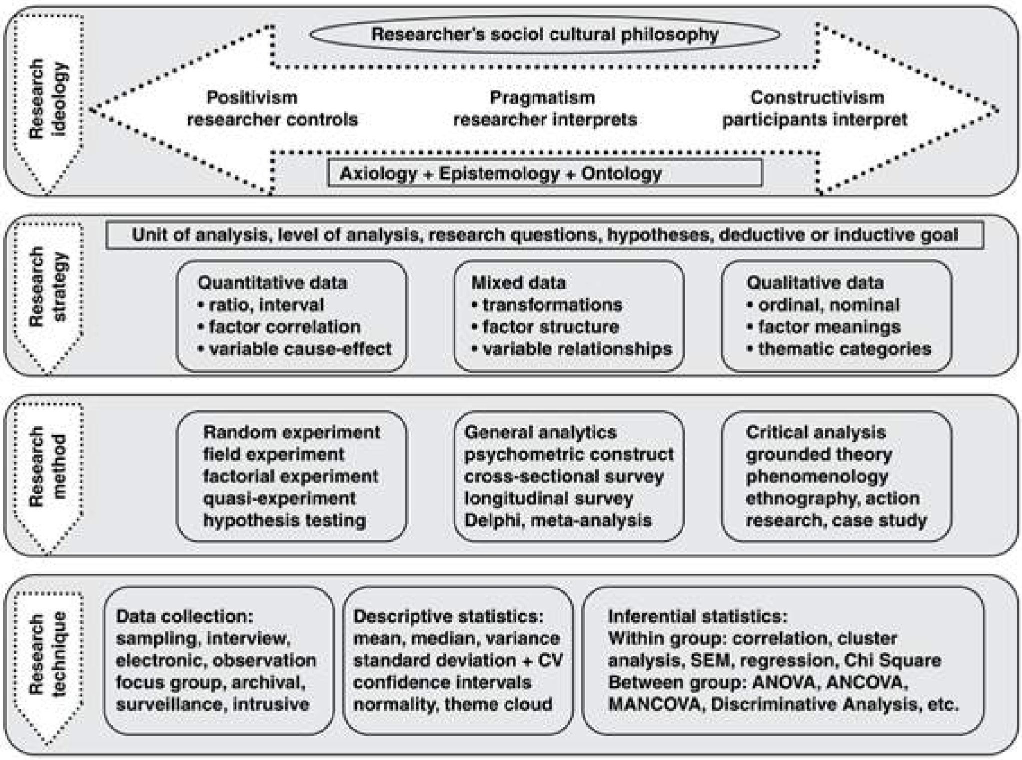

Figure 1[†]: Four-layer, top-down research topology [23]

2.2 Novelty of the research

One additional result of the literature survey indicated that very little has been written to date of the importance of communication in the systems thinking process.

2.3 Systems thinking principles

The origins of systems thinking can be traced back to the 1940s and 1950s with the work of Ludwig von Bertalanffy and Norbert Wiener. The main reason for their work was to understand what was termed "systems of organised complexity". Over the years' systems thinking has continued to evolve. These evolutions included systems engineering, systems analysis, systems dynamics, and soft systems thinking. This evolution was often triggered by instances where a particular methodology did not work or could not be applied under specific circumstances [28].

Systems thinking is a process of thinking about systems. Arnold and Wade [29] provide a concise definition:

> *"Systems thinking is a set of synergistic analytical skills used to improve the capability of identifying and understanding systems, predicting their behaviour, and devising modification to them to produce desired effects. These skills work together as a system."*

[†] SEM: Structural equation modelling, ANOVA: Analysis of variance, ANCOVA: Analysis of covariance, MANCOVA: Multivariate analysis of covariance

Cabrera et al. [30] identify four waves in the development of systems thinking. The first wave spanned the period from the 1950s until the late 1970s and produced methodologies such as system dynamics, system analysis, systems engineering and the viable systems model. The second wave spanned the late 1970s to the late 1980s and produced methodologies such as soft systems methodology, interactive planning, strategic assumption surfacing and testing, and Churchman's system approach. The third wave spanned the late 1980s until the early 2000s and produced methodologies such as critical system heuristics, critical system thinking, boundary critique, systemic intervention, theories of power, conflict, and marginalisation. The fourth wave spans from early 2000 until the present and has produced methodologies such as DSRP[‡] system thinking and VMCL[§] systems leadership.

Systems thinking provides tools and methodologies for dealing with "organised complexity", where traditional methodologies used in natural and management sciences do not deliver the desired results [28]. Systems thinking provides skills to view a problem holistically and to identify the various parts of the system, the relationships between the parts and the emergent properties [14]. Systems thinking aims to learn about the problem by looking through a systems lens, identifying places and methods of intervention, and bringing about change [31], [32]. This outcome is achieved by discovering, learning, diagnosing, and talking, which results in sensing, modelling, and discussing the real world to understand better, define, and work with systems [33]. Systems thinking skills include the following activities [29]:

- Recognising interconnections.
- Identifying and understanding feedback.
- Understanding system structure.
- Differentiating types of stocks, flows and variables.
- Identifying and understanding non-linear relationships.
- Understanding dynamic behaviour.
- Reducing complexity by modelling systems conceptually.
- Understanding systems at a different scale.

The strength of using a system's thinking approach when investigating complex problems is that the problem is viewed from several different perspectives and possibly using different methodologies. The challenge that arises is which of the numerous methodologies available are the best to apply under specific circumstances. One possible approach to answering this question is to approach the complex problem domain from a Systems of Systems Methodology (SOSM) or multi-methodology approach defined by Jackson [28]. This approach is described in more detail and presented in Table 2.

Irrespective of the specific approach or methodology applied, it is postulated that communication plays a significant role in the successful intervention within the complex problem domain.

‡ distinctions, systems, relationship, perspectives

§ vision, mission, capacity, leadership

Table 2: Multi-methodology approach as defined by Jackson [28]

Step	Activity
Step 1: Explore the problem situation.	• View the problem situation from a variety of system perspectives. • Identify primary and secondary issues.
Step 2: Produce an intervention Strategy.	• Appreciate the variety of systems approaches. • Choose the appropriate systems methodology. • Choose appropriate systems models and. Methods. • Structure, schedule and set objectives for the intervention.
Step 3: Intervene flexibly.	• Stay alert to the evolving situation. • Stay flexible about appropriate methodologies, models, and methods.
Step 4: Check on progress.	• Evaluate improvements achieved. • Reflect on the systems approaches used. • Discuss and agree on the next steps.

2.4 Paper layout

Section 1 of the paper presents a rationale for the research. Section 2 presents the research methodology and paper layout. Section 3 provides an overview of systems thinking and complex systems (Please note that this is not an exhaustive review of systems thinking methodologies and approaches but rather a review of the application of systems thinking concepts for intervening in complex problems). Section 4 discusses the role of communication in the systems thinking process. Section 5 examines the role that communication plays in the systems thinking process and the challenges that manifest during the communication process. Section 6 provides a conclusion for the paper and recommends further research.

3 SYSTEMS THINKING AND COMPLEX SYSTEMS OVERVIEW

3.1 General characteristics of a system

A system can be visualised as several interconnected elements that function together, intending to achieve a common goal or purpose [9], [34]–[36]. The elements of the system are contained within a system boundary. Inputs and outputs to the system travel over this boundary and provide an interface to the external environment world. The concept of a system is shown in Figure 2. From this diagram, the following parts of a system can be identified:

a. Elements: Elements are the individual building blocks of a system. Elements may represent a physical item but may also be intangible [29], [36].
b. Interconnections or relationships: Elements interact via the interconnections or relationships between them. These interconnections or relationships can be challenging to identify as they may not be physically visible but represent a flow of information. Altering any of the interconnections or relationships will impact the overall functioning of the complete system [36].
c. Function or purpose: A system exists to fulfil a specific function or purpose. The term function is typically reserved for non-human systems and the term purpose when referring to a system containing humans.

d. Boundary: A system is further defined by the boundary that separates it from the environment. The system is interconnected to the environments and other systems via the inputs and outputs [34].
e. Environment: The system's function can change and react to the environment around them. They respond to changes and find ways to survive when things go wrong. This response to change is valid whether it is a living or non-living system [36].
f. Feedback Loops: Elements may be interconnected to create feedback loops. These feedback loops can either result in goal-seeking behaviour (negative feedback loops) or an unstable condition (positive feedback loops).
g. Delays: The flow of information between two elements may be delayed. These delays may again cause instability in the system or, on the other hand, may act as a filter to dampen some undesired behaviour.

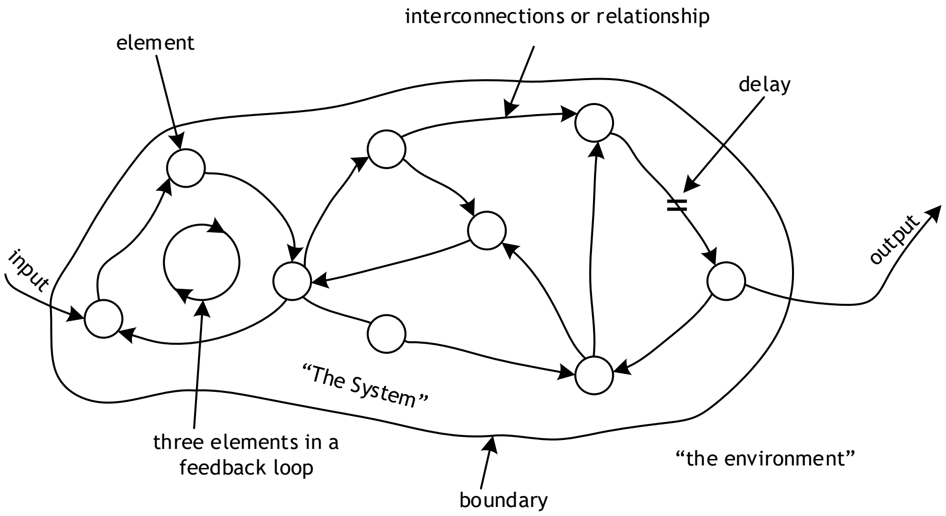

Figure 2: Structure of a generic system [34]

A system is more than just the sum of its parts [37]. A system may exhibit changing or emergent behaviour over time, manifesting as adaptive, dynamic, goal-seeking, self-preservation, and sometimes evolutionary, all depending on the number of elements present in the system as well as the types of feedback loops present and the nature of the delays observed in the system.

A system further operates within a specific environment and reacts to changes within the environment to try and maintain its existence [34], [38]. A system can also achieve a state of homeostasis when it maintains itself in a dynamic, steady state when operating in a changing environment. It is done via the control mechanisms in a system that operates via the feedback loops present in the system. This ability of a system to adapt to its environment also increases its resilience.

Systems also have an identity that helps to define the unique elements or the specific instance of realisation [34]. Systems can be divided into smaller systems, each with its own characteristics and identities [34]-[36].

A system can be classified as being either open or closed. A system can be considered open if the boundary allows inputs and outputs. An open system can attain a stationary condition. This condition occurs when the system's state appears constant, even though inflow and outflow are still happening. Closed systems are characterised as systems where materials are not entering or leaving. In a closed system, interactions only happen within the system. A closed system is shut off from the outside environment, and every interaction happens only within that closed system.

3.2 Characteristics of complex systems

The organisation of their properties can define the characteristics of complex systems. The following characteristics can be observed:

a. The parts of a complex system can be complex themselves.
b. A system can consist of simple parts but exhibit complex behaviour (emergent complexity).
c. A system can have complex parts but exhibit simple behaviour (emergent simplicity) [39].

A first-order indication of the complexity of a system can be obtained by looking at the amount of information needed to describe the system [39].

An alternative view of the characteristics of complex systems is shown in Figure 3.

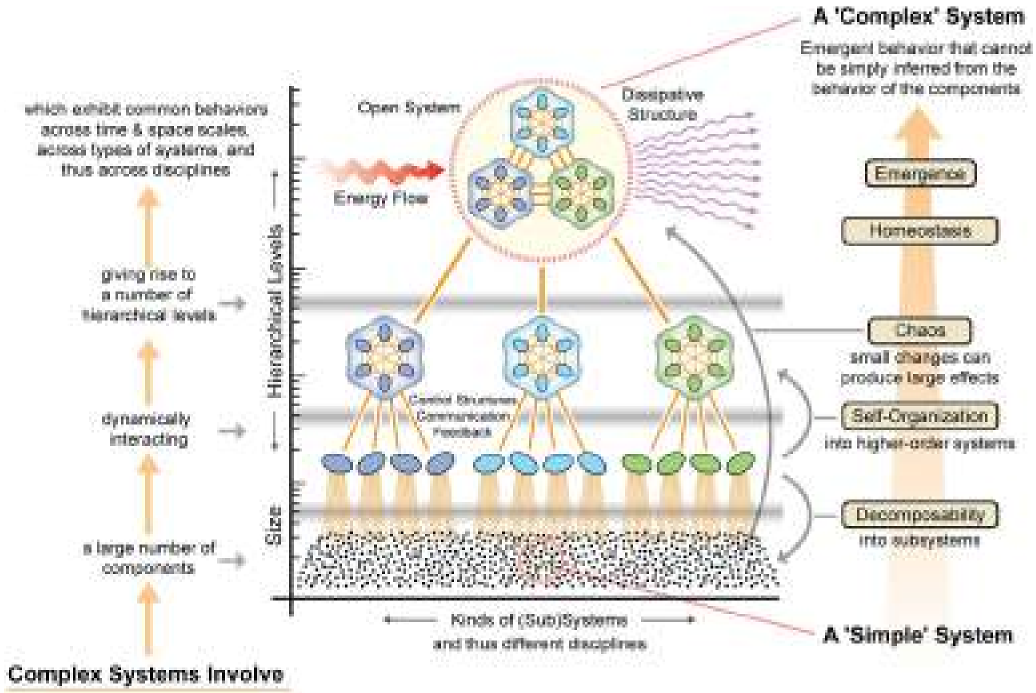

Figure 3: Characteristics of Complex Systems [40]

3.3 The application of systems thinking to a complex problem situation

The primary role of the systems thinker in a complex problem situation is to implement the typical activities associated with steps 1-4, as defined in Table 2. The systems thinker can approach the systems thinking process from one of two perspectives. The first approach is to follow an observation strategy and not get directly involved within the system of interest. Popper, as quoted by Midgley [41], states that for an event to be observable, it must be testable, thereby providing "inter-subject agreement". The observer should not influence the observed in any way. The second approach is to follow an intervention strategy where the systems thinker gets directly involved in the system of interest. The intervention approach is closely aligned with the practice of action research. In action research, the focus is to conduct the aim not just to satisfy the curiosity of the research but for the benefit of society [41].

3.3.1 Exploring the problem situation employing observation

When the systems thinker approaches the system of interest from an observation point of view, the primary intention is to ensure that the problem situation can be inspected without causing any changes or interference within the observed problem situation. The interaction between the systems thinker and the system of interest can be visualised, as shown in Figure 4.

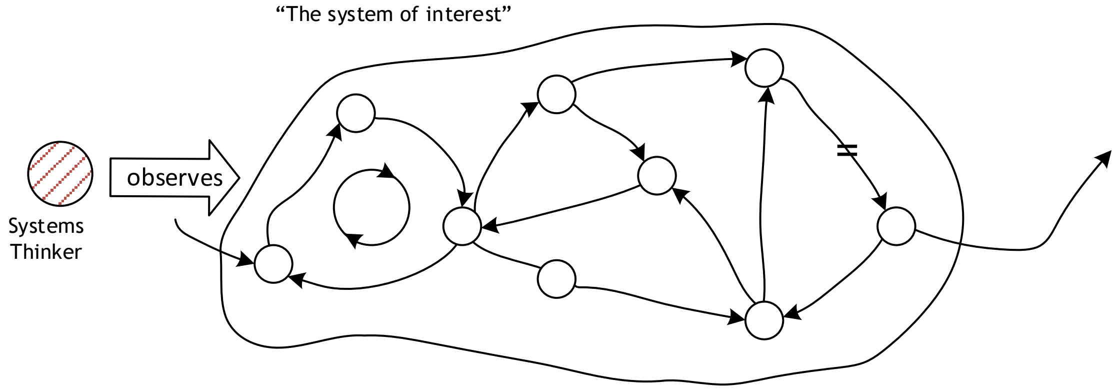

Figure 4: Interaction between the systems thinker as an observer and the "system of interest" (Own contribution)

The information the systems thinker requires to explore the problem can typically be obtained from two sources. These two sources are the various stakeholders that are either directly involved in the system or represent elements of the system and documentation relating to the functioning and construction of the system that may provide additional insight into the problem situation [42]-[45]. Collecting the necessary information can include structured interviews, questionnaires, and task analysis [45], [46]. This form of communication is highly structured and leaves no room for additional clarification of the questions or answers. This type of communication can be specifically problematic since the interviewed stakeholders express their views based on their implicit understanding of the problem (which may be incorrect, misinformed, or suffer from a lack of drive or perceived ownership of the problem). This approach may lead to different stakeholders expressing the same problem situation but in different ways that may not always be related to one another. Organisational issues and political factors within the problem situation may also lead to stakeholders not communicating the complete truth. Since the interview is structured and, in many cases, impersonal, there is a risk that a flawed view of the problem situation will be obtained, leading to a flawed improvement activity.

These one-way communication channels are often time-consuming depending on the size of the system of interest and, in many cases, resort to some form of written communication. Curtis et al. [47] have observed that written information is often ineffective as it does not provide any means to help resolve misunderstandings.

3.3.2 Exploring the problem situation through intervention

When the systems thinker approaches the exploration of the problem from an intervention point of view, they become actively involved in the problem situation [WordWeb] [41], [48]. In doing so, the systems thinker must approach the problem under investigation as an improvement problem.

The systems thinker stands within the system's boundaries and becomes, in essence, one of the elements. This additional element and interface of the system may result in potentially changing the function of the system. The concept of the systems thinker intervening in the problem situation is shown in Figure 5.

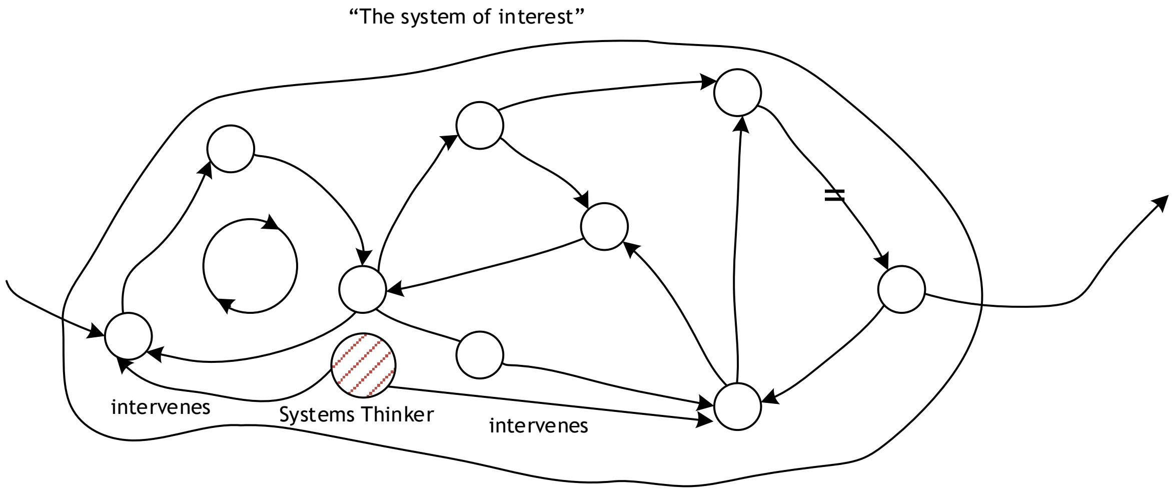

Figure 5: Interaction between the systems thinker as intervenor and the "system of interest"

4 THE ROLE OF COMMUNICATION IN THE SYSTEMS THINKING PROCESS

4.1 Classification of communication

Communication is defined as transferring information and, in complex systems, usually occurs between people or groups of people [48]. Communication can take place in different forms depending on the specific intention of the communication or the setting in which the communication takes place. These forms of communication typically include verbal communication, which includes both speaking and listening; non-verbal communication; written communication; and visual communication. Within this communication concept, the act of listening requires both comprehension and understanding. Communication can also take place on a one-to-one basis (for example, a personal interview), a one-to-many basis (for example, a speaker at a conference), a many-to-one basis (for example, a panel interview), or a many-to-many basis (for example during interactions between different groups). There are different parts involved in communication process. These parts are summarised in Table 3.

Table 3: Different aspects involved in the communication process

Part of the communication process	Description
Sender	The person who initiates the communication process
Encoding	Converting the information into words, symbols, and expressions
Message	The information to be communicated
Channel	The way that the information is transferred between the sender and receiver (speech, text, diagrams, models)
Receiver	The intended recipient of the message
Decoding	Converting the words, symbols, and expressions back into information
Feedback	Any acknowledgement that the information was conveyed correctly
Noise	Disturbances that may form a barrier to or corrupt the communication process.

4.2 General challenges in the communications process

The quality and success of communication can be compromised due to various reasons. The following list identifies some of the more common reasons as well as which part of the communication process could be impacted:

- Lack of a standard dictionary or ontology to define the concepts. (Impacting the encoding or the decoding of the message)
- The level of domain knowledge is present at both the sender and the receiver. Both parties and the other stakeholders require a certain amount of knowledge of the nature of the business and the needs that must be solved. The level of familiarity that is required does not only include familiarity with the operation of the business but also extends to domain knowledge that describes the nature and culture of the organisation (including specific terminology and abbreviations that may be used within the organisation) [49]. (Impacting the encoding/decoding of the message.)
- Different first or home languages. (Impacting the encoding/decoding of the message as well as the addition of noise into the communication process)
- Different levels of domain knowledge of the subject at hand. (Impacting the encoding/decoding of the message) [50]
- Communication across national or international borders or by multi-national stakeholders. (Impacting the encoding/decoding of the message and the addition of noise into the communication channel. A further impact to the level of engagement of both the sender as well as the receiver if there are significant time zone differences)
- Lack of face-to-face communication or cultural and emotional aspects may present. (Impacting the encoding and/or decoding of the message and the addition of noise into the communication channel).
- Conflict within the communication process. Ahmad [51] identified that when the systems thinker deals with the various stakeholders, it will be inevitable that a certain level of conflict may occur. This conflict arises because each stakeholder, as an individual, has his or her perspectives and perceptions of what the problem is. However, as stakeholders, they also represent the larger organisation. In that role, they may have different concerns, priorities, and responsibilities and, as such, communicate it via different systems perspectives than is the case. This duality in the nature of the stakeholder is shown in Figure 2. (Impact on the engagement of sender and receiver, the encoding or decoding of the message, and the addition of noise into the communication channel).
- Trust within the communication process. A certain minimum level of trust is required to transmit the message from the sender to the receiver successfully. (Impacting both the sender and receiver and the level of noise present in the communication channel [52].
- Stakeholder-introduced misinformation may surface an incorrect description of the problem. This type of situation may occur when the systems thinker does not have access to the actual stakeholders experiencing the problem but rather to intermediaries that interpret the problem situation and then convey it to the system thinker. This situation is more likely to occur in organisations with a solid hierarchical structure, such as large corporate/government or military organisations. In such a case, the systems thinker may only have access to middle or senior management. These stakeholders may perceive the needs but lack first-hand experience [53]. (Impacting the encoding of the content of the message being transmitted).

The net effect of these challenges is that it can result in an incorrect problem situation being analysed and a potentially failed intervention project in the end [50].

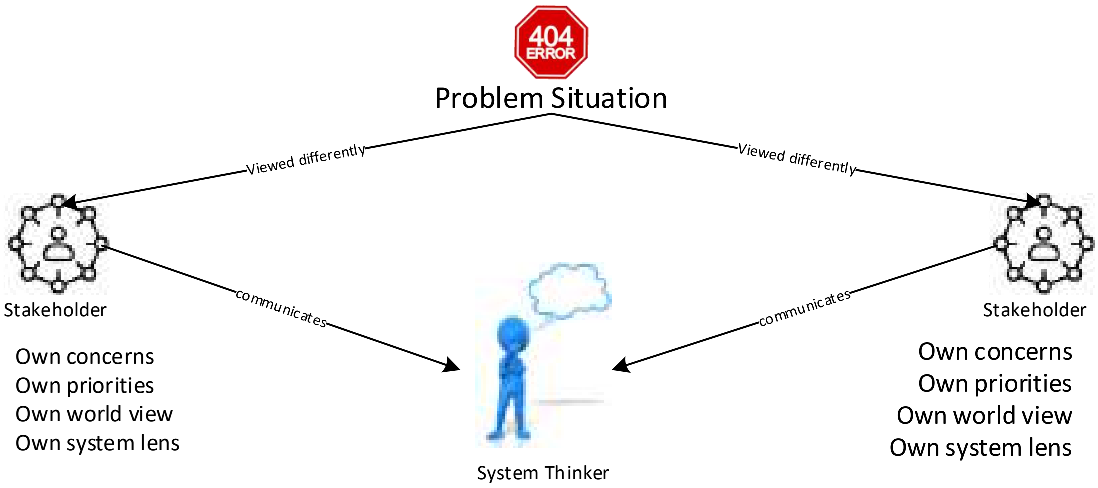

Figure 6: Duality in the nature of the stakeholder (Own contribution)

4.3 The importance of communication in a complex system

Independent of the means of communication, it is clear that effective knowledge sharing and information exchange between different stakeholders in a complex system can only take place when there is effective communication [54]. A multi-methodology systems thinking approach was introduced in Table 2. The advantage of this approach is that it allows the systems thinker to select an appropriate methodology based on the characteristics of the problem situation and the nature of the stakeholders involved as well as the appropriate communication strategy required by the selected method. The role of proper and successful communication during the different phases of the multi-methodology systems thinking approach will require different communication skills. These items are highlighted in the following sections.

4.4 Multi-methodology Step 1: Explore the problem situation

The main objective for a systems thinker when approaching a complex problem situation is to ideally find a solution to the problem or, at the very least, since it is a complex problem situation, find ways to improve the problem situation. Whatever the outcome of the exercise, the systems thinker will need to explore the problem situation to gain an understanding of the complete scope of the problem. If the systems thinker identifies the incorrect problem or a partially incorrect problem, the quality of the solution and intervention proposed could be doubted. The systems thinker must engage with the various stakeholders to gain this understanding of the actual and complete problem. The stakeholders are not just the person directly involved with the system but also include various other groups of people, such as the community, who may be affected by aspects resulting from the system's operation. The stakeholders further have specific characteristics that will directly influence the range and quality of the information they can obtain. The characteristics typically include the following:

- Inherent knowledge (domain or technical);
- Experience;
- Role within the organisation (strategic, tactical, or operational); and
- Interpersonal skills [42].

This engagement between the systems thinker and the stakeholders can be approached from two fronts. The first approach that can be used is to observe the problem situation and interact with it so that the situation is not influenced in any way [41]. The second approach to engaging with the stakeholders will be directly intervening in the problem using an approach such as action research. Action research can be defined as a research approach that places the research within a local context and focuses on a local issue. The research is conducted by the systems thinker and for the systems thinker. The result of the research may lead to some form of action or a change that may be implemented by the systems thinker in the problem context in order to improve [55]–[57].

The type of communication required in this first step will include verbal and written communication that can be obtained during one-to-one or one-to-many situations. The systems thinker or investigator need to ensure that following elements of the communication process is correctly included:

- Sender
- Encoding
- Message
- Channel
- Receiver
- Decoding
- Feedback
- Noise

4.5 Step 2: Produce an intervention strategy

During the second step in the critical systems thinking process, the systems thinker focuses on producing a muti-methodology intervention strategy. This activity can be done independently from the stakeholders involved in the problem and thus independent from any need of communicating with them.

4.6 Step 3: Intervene flexibly

During the third step of the critical systems thinking process, the systems thinker must introduce the intervention strategy sensitively and flexibly into the problem situation. Communication between the various stakeholders will be crucial to be immediately aware if the intervention strategy is causing harm or has unanticipated and undesired side effects. Again the systems thinker or investigator will have to ensure that all of the elements of the communication process is addressed in detail as identified in section 4.4 above.

4.7 Step 4: Check on progress

In the introduction of this paper, it was discussed that it will not always be possible to produce an absolute solution to a complex problem but rather only to achieve an improvement. To determine if an improvement has been achieved, it is necessary to have a comparison of the problem situation prior to the application of the intervention strategy and after the application of the intervention strategy. Again, communication between the stakeholders will be vital to provide information about this evaluation process and in a similar way the systems thinker or investigator will have to ensure that all of the elements of the communication process is addressed in detail as identified in section 4.4 above.

5 SUMMARY AND CONCLUSION

We live in a world that presents us with complex problems daily. Systems thinking provides an approach to intervening in these complex problems with the aim of bring about an improved situation. Various system thinking methodologies have been identified in the literature, each with their strengths and weaknesses. It is recommended that a multi-methodology approach is used for the systems thinker to explore the problem situation and to implement and evaluate the success of the solution.

The success of this process is highly dependent on the correct identification and understanding the actual problem situation to be addressed as well as the subsequent evaluation of the result of the implementation. This understanding highly depends upon successful and clear communication between the stakeholders, including the systems thinker or investigator.

The paper further identified communication challenges the systems thinker might experience during the intervention process. It is hoped that advanced knowledge of the possible presence of such challenges can forearm the systems thinker to minimise the effect on the process.

5.1 Further research opportunities

The research presented in this paper is based on literary review and inductive reasoning based on the researcher personal experience. This research can be further expanded by the conducting of interviews and the analysis of such results to provide confirmation (or the disproving) of the identified challenges, the identification of missing challenges as well as the prevalence and ranking of these challenges.

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BENEFIT REALISATION OF RAILWAY TECHNOLOGY INVESTMENTS

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ABSTRACT

Measuring the effectiveness of IT projects and their impact on company performance is a topic that will be debated for many years to come. Meanwhile, businesses are investing billions of rands in building, maintaining, and upgrading their IT infrastructure. Putting aside the criticism of big investments' financial returns and bottom-line development, there is a more serious long-term concern: the detrimental impact of the organisation's incapacity to effectively manage IT. The shift in focus for technology projects from the delivery of technical solutions to the realisation of business advantages indicates a gap in the literature about how to best implement benefits realisation in the railway industry. This study examines the organisational impact of poor benefits realisation management and seeks to identify and remediate inhibitors of benefits management. A comparison of the benefits management models employed in the railway sector with industry recognised best practice is also performed.

Keywords: Benefits management, organisational impact, inhibitor, technology investment, value, railway

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1 INTRODUCTION

Organisations have been forced to spend significantly on Information Technology (IT) because of the digital revolution. Companies as well as governments spend a lot of money on IT-related services. An annual increase of 2.7% indicates that IT is a continuous investment. This continuous investment in IT is also evident from a South African perspective where South African companies spend R87 billion in 2020 [1, 2]. Empirical studies indicate a correlation between IT capability and organisational performance, and further, denote an opportunity for sustained competitive advantage [3].

Allowing technology to drive business plans results in information systems (IS) that invariably influences a company's economic performance and employee working conditions [4]. IT-driven organisational transformation changes the company processes and work habits in favour of lower costs, higher output quality, improved innovation and product creation, and better customer service. These advantages highlight the significance of IT investments [5]. Reports such as the Chaos Chronicles indicate that IT project success is still below acceptable norms [6]. Different sources provide different statistics on IT project success but the average success rate of IT projects is about 30– 40% [1, 6]. While the financial costs of project failures are significant, the missed opportunities and projected economic gains should be prioritized [7].

The evaluation of IT investments and the realisation of the benefits is a convoluted maze of financial, social, organisational, technical and procedural pathways, of which many are either avoided or ineffectively navigated [2]. The organisational relevance lies in the fact that some companies can identify, execute and realise benefits from their IT investments whilst the rest are clouded as to what the outcome will be when the new technology is deployed. The research aim is to investigate the failed approach to successfully implementing benefits management as per industry-accepted best practice guidelines in the railway sector. This leads to the fruitless investment of corporate funds without any significant improvement in operational or financial performance. Furthermore, the importance of value generation and the elimination of wasteful activities are emphasized in the programme development implementation and delivery such that clear links are established between benefits realisation plans and outcomes [8].

2 LITERATURE REVIEW

Using benefits realisation management (BRM) methods increases the likelihood of projects meeting their organisational goals in relation to IT investments. Companies that implement IT, seldom implement benefits management plans, and only a small percentage of companies use a comprehensive life-cycle strategy [9, 10]. Scholars ascribe this to a lack of understanding of the usefulness of such methods, as well as organisations that are not trained enough to apply them [9]. Furthermore, management practices have gotten preoccupied with manipulating return-on-investment statistics and have neglected to consider how IT might provide significant value to the organisation [11]. Whilst pre-investment and post-investment appraisals do carry weight for evaluation purposes, they are inadequate for guaranteeing that the benefits required are realized. More than 20% of all Chief Information Officers (CIOs) believe their IT expenditures have failed to provide positive business results [11]. A recent report suggested that 88% of CIOs believe that business is frustrated by IT’s failure to deliver value [12]. An increased focus on BRM might help to address the high failure rate of IT-enabled transformation programmes and contribute positively to the interaction between the organisation and its employees [11].

2.1 Benefits Management

Benefits management or Benefits Realisation Management, is a guideline to increase the probability of success for IT projects [13]. Benefits Realisation Management signifies the process of managing and organising, such that the prospective benefits arising from investments in change are achieved [10, 11]. A benefit can be described as an outcome of change that is perceived as positive by a stakeholder [10]. Contrarily, disbenefits are outputs of change that are negatively viewed by stakeholders. Benefits can further be detailed as improvements or contributions toward business value from a broader perspective including shareholders, customers, suppliers, and the greater society [14].

For organisations to extract benefits from IT and technology innovations, the business must develop a multidisciplinary benefits realisation capability that is not purely focused on the technology or IT function [3]. The mistaken understanding of "benefits" and "value" is one of the issues that may explain BRM's low adoption [15]. This is due to the terminology's many meanings and the lack of uniformity in the definitions [10]. This indicates a lack of consensus on how benefits should be classified and quantified. Stakeholder value is delivered through good business strategies, which can take the shape of long-term revenue generation in the private sector or the ability to offer value to the public in the government sector. The adoption of strategic initiatives and innovative practices fills the value gap by enabling new capabilities and encouraging changes through the outcomes of a program with a defined set of projects [14]. The concept of BRM is synonymous with value and Value Management (VM) which compels projects to be justified in terms of a balance between the strategic needs versus the resource utilization [10]. It is the changes to organisational processes and relationships that generate the most business benefits and these need to cohabitate with the technological changes [16].

The rationale behind a benefits management process model emphasizes the significance of developing a realistic and comprehensive image of the costs relating to business changes required for benefits delivery. This serves as an extension of the traditional technology development and integration costs [16]. The adoption of a benefits management model complements the investment appraisal and justifies the investment. The analysis and cross-evaluation of the different models for benefits management indicate several disparities between them. Whilst some models provide a detailed discussion on benefits identification, others lack context with regards to the guidelines for the realisation of benefits.

The framework developed by [17], serves as a guide to compare models using a basis of philosophy (paradigm, target, domain and objectives), model, scope, outputs and practice. The philosophy is underpinned by a set of principles that underlie a method. The paradigm of a philosophy denotes the application of a specific rationale when thinking about problems. This may take the form of either science or systems. The science paradigm uses formalisation and repeatability to describe the world and, as a result, accumulates knowledge through the refutation of hypotheses. The holistic view, as well as emergent features and interrelationships, are the focus of the systems paradigm.

The philosophy’s target defines which tasks and environments the approach is appropriate for. Two approaches are identified i.e. instrumental and social. The instrumental approach focuses on objects of the method, assessment criteria of the method, support of the decision-making process, and the measuring scale of the technique. The social approach concentrates on how to raise the project's value through the improvement of the project's benefits. The model specifies the constructs that are used to mimic the real world, and the scope of the model identifies the various phases of the benefits management life cycle i.e. identify, realise, assess and quantify. The importance of benefit quantification forms part of the evaluation criteria due to the importance expressed by stakeholders. The backdrop of the method, academic and commercial are defined in the practice of a specific benefits management method. The allocation of roles and responsibilities are factors that are also examined in this criterion. When the roles and responsibilities in each phase are detailed, it is considered to be briefly explained and when the collaboration between the specified roles is addressed or their duties are established, it is considered thoroughly discussed.

Furthermore, an item was labelled as briefly discussed if it was merely cited as a process step or mentioned, but it was labelled as discussed if considerable information and techniques were offered. Using the collective work of [18] and [17] allows for the comparison of different benefits management methods with a detailed overview. An outline of the legend for the BRM cross-evaluation table, seen in Table 1, can be summarised as follows: Science (H), Systems (S), the subject discussed (√), academic (A), commercial (C) briefly discussed (±), not discussed (×) and both (B).

Table 1: BRM method comparison

Method	Philosophy	Target	Practice	Model	Instrumental Approach				Social Approach	Scope				Roles
					Measurability	The evaluation process of benefits	Organisational change	Performance	Opportunities exploitation	Identify	Realize	Assess	Quantify	
Cranfield Process Model of Benefits Management	B	IT	A	Process model, verbal guidelines	√	√	√	√	√	√	√	√	√	√
Benefits Realisation Management Framework - Project Management Institute	B	Any	A	Verbal (process) guidelines	√	√	√	×	±	√	√	√	±	√
Benefits Realisation Approach	S	IT	C	Verbal (process) guidelines	√	±	√	√	√	√	√	±	±	√
The “Best Practice” Framework for Benefits Realisation	S	IT	A	Process model, verbal guidelines	×	×	±	×	±	±	±	±	±	×
Active Benefits Realisation (ABR) Approach	B	IS	A	Process model, financial model, verbal guidelines	√	±	√	√	√	√	√	√	√	±
Benefits Realisation Capability Model	S	IT	A	Process model, verbal guidelines from literature	±	×	±	√	±	√	√	√	√	×
ORBIT Model	S	IT	C	Process model, verbal guidelines	±	±	±	±	±	±	±	±	±	±

The Cranefield Process Model was chosen as the baseline evaluation because it is the most holistic and is based on a life-cycle approach [19]. To optimise business value, the Cranfield Process Model lays out several interrelated processes that will assist firms in identifying, defining, justifying, planning, implementing, and evaluating benefit-driven IT/IS activities. The framework also effectively addresses, engages, and connects stakeholders with benefits as benefit owners, resulting in stakeholders' knowledge and commitment to the realisation of the defined benefits. The inclusion of customers in the benefits realisation process increases the alignment of business and IT.

2.2 Responsibility for Benefits Realisation Management

Confusion often arises as to who is responsible for the realisation of benefits [20, 21]. The target audience for the majority of the prescriptive work which details the resources required and methods for benefits realisation has generally been managers and not the practitioners who deliver the technological solution [22]. This shortcoming was noted as a challenge for the adoption of benefits-oriented practices as technology development clients and consultants may both view it as the other party's responsibility to ensure that benefits are realised [23].

It was discovered that the majority of the focus for role players in benefits realisation has been placed on the project manager, project team, project management office (PMO) and program manager [20]. However, the roles and key responsibilities are inconsistently recorded and key officials such as the project champion, project sponsor, customer and client have often been overlooked in the benefits realisation process. A common trait amongst modern scholars is the introduction of the role of a "project owner" to lead the benefits management process. This refers to a person who is responsible for carrying out the project's business case and achieving its objectives [20, 21].

An overview of the roles and responsibilities of the project owner is presented in Figure 1. The weight of project costs, project delivery and benefits cannot be observed in insolation. This calls for tight-knit cooperation between the project manager and the sponsor/ project owner. Further investigation of the academic work presented in [21] conflicts with that of [24], regarding the synonymity between the role of the sponsor and the project owner. The sponsor is an organisation's senior executive manager who offers resources, leadership, and political or top management support to the project team during execution. As a result, because the sponsor frequently represents the interests of a third party in the project, they are unable to be held liable for the strategic and long-term benefits sought by the funding body that began it.

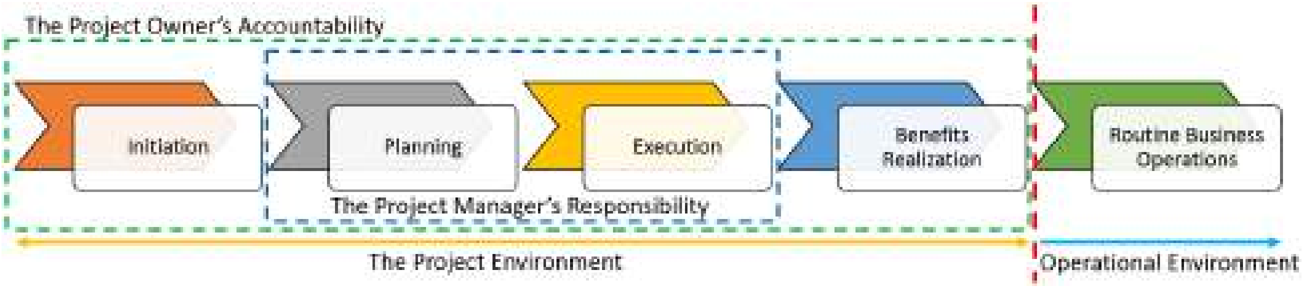

Figure 1: Project benefits management phases [21]

2.3 BRM Inhibitors

Literature reviewed indicated a vast distribution among the types of inhibitors encountered in the practice of benefits realisation management and demonstrated common traits encountered in the industry. Employee opposition to new ways of working was the most identified organisational barrier. Financial managers lacked flexibility and were resistant to adopting new benefits management strategies, preferring to cling to the old routines [5]. Furthermore, BRM practices imposed uniformity that did not reflect managers' experience. The second organisational hurdle referred to varying levels of departmental acceptability, which reflected a lack of consistency [5]. There were also two technological obstacles. These are connected to sluggish response times and poorly developed reports. The BRM's normal report outputs reflect the expectations of budget holders and accountants, but they may also reflect a desire to maintain long-standing traditions [5]. As a result, these impediments reinforced a lack of engagement by individual managers and departments.

3 RESEARCH METHODOLOGY

The research problem of low benefits realisation from technological investments in the railway sector is the foundation for a definitive understanding of this topic. The consequences of this phenomenon not only result in lost economic opportunities but also in a never-ending cycle of poorly managed IT initiatives and decreased IT system reliability. The study's goal was to alleviate the crisis of unsatisfactory benefits realisation by offering a detailed diagnosis and treatment of the problem. Part of the diagnosis entailed comparing the current benefits management method with that of the Cranefield Process Model as well as identifying the barriers that prohibit the adoption of BRM.

A qualitative case study approach was used since it is a comprehensive analysis of a specific event or circumstance conducted in the field. The case study's purpose was to show how a phenomenon operates in context. One of the advantages of using a case study method is the capacity to perform in-depth investigations of specific empirical circumstances [25]. The case used for this study is a heavy haul railway organisation that has executed technology investment initiatives to improve operational performance. The unit of analysis for the case study is the process followed for benefits realisation management regarding technology initiatives. The departments within the division of Capital Projects and Information and Communications Technology Management are relevant for data acquisition.

The data collection methods utilized were electronic questionnaires and organisational documents. Document analysis is a systematic method for analysing and evaluating documents, both printed and electronic, to extract meaning and generate empirical knowledge [26]. Information was collected from several railway business cases, project documents, meeting minutes and corporate strategy studies.

Questionnaires provide case study researchers with a data collection technique that depends on written self-reports to gain qualitative data on an individual knowledge or attitudes toward a specific topic. Closed-ended questions, which enable respondents to pick their replies on a form, are frequently used in questionnaires. As a result of this, responses are pre-coded [25]. To measure each respondent's degree of importance, frequency and level of agreement or disagreement to which an activity is conducted or inhibitor is scored, a Likert scale was employed as the measuring tool. The data were converted to a numerical format so that they could be analysed using computer software. The questionnaires were designed and administered to a sample population of senior management, project managers, project engineers and project team members who interact with technology projects daily and were familiar with the benefits realisation. The questionnaire consisted of two main sections. The first section provided the participants the opportunity to evaluate BRM practices based on importance and frequency. The second section focuses on the challenges that the participants experience regarding BRM. A Likert-scale was used to measure the respondents' answers. Using Google Forms as a survey administration tool, the questionnaires were sent to various individuals within the relevant technological departments. The questionnaires were distributed to 28 participants, of which 16 individuals responded in total. This equates to a response rate of 57.14%. Literature denotes that the 42% to 58% range is generally anticipated for a questionnaire response rate from senior management or executives of Information Systems [27]. To avoid biased results, a correction technique known as weighting was introduced. Weighting is one of the most essential corrective approaches for nonresponse. As it implies that each observed object in the survey is allocated a weight, and population characteristics are estimated by processing weighted data rather than the unweighted observations [28, 29].

All ethical codes were stringently implemented and participation in the study was completely voluntary.

4 RESULTS AND DATA ANALYSIS

4.1 Comparison between Railway BRM Model and Cranefield Process Model

The approach to evaluating differential weights was to list the different aspects in rank order. A numerical weight was then allocated to each attribute based on the respective rank on the list. The respective weighted product of each element in the Likert scale was calculated using the allocated weighting factor and the frequency of observations for statements on the scale. The weighted average was calculated to indicate the relevant degree of importance or the lack thereof. In the importance questionnaire analysis, a minimum score of 3.41 was required to qualify for a passing score. The minimal pass score for the frequency questionnaire analysis was 2.51 respectively.

The business cases of six projects were analysed using the same BRM practices as per the questionnaires. In an instance where an item in a statement had been perceived to be true, a 1 was allocated to that item. Contrarily, in an instance where a specific item had been perceived to be false, a 0 score was allotted. Furthermore, for the document analysis, a minimum arithmetic mean of 0.51 was required for a passing grade.

The results collected from the questionnaire and the organisational documents were then subject to case study rigor testing. This was done to eliminate bias and promote the trustworthiness of the findings. To test the reliability, the Cronbach alpha coefficient was used and yielded a favourable outcome of 0.88 for the importance questionnaire, 0.86 for the frequency questionnaire and 0.80 for the inhibitors. Validity was implemented using triangulation. Triangulation is a strategy for combining information that may be classified into two main types namely convergence and divergence [30]. This type of analysis was also congruent with the study's theoretical goals, which were to investigate various forms of knowledge. The tabulated results for the questionnaire and the document analysis along with the gap observation are presented in Table 2. Where all three datasets had met the objective for that statement, a gap is therefore not observed, meaning the organisation is compliant in that regard. This was indicated with a No response in the Gap Observation column. In an instance where all three datasets failed to meet the criteria for a specific statement, a gap is evident, and the organisation is regarded as non-compliant. This was noted with a Yes in the Gap Observation column. The mixed-case where one or two statements out of the three either meet or do not meet the criteria for a statement indicates an instance of partial compliance. This was noted with a PC (Partial Compliance) in the Gap Observation column.

Table 2: Benefits Realisation Management triangulation matrix

Category	Number	Statement	Questionnaire Data (Importance)	Questionnaire Data (Frequency)	Organisational Documentation	Gap Observation
Benefits Identification	1	Procedures are followed for identifying and specifying indicators for the intended business benefits in IT projects.	Pass	Pass	Pass	No
	2	Tangible (hard) benefits are considered when evaluating IT projects.	Pass	Pass	Pass	No
	3	Intangible (soft) benefits are considered when evaluating IT projects.	Pass	Pass	Pass	No
	4	All project benefits are recognised using the current BRM method.	Fail	Fail	Fail	Yes
	5	The allocation of KPIs or objectives is associated with the benefits of the projects that were selected.	Pass	Pass	Pass	No
Benefits Realisation Planning	6	Benefit planning mechanisms exist for IT projects.	Pass	Pass	Fail	PC
	7	The responsibility for achieving business benefits is delegated to a specific project owner for IT projects.	Pass	Pass	Pass	No
	8	A system is in place to guarantee that IT initiatives are aligned with business goals.	Pass	Pass	Pass	No
Review and Evaluate Results	9	Processes are in place to track the benefits of technology projects.	Pass	Pass	Fail	PC
	10	IT projects do post-implementation assessments of the project's commercial benefits.	Pass	Pass	Pass	No
	11	The current process adequately quantifies the relevant benefits.	Fail	Fail	Fail	Yes
Establish Potential for Further Benefits	12	A procedure exists for ensuring the benefit's long-term viability.	Pass	Pass	Fail	PC
	13	A procedure is in place to facilitate a smooth handover of benefits.	Pass	Pass	Fail	PC
General	14	Project benefits governance is adopted to improve project success.	Pass	Pass	Pass	No
	15	The current process overstates the benefits to get approval.	Fail	Pass	Pass	PC

4.1.1 Benefits Identification

The review of the triangulation matrix indicates a general sense of compliance. Only statement number four had revealed a gap in this category. Mathematical analysis indicates that 12 out of 15 items were deemed to meet the pass criteria and this equates to an 80% compliance score. The common theme in this category is that processes are in place to identify benefits and assign indicators to the relevant technological projects. The triangulation suggests evidence of this in the creation of relevant measurements and key performance indicators to compare the actual delivery of benefits to the benefits that were planned. However, the notion exists that there is a lack in the identification of all the benefits which may be realised from IT projects. This points towards an incoherent or rushed approach to benefits identification as only the apparent or noticeable benefits are recognised whilst little thought is given to further elaborate on additional benefits that may be achieved to validate the capital investment. Hard and soft benefits are equally recognised in the triangulation matrix which indicates a balanced approach to benefits identification.

4.1.2 Benefits Realisation Planning

The triangulation matrix suggests that adequate protocols are implemented in the planning phase of benefits management. The results indicate that individuals complete the benefits planning mechanism but this is juxtaposed with what was discovered in the organisational document analysis. For this category, 8 out of 9 statement items had achieved a passing grade which relates to an 89% compliance score. The document analysis revealed that individuals did not adequately plan for when benefits may be realised and what the baseline metric will be. This shows partial compliance when compared with the Cranefield baseline model.

The allocation of specific project owners was seen as a compliant area, as well as the use of a system to ensure that the project outcomes are aligned to the business goals. This shows that individuals and the business understand the different core project roles and the associated key performance criterion. The criticality in establishing unambiguous benefits and giving ownership to people to plan and oversee their realisation is essential to maximising the value returned from capital investments in technological projects.

4.1.3 Review and Evaluate Results

The post-evaluation activities are seen to be a major obstacle for the organisation. Two of the three statements indicated that the business has some form of non-compliance. From a statistical perspective, the individual item scores indicate that 5 out of 9 items obtained a passing score or a 56% compliance score. Furthermore, it was noted that individuals recall using processes to track the benefits of specific projects, but this was found to be a gap in the document analysis. The documents reviewed did not suggest that benefits are tracked and often found the project close-out reports to be missing or incomplete.

Post-implementation assessments were done by internal and external auditors to evaluate whether the deliverables proposed in the business case had been met. This was a commendable result as it illustrated stringent control measures to try and realise the commercial benefits. The insight gained indicates that the benefits often quantified during the business case may not be relevant or measurable during the project lifecycle. This was seen as a common obstacle in both the questionnaire and document analysis.

4.1.4 Establish Potential for Further Benefits

The ability to promote sustenance for technological benefits is a significant drawback for the organisation. The compliance score attained for this category equated to 67% as 4 out of 6 items achieved a passing grade. The use of procedures to ensure the long-term viability of benefits was deemed partially compliant. The evidence reviewed indicates that participants are aware of and make use of the necessary procedures, but this is contradicted by the document analysis. In the documents reviewed, most of the projects had not planned for long term sustainability initiatives. This is further supported by partial compliance with the smooth handover of benefits. Similarly, participants attest to the importance and frequent execution of these activities but the business documents reviewed contract this. With these measures in mind, it is evident that operational readiness is often not done and at best partially completed. The significance of this is seen through two lenses, namely change management and knowledge management. Poor document repositories and record-keeping indicate that critical reports in this category are either not prioritised or distributed accordingly. This leads to the inability to record the lessons learned from different projects for improvements in future initiatives. Furthermore, the half-hearted approach to change management leads to meagre employee readiness, low facilities and tools readiness and poor technology adoption.

In essence, technology allows for new procedures and methods of working, which must be handled as a business transformation programme.

4.1.5 General

The adoption of good project governance was a compliant area for the organisation. As a collective, this category accomplished an 83% compliance score where 5 out of 6 items manifested a passing grade. The benefits realisation process should be synchronised with the project business case and project plan. This alludes to an interconnection between program governance and benefits procedures. The overstatement of benefits was found to be a recurring theme. Instances of ambiguity were noted where a heavy emphasis is placed on the financial factors as opposed to the actual benefits. In addition, the reasons for project failure were extensively documented using traditional metrics. The factors often attributed to this include lack of clarity on how to execute the project or establish a business case for the investment, insufficient attention on measuring progress rather than benefits realised throughout implementation and communication issues between stakeholders and project teams. Another reason is conduct, notably project managers' lack of knowledge of their clients' expectations. This might be due to communication problems. Projects that were not evident failures but may have been inadequate in terms of giving long-term benefits may be of concern. Organisations need to make a clear distinction between project success and the realisation of project benefits.

4.2 BRM Inhibitors

The questionnaire also aimed to identify and assess the eminence of BRM inhibitors identified in the literature with that experienced. This is because the inherent problems of identifying and analysing the benefits and costs of IT adoption are frequently a source of scepticism regarding the investment's potential impact on the organisation. The publications examined divided the benefits management obstacles into two categories: organisational and technological. The accurate identification and appraisal of inhibitors towards BRM allow remedial measures to be tailored to that of the railway sector and implemented accordingly. The identified inhibitors and respondent feedback towards inhibitors of BRM are presented in Figure 2.

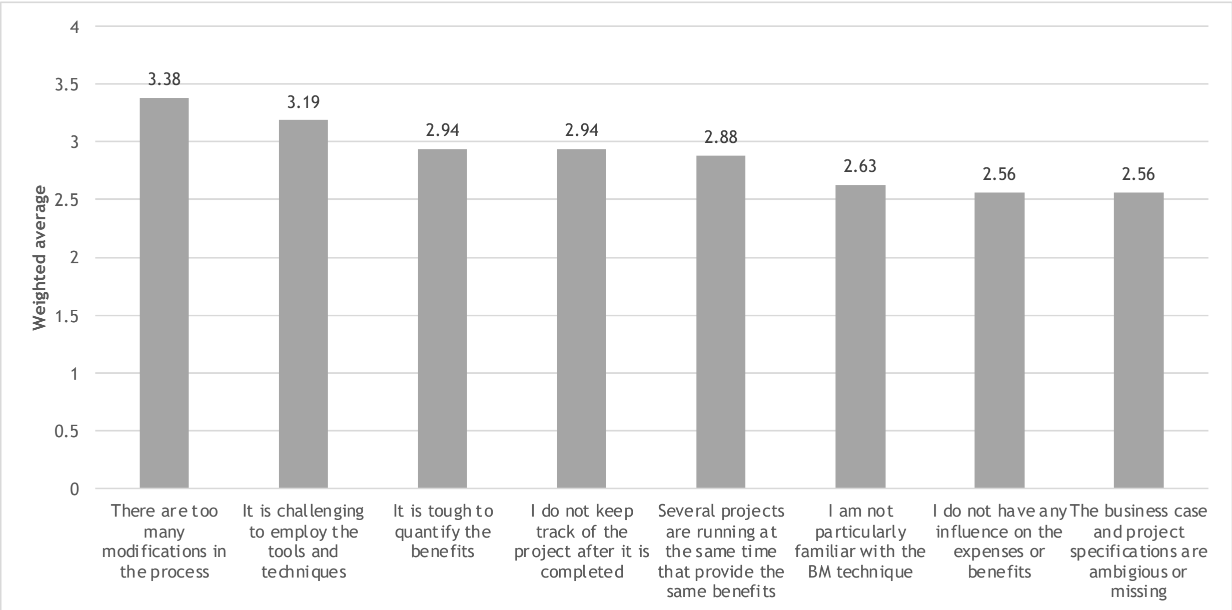

Figure 2: Inhibitors to benefits realisation management for technological projects

4.2.1 Organisational Inhibitor

The first inhibitor, benefit quantification, shows that most respondents have no trouble determining how to measure the advantages. However, a small but significant number of respondents acknowledged that quantifying benefits for technology-based projects poses some difficulties. This inhibitor's overall result is a weighted average of 2.94, which places it third on the list of inhibitors. As a result, some people may have been taught to recognise and measure advantages. Alternatively, some respondents may have worked on projects where the project advantages were primarily driven by regulatory compliance rather than being business-driven. When the findings of the first inhibitor are compared to the results of the second, a similar picture emerges. The second inhibitor tested people's knowledge of the benefits management method. According to the input received, half of the people are at least somewhat familiar with the present BRM approach. The weighted average of participants' knowledge of the benefits management method was 2.63.

The third inhibitor dealt with the impact of participants on the potential costs and benefits of an IT project. Most respondents believe they have some control over the project's outcomes. The remaining respondents were very evenly split when it came to their impact on the benefits. This inhibitor had a total score of 2.56. As a result, the challenges in estimating and realising benefits may be linked back to the tools and planning procedures used to assess their worth. The challenge may often be that the tools used are not adequate for measuring benefits and results in difficulty when planning for when the benefits may be realised [31]. The results relating to tracking benefits post project execution attest to this barrier in effectively employing benefits management.

The fifth inhibitor investigated was the simultaneous execution of initiatives that produce the same benefits. In comparison with the other inhibitors, an overall weighted average score of 2.88 was regarded as high. The rationale for this may be that technological systems do not always immediately deliver on the increased operational efficiencies and often take years to achieve any utility. The foundation of the problem might be a lack of technological adoption, with business procedures not being updated to keep up with new technologies. The ease with which benefits management approaches were applied was identified as the sixth BRM inhibitor. The bulk of the replies were neutral, indicating that using the present benefits management toolset is neither difficult nor easy. The findings of the questionnaire analysis result in a weighted average of 3.19 for this inhibitor. As a result, it's clear that corporate change procedures are frequently employed to generate benefits, and managing these changes while also managing stakeholder expectations is a difficult task. Organisations can use current change management methods in combination with a benefits realisation management programme to be more effective.

The BRM technique was mentioned as the seventh barrier, along with the necessary improvements to the process. According to the opinion of six responders, the method has too many adjustments. A quarter of the participants thought the changes were adequate, while another four people expressed their indifference with a neutral response. This inhibitor had the highest computed weighted average of the list of inhibitors presented to the workers, at 3.38. This indicates that the respondents find it challenging to use the benefits management strategy successfully. In addition, the list of essential changes includes taking a holistic view of change, managing the benefits realisation portfolio, and defining project success, all of which are restricted to the individual's ability. Thus, BRM is especially important since it forces businesses to think about the life cycle of their products and services, as well as the efforts that help them grow.

4.2.2 Technical Inhibitor

The aspect of project benefit record-keeping was studied as a potential stumbling block. According to the responses, four respondents acknowledged that they did not preserve any records of the project's benefits after it was completed. The results of the analysis show that three people stated that they maintain track of project benefits after it is completed, while another group of people stated that they are committed to keeping track of project advantages after it is completed. This statement received a weighted average of 2.94 from the aggregate inputs, putting it in third place. The rationale behind this high weighted average may relate to a shift in attention from project managers and the PMO, frequently owing to a lack of resources and time horizons [31]. Another issue may be the lack of consistent criteria or measures for assessing benefits.

The last inhibitor addressed the uncertainty in the business cases and project specifications, as well as a lack of documentation. Six individuals said the project documentation is clear and comprehensive. The remaining respondents had a mixed reaction to the project documentation. A weighted average of 2.56 was obtained. The modest result suggests that the inhibitor does not play a substantial role in the unsuccessful implementation of benefits management. However, unrealistic business cases or motivations for executing projects are among the key issues, resulting in futile project evaluations and ultimately project failure.

5 CONCLUSION

Organisational performance is composed of measures that are not purely financial in nature. Thus, a balanced approach should be taken to measure organisational performance [32]. Optimising an organisation's performance should start long before the benefits of individual initiatives are established, their execution monitored, and their completion recorded. Thus, the relation to poor benefits management is seen in the unwise selection of projects that are not aligned with the business plan or do not contribute any value to the organisation.

5.1 Impact on Organisational Performance

Analysing the impact on organisation performance through a financial lens, indicates that the poor adoption of benefits management has hindered the organisations' ability to achieve its annual targets and contributed to unwarranted financial expenditure. The reviewed documents revealed that multiple technological initiatives had been undertaken to improve the organisation's core purpose. Reflecting on some of the projects indicates that the implementation of project management principles was managed well. However, project management is not the only metric for project success. The technological investments had often failed to generate additional revenue or contribute to cost savings. Linking back to the literature on benefits management, some benefits were proposed but no measures were detailed for evaluation. In other instances, the benefits suggested were not related to the actual project in its entirety. Further, instances were noted where the benefits had been significantly exaggerated and the technology employed was of no contribution to the organisation's core principles. Therefore, simply having a new corporate IT system failed to guarantee the materialisation of benefits.

Hierarchically analysing the performance of the individual categories reveals that Benefits Realisation Planning was the best performing category with a compliance score of 89%. The second-best performing category was the benefits execution category. This category achieved a compliance score of 83%. This denotes good project management and the instillation of stringent project governance measures. Benefits Identification achieved a bronze status as per the ranking order with a compliance score of 80%. The current model for benefits identification had made provision for the identification of both hard and soft benefits but fell short in a detailed examination of all the potential benefits that may be extracted from a technological investment. The category that fell into fourth place was the ability to Establish Potential for Further Benefits category which ultimately scored 67% regarding its compliance score. The document appraisal revealed that project participants had often failed to develop sustainability measures to ensure the sustenance of project benefits or the smooth handover of project benefits.

The lowest-ranked category was the Review and Evaluate Results stage which scored 56%. A concern spotlighted by the organisational documents was the shortage of benefits tracking. No account was made for when benefits would be realised or in what format. Moreover, the identification and quantification of benefits were flagged in both the benefits identification and the benefits evaluation phase for non-compliance. Thus, the organisation is crippled by the inability to thoroughly assess all the project benefits, as well as disbenefits, leading to untapped potential in revenue and operational enhancement.

5.2 Identification and Remedy of Inhibitors to BRM

The highest-ranked inhibitor was the complexity and the number of modifications in the benefits management process. This illustrates that participants were perplexed by the BRM process and found IT initiatives to be a lengthy and difficult process with several phases to follow. This lack of consistency was further validated by the difficulty in utilising benefits management techniques. Completing a project's business case, calculating the NPV, and tracking the project's expenses and benefits were regarded as difficult tasks that require knowledge of finance and project management. The difficulty in quantifying the benefits and ensuring that adequate benefits tracking was ranked third on the inhibitor list. Furthermore, intangible benefits such as quality and innovation are not regarded as genuine benefits when developing a business case.

The fourth-ranked inhibitor addressed the concurrent execution of projects with similar benefits. This draws back to the project scope and poor benefits identification such that all the project deliverables are perceived to be the same. The lack of familiarity with benefits management techniques ranked fifth. The insight gained from this alludes to individuals utilising the benefits management technique without adequate training. This may address the high weighted average scored when participants battled to implement the benefits management toolset. The lowest-ranked inhibitors addressed the influence of participants on the project benefits and the clarity or completeness of project documents. The low ranking indicates that these factors are not of significance to the poor adoption of benefits management.

To resolve the inhibitors, the BRM process must protect the project owner's independence and equip him with management tools that ensure that the promised IT project benefits are captured. Moreover, to effectively ensure value realisation, organisations should establish an IT BRM designed specialised for technological projects with short business cases, gate reviews, and small committees made up of lower executive levels [13]. Nevertheless, to avoid missing out on strategic opportunities, a supplemental executive committee should be established to examine IT initiatives based on non-financial measures [33]. Furthermore, the requirement for training and a standard protocol for benefits management should be deeply instilled within the organisational framework.

Most projects have difficulty describing what the expected benefits of a project will be when it has not yet obtained approval from the investment committee. As a result, benefits management practitioners might initiate conversations inside the organisation about how benefits are conceived, as well as the notion of different factors regarding is perceived as benefits. Openly expressing and addressing these opinions serve as low hanging fruit for resolving any gaps in the BRM process [18]. Further, a variety of methods exist for dealing with the difficulty of maintaining continuity in the administration of benefits once a project is completed. One method alludes to the involvement of the project sponsor in post-project activities. This keeps the project sponsor interested and informed on the benefits [18].

6 LIMITATIONS AND FUTURE RESEARCH

During the research design phase, efforts were made to contain potential risks to the research study's validity. However, it is not always feasible to eliminate all risks. As a result, the study's potential limitations entail the introduction of sampling bias through the snowball sampling method. This sampling method introduces bias due to the chain referral of respondents who have a high number of social connections and refers the researcher to a large proportion of other respondents, who may have similar characteristics. Moreover, the relevant experience and project exposure of research participants. The sampling technique may have recruited some individuals who have not extensively worked on technological projects where benefits management was employed. Thus, the possibility exists that the practitioners of benefits management may not have been consulted or the department overlooked as a whole.

The goal of this study was to investigate the benefits management strategy for the railway sector. This was accomplished by determining the business impact and inhibitors of BRM, as well as comparing the present model to “best practice” standards. Even though the research's findings were communicated, it is unclear how effective the proposed remedial efforts will be in improving the organisation's BRM performance. Longitudinal studies to assess the development of benefits realised and evaluate the usability of the benefits management will be particularly important in terms of follow-up research.

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A GENERIC FRAMEWORK FOR MODELLING INVOICE PAYMENT PREDICTIONS

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ABSTRACT

Credit sales have become standard practice in most companies. This service, although sought after by many customers, creates a risk of bad debt or cash flow problems occurring if not managed appropriately. Consequently, companies often employ manual, time-consuming, and expensive techniques to follow up on outstanding invoices. We recently proposed a novel approach towards proactively identifying invoices from accounts that are likely to be paid late, or not at all, thereby facilitating intervention strategies more effectively. Several computational techniques from the realms of survival analysis or machine learning may be embedded in this approach. A generic framework for modelling invoice payment predictions is presented in this paper, with the aim of facilitating the process of data preparation, feature generation, and selecting and ensembling various models for predicting invoice payment times. Results obtained from a real-world case study in the South African private education sector are also presented in this paper.

Keywords: Survival Analysis, Machine Learning, Predictive Analytics

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1 INTRODUCTION

Except for a select few retailers or 'high street' shops, most companies offer credit sales to their customers, providing them with financial services and access to their essential goods or products. By offering such a credit facility, a company may potentially increase its sales turnover. Granting credit, however, creates certain risks if not managed appropriately, including capital tied up in accounts receivables, an increased administrative workload, and a heightened probability of incurring bad debts. A delicate trade-off, therefore, exists between increased turnover earned from sales on credit, on the one hand, and the cost and risk associated with these sales, on the other [21].

In order to manage the risks associated with offering credit, companies frequently employ a suite of intervention activities, commonly referred to as the invoice-to-cash process. Examples of these activities include providing discounts or establishing customised payment agreements, enforcing debit orders, and employing administrative employees in call centres to follow up on outstanding payments. While these techniques have achieved varying levels of success [18], they are primarily reactive and manual. As a result, these activities may be time-consuming and expensive [22], and become increasingly cumbersome as the number of credit sales increases.

The problem of managing customer credit sales has inspired a new body of research dedicated to the development of preventative techniques aimed at proactively identifying accounts likely to be paid late or not at all. This problem, often referred to as the *invoice payment prediction problem* (IPPP), has conventionally been addressed by applying statistical techniques, particularly those from the realm of survival analysis. The objective pursued in such a study is typically to estimate the potential payment date of a particular invoice. Once a payment date has been estimated, a focused intervention approach may be adopted, whereby all collection activities are directed towards high-risk customers first. Adopting such a strategy can potentially save a company valuable time and increase the potential return.

Studying invoice payment models through the lens of a statistical analysis presents additional advantages. One such advantage is that a company may estimate the number of accounts to write off as bad debt more accurately than when employing the other percentage-based methods currently prescribed in *International Financial Reporting Standards* (IFRS) 9 [19]. Furthermore, by conducting a statistical analysis, a company might uncover unexpected underlying patterns in its current customers' historical payment behaviour, thus improving its understanding of which attributes characterise a high-risk customer rather than a low-risk customer.

While abundant research has been dedicated to creating models for customer credit scoring, there is a relatively small body of work in the literature on how to apply these models in the context of the IPPP. Smirnov [6], for example, studied the application of survival analytic models in order to predict payment outcomes of right-censored invoice data. The IPPP has also been modelled as a supervised machine learning classification problem, in which a set of records (invoices) and features are used to classify each invoice as a member of a target class representing the predicted debtor's ageing period. Examples of machine learning approaches towards solving the IPPP include those of Zeng et al. [9] and Peigang et al. [10].

Our main aim in this paper is to propose a generic framework for modelling invoice payment predictions with a view to guide research related to instances of the IPPP. Our framework supports modelling approaches from both the realms of machine learning and survival analysis, enabling an analyst to study the relative performances of various modelling approaches. We also demonstrate the framework's application in an illustrative case study related to a private education company in South Africa. This case study illustrates how, when considering various time windows during a payment behaviour analysis, the relative performances of models and the underlying predictive features selected may vary considerably.

The paper is organised as follows. Section 2 contains a brief overview of the literature related to the IPPP. Next, we describe our generic framework briefly in Section 3. This is followed in Section 4 by a presentation and discussion of the results obtained when applying the framework in a practical case study. The paper finally closes with a brief summary of its contributions and ideas for future work in Section 5.

2 LITERATURE REVIEW

Several approaches put forward in the literature for solving the IPPP have originated from the related domain of credit scoring. In credit scoring, the objective is to determine *whether* credit applicants will result in 'good' or 'poor' payers, based on their recent credit repayment history. Examples of techniques employed in this domain include, among others, discriminant analysis [1], logistic regression [2], and genetic algorithms [3]. An extension to the credit scoring problem often pursued in the related literature refers to the problem of determining *when* applicants will likely default, given that they are poor payers [4]. This problem has traditionally been addressed by means of statistical techniques, such as the Cox proportional hazards model [5] — an approach taken from the survival analytic literature. Models in the survival analytic literature are suitable for use when the objective is to predict *when* an event will occur, rather than *whether or not* it will occur — such as in the IPPP.

Following the work in the credit scoring domain, Smirnov [6] studied the effectiveness of survival analytic methods when applied to IPPP instances. In his PhD thesis, he proposed the notion of *random survival forests* — a novel supervised machine-learning classification algorithm. Smirnov gathered data from a credit provider in Estonia and concluded that random survival forests outperformed the Cox proportional hazards model when fitted to this particular data set. In a related study, Nanda [7] studied methods for improving accounts receivable collection. In this case, the number of days to payment for a particular invoice was modelled as a continuous variable. Based on this study, the author concluded that random survival regression [8] outperformed the other algorithms considered.

As mentioned earlier, a relatively small body of work exists in which IPPP instances have been considered as supervised machine-learning classification problems. One influential study adopting this approach was that of Zeng *et al.* [9]. In that study, invoices were classified as belonging to one of five classes: On time, 1−30 days late, 31−60 days late, 61−90 days late, or more than 90 days late. Various features were generated to provide machine learning models with a sufficient history of recent payment behaviour of customers, such as the percentage of invoices previously paid late. The authors noted that a machine learning classification algorithm's prediction accuracy could be increased by including features representative of recent payment behaviour. The best-performing algorithm in this case study was a decision tree algorithm, which achieved an overall accuracy of 79%.

In another study, Peigang [10] formulated the IPPP as both a dichotomous classification problem (in which case invoices were either classified as being paid late or paid on time) and a multi-class classification problem (in which case invoices were classified as belonging to one of four classes: No delay, 1−30 days, 30−90 days, or more than 90 days late). Several supervised machine learning classification algorithms were tested in both variations of the IPPP formulation, including decision trees, random forests, adaptive boosting, logistic regression, and support vector machines. In both problem instances, a random forest algorithm outperformed the other algorithms in terms of classification accuracy.

Several other authors have also modelled the IPPP as a dichotomous classification problem. Appel *et al.* [11] collected data from a multinational bank in Latin America and studied methods for improving the allocation of collection resources at the bank by proactively prioritising overdue accounts receivable. Each invoice in the data set was classified as either being paid on time (within 5 days) or late (after more than 5 days). Five classification algorithms were employed in this study, namely a naïve Bayes classifier, logistic regression, the *k*-nearest neighbours algorithm, random forests, and gradient-boosted decision trees. A parameter referred to as the window size was considered, denoting the number of look-back periods that should be considered over which to determine a customer's payment history. This parameter was introduced to emphasise recent payment behaviour more when generating features that encapsulate an account's payment history. A suitable window size for each algorithm was determined empirically, by evaluating the relative performance of each algorithm for different values for this parameter. The best results were obtained by the random forest algorithm and gradient-boosted decision trees algorithm, both employing a window size of three. These algorithms achieved classification accuracies of 77% and 76%, respectively.

Tater *et al.* [12] analysed a variation of the IPPP in which they specifically focused on predicting accounts payable rather than accounts receivable. In this context, accounts payable pertain to invoices issued by a vendor to a company which are associated with a predetermined payment timeframe. The authors interpreted the problem as a dichotomous classification problem and employed supervised machine learning algorithms to determine the likelihood of a company settling an invoice late or on time. The classification algorithms considered included gradient-boosted decision trees, random forests, logistic regression, support vector machines, and neural networks. Similar to *Appel et al.* [11], the authors found that the best-performing models were gradient-boosted decision trees and random forests, achieving F1-scores of 95.85% and 95.21%, respectively.

3 FRAMEWORK

A generic framework for modelling the IPPP is proposed in this section. As mentioned earlier, the aim of this framework is to guide users through the complex resolution process of IPPP instances. The framework has been designed to be both modular and generic, so that it is applicable in various application domains. A high-level overview of the framework is presented in §3.1, after which its constituent components are described in more detail in §3.2—3.4.

3.1 High-level overview

A high-level schematic overview of the framework is presented in Figure 1 in the form of a level-0 data flow diagram. The working of the framework is based on the notion that the payment date of an invoice is primarily influenced by the account holder's characteristics and recent payment behaviour. An account holder, in this context, refers to any individual or business that has purchased a product or service and has received an invoice requesting payment. The framework has been designed to facilitate the process of estimating payment dates, and it comprises three main parts: A database, a central functional unit, and a graphical user interface. The central functional unit further comprises three components: A processing component, a modelling component, and an analysis component.

The database component is the foundation on which the framework is built. It is utilised to store and retrieve relevant input and other intermittent data by invoking the various sub-components of the central functional unit. The database component comprises five data stores, each representing a distinct data set to be used or generated during framework execution.

The working of the framework relies heavily on feedback received from the framework user. A graphical user interface component is included for this purpose, facilitating the exchanges between the user, when issuing commands, and the central functional unit, when returning predictions and other information.

The modules in each component of the central functional unit are described in more detail in §3.1. It is important to reiterate, however, that the framework has been designed to be modular in nature. The modules described in §3.1 may, therefore, may be modified, substituted, or deleted, depending on the application of the framework to a particular IPPP instance and the personal preferences of the user.

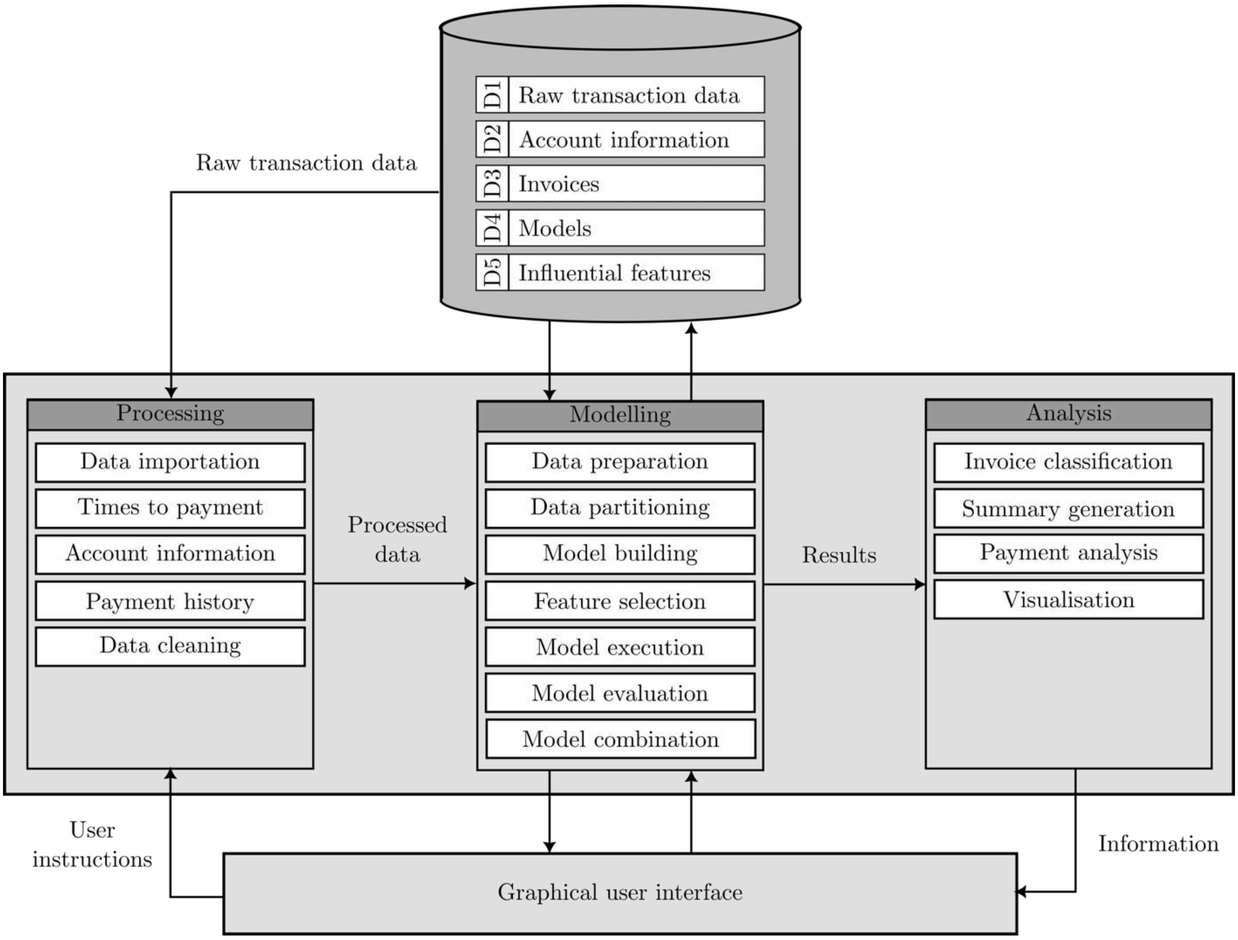

Figure 1: A schematic representation of the proposed framework for solving IPPP instances.

3.2 The processing component

The first component in the central functional unit is its processing component, which facilitates the transformation of raw data to a format suitable for modelling. This component consists of five modules: *A data importation* module, a *times to payment* module, an *account information* module, a *payment history* module, and a *data cleaning* module.

The processing component is initialised by invoking the *data importation* module, into which two data files are imported: A raw transactions data file and an account information data file. As the names suggest, the raw transaction data file contains a full transaction history of the accounts considered in the IPPP instance, while the account information data file contains supporting information recorded about all relevant accounts, for a particular year.

Once the two transaction data files have successfully been imported and formatted, the *times to payment* module is invoked to determine the payment date of each invoice contained in the aforementioned transaction data file. The working of this module depends on the underlying accounting methodology employed by the framework user. If a *balance-forward* methodology is employed, all payments from a particular account are allocated to its oldest debt first. An additional transformation of the transaction data file is therefore required first in this case to construct a debt ageing matrix. If, however, an *open-item* methodology is employed, payments are allocated to a specific 'open' invoice. In this case, the payment and invoice data sets need only be matched by means of a unique identifier value.

Once the various payment dates have been determined for the invoices included in the IPPP instance, the *account information* module is invoked to merge the supplementary account information data file with the transaction data file. The merged data set is then subjected to a feature engineering process, which is facilitated by the *payment history* module. Various features may thus be generated to capture recent and earlier payment behaviour associated with the various accounts. A variable window size may also be specified by the user so as to emphasise the recent payment history of an account. All erroneous or missing data values are finally removed from the data set by invoking the *data cleaning* module.

3.3 The modelling component

The second component of the central functional unit is its modelling component, which is aimed at developing relevant survival analytic and machine learning models in pursuit of resolving the particular IPPP instance. The first step in the modelling component is the *data preparation* module, in which various data pre-processing steps may be applied, depending on the model selected by the framework user. A *data partitioning* process is invoked in the next module. This module is aimed at partitioning the data set into a training set and a validation set, adopting a *rolling time window* approach with a view to minimise data leakage, as recommended by Appel *et al.* [11]. To combat the problem of class imbalance often encountered in IPPP instances, various class balancing techniques may be employed during the execution of the data partitioning module, including the *synthetic minority oversampling technique* (SMOTE) [13], under-sampling, over-sampling, or hybrid approaches.

A set of candidate models may then be generated in the *model building* module of the framework, after which appropriate feature selection techniques may be applied to arrive at a suitable set of predictive features (employed later in the *model execution* module). Subsequently, a *model evaluation* process commences, during which the framework user may assess the relative performances of the candidate models. Various performance evaluation metrics may be employed in this module, including the *area under the receiver operating curve* (AUC) [14], classification accuracy, and the F1-score [15]. The user may, furthermore, attempt to improve the performances of the various models by adjusting or fine-tuning the underlying hyperparameter values of each model considered. Finally, the framework user might also attempt to create an ensemble of models in the *model combination* module of the framework. The framework user may then be presented with a similar performance comparison as that mentioned in relation to the previous module.

3.4 The analysis component

The final component of the central functional unit is its analysis component. This component is included to support the analysis and synthesis of results generated in the modelling component, with an aim of relaying actionable insights to the framework user. The first module of the analysis component facilitates the process of *invoice classification*, whereby new invoices are classified upon having executed the models created in the modelling component. The framework user may, furthermore, specify a filter or aggregation setting through which an actionable results summary may be created in the *summary generation* module.

The framework user may also conduct a *payment analysis*, during which the observed payment times associated with the accounts considered in the IPPP instance are visualised. Such an analysis might, for example, involve creating survival curves by means of the Kaplan-Meier method [16] so as to gauge the probability of receiving payment over time for a particular stratified data subset specified by the user. In the final module of the analysis component, the framework user is also afforded the opportunity to conduct further analysis of the results generated in the *visualisation* module. A visualisation depicting the relationship between two features, or a feature and the predicted corresponding payment class, may, for instance, be generated with a view to improve the interpretability of the results.

4 CASE STUDY RESULTS

In this section, we present a real-world case study showcasing the practical applicability of the framework described in the preceding section. In this case study, the generic framework components are first replaced with specific elements to arrive at a computerised framework instantiation. The framework instantiation is subsequently applied to analyse an invoice data set received from a private education company in South Africa.

The case study opens with a brief discussion in §4.1 on the company background for added context. Next, the data sets provided to the authors are analysed in some detail in §4.2. This analysis includes a discussion on the necessary transformations applied during execution of the framework's processing component. The steps involved in the modelling component are presented in §4.3 in a discussion on the influence of a variable time window when solving IPPP instances, particularly in terms of classification accuracy and feature selection. The case study closes in §4.4 with a discussion on visualisations generated based on the underlying data sets.

4.1 Background to the case study

The company represented in the case study manages, acquires, and constructs independent schools across southern Africa. Its footprint in southern Africa is significant, with schools in all nine South African provinces, Botswana, and Namibia. Such a large client base presents unique challenges, one of which is the monthly collection of accounts receivable aimed at ensuring a healthy cash flow and business continuity.

In order to address the challenges of collecting accounts receivable, the case study company currently employs an array of business processes, starting on the date on which an account receives an invoice and terminating once debt has been written off as bad debt. During the first 30 days of tuition fees being outstanding, several bursars at the various schools contact the account holders to facilitate payment collection. Subsequently, a centralised call-centre is employed to collect the debt outstanding should an account remain delinquent for longer than 30 days, but for fever than 90 days. Finally, accounts that have invoices outstanding for more than 90 days are handed over to external debt collectors who facilitate various legal actions aimed at ensuring the successful collection of outstanding debt.

The company adopts a prioritisation criterion throughout the various business processes described above. Primarily based on experience and anecdotal evidence, this criterion dictates that those accounts with the largest outstanding balances which have not made any payment for the longest periods of time should be prioritised above other accounts. Such an inexact rule-of-thumb might, however, prove problematic if its underlying assumption (namely that customers with larger outstanding balances are likely to take longer to pay invoices) does not accurately reflect account repayment risk. A predictive model capable of pre-emptively identifying accounts that are likely to become delinquent within the next payment period is therefore clearly desirable, because it may likely lead to better streamlined collection efforts by the company.

4.2 Data set analysis

The transaction data set provided to the authors by the company contains a sample of 20 000 accounts, for which a total of 607 312 invoices were issued from January 2016 to October 2022. Other transaction types included in this file are payments, credit notes, and journal entries. The invoice distribution per year is summarised in Table 1.

The account information data set contains information about each account per year. This information includes, for example, the geographical area in which the account holder resides, the number of dependencies linked to the account, the age of the account holder, and the age of the eldest learner associated with the account.

Table 1: Distribution of invoices per year.

Year	2016	2017	2018	2019	2020	2021	2022
# Invoices	27 104	50 744	67 117	88 974	112 821	136 217	124 335
% of invoices	4.46%	8.36%	11.05%	14.65%	18.58%	22.43%	20.47%

In order to determine the time to payment for each invoice, the company employs the *balance-forward* accounting methodology. As mentioned earlier, the theory that underpins this methodology is that payments received from an account are always allocated to the oldest debt associated with the account first. Therefore, a monthly ageing matrix was required to partition an account's debt according to the period over which each invoice was outstanding, so that the time of payment for a particular invoice could be determined. The format of this matrix typically involves intervals of lengths which are multiples of 30 days, so that if an invoice remains unpaid during any month, it is moved on to the next interval during the following month. Consider the hypothetical scenario presented in Table 2 to demonstrate this concept. In this example, suppose that an account holder has received three invoices I_1–I_3 over three consecutive months, but has only made a payment P_1 during the third month.

Table 2: An ageing matrix for determining the oldest debt associated with an account.

Month	Invoice amount	Payment amount	Balance	Current	30 Days	60 Days
2016-01	I_1	0	I_1	I_1		
2016-02	I_2	0	$I_1 + I_2$	I_2	I_1	
2016-03	I_3	P_1	$I_1 + I_2 + I_3 - P_1$	I_3	I_2	$I_1 - P_1$

In this scenario, the oldest debt associated with the account during the third month is invoice I_1, which has remained unpaid for more than 60 days. The payment amount P_1 is therefore subtracted from I_1 first, and the payment date of I_1 becomes the date on which the payment P_1 was received. Using this matrix, the time to payment for each invoice was determined by invoking an incremental search algorithm, similar to that employed by Schoonbee *et al*. [17].

The ageing values in this matrix could not, however, be utilised directly by a machine learning algorithm, since it contains information about the outcome of an invoice during a month. To address this issue, the ageing information of each account during a particular month was offset by one month. This implies that the ageing values associated with an invoice now become the *known* ageing values of the previous month. As a result, each observation now only includes information about historical payment behaviour, but not of future payment behaviour.

As explained in Section 2, other similar studies in the literature have noted that the introduction of additional features capturing the payment behaviour of accounts has resulted in increased prediction accuracies. A few authors have even noted that implementing various time windows representing the number of look-back periods that should be considered when determining a customer's payment history, significantly influenced the performance of various time algorithms [9, 11, 20].

In this case study, a set of features was generated upon having adopted time windows ranging from 1 to 8 months. For each time window, additional features described in Table 3 were generated, and the resulting pre-processed files were stored separately. A limitation exists, however, when applying a rolling time window approach to generate historical features, since the first few entries (*i.e.* the entries corresponding to time periods that had elapsed before one complete look-back period could be observed) will not have previous information available. In this case, the missing values were substituted with zeros.

Table 3: Historical features engineered.

Feature	Description
MaxBucket	The oldest debt associated with an account, measured in 30-day intervals.
Status_NP	The percentage of months during which the account made *no payment* (NP) during the time window.
Status_PP	The percentage of months during which the account made a *partial payment* (PP) (*i.e. paid less than the invoiced amount)* during the time window.
Status_FP	The percentage of months during which the account made a *full payment* (FP) (*i.e. paid exactly the invoiced amount)* during the time window.
Status_AP	The percentage of months during which the account made an *advanced payment* (AP) (*i.e. paid more than the invoiced amount)* during the time window.
Status_NP_invamt_csum	The cumulative invoiced amount for which the account made NP during the time window.
Status_PP_invamt_csum	The cumulative invoiced amount for which the account made a PP during the time window.
Status_FP_invamt_csum	The cumulative invoiced amount for which the account made a FP during the time window.
Status_AP_invamt_csum	The cumulative invoiced amount for which the account made an AP during the time window.
Days_Since_Last_Payment	The number of days since the account made a payment.
Days_To_Payment_Average	The average number of days to payment for a particular account during the time window.
Days_To_Payment_Std	The standard deviation of the number of days to payment for a particular account holder during the time window.
Paid_Late_Count	The number of invoices paid late by a particular account during the time window.
Paid_Late_Percentage	The percentage of invoices paid late by a particular account during the time window.

Features 1—9 are unique contributions to the literature and were generated to capture any change in *payment amount* behaviour by the account holder observed during recent months. Furthermore, features 10 and 11 were introduced to capture the account holder's change in *time to payment* behaviour observed during previous months. Finally, features 13—15 were generated to represent the number of payments and the payment amounts made late during the time window.

4.3 Model development

Once all the model data had successfully been cleaned and stored in the database, further analysis was conducted *via* the modelling component. A computerised instantiation of the modelling component was created in the programming language Python, utilising various open-source packages.

In order to create a model that makes predictions based on unseen data during model training, the processed data set was split with respect to time into training and testing data subsets. In this case, 2022 was selected as the testing set, which accounts for 20.47% of all invoices in the data set. The distribution of the payment times for the training and testing subsets is summarised in Table 4.

Table 4: Distribution of payment classes for the training and testing data subsets.

	Invoices	0—30 Days	31—60 Days	61—90 Days	91+ Days
Training set	482 977	256 675 (53%)	121 379 (25%)	38 829 (8%)	66 094 (14%)
Testing set	124 335	57 888 (46%)	34 404 (28%)	13 399 (11%)	18 644 (15%)

As may be observed in Table 4, the training and testing data subsets exhibited similar distributions in terms of payment times. Moreover, there exists a large class imbalance in the data, with the majority of invoices being paid within 30 days. To combat this imbalance, various sampling techniques were employed and tested, including SMOTE, under-sampling, over-sampling, and other hybrid approaches combining under-sampling and SMOTE.

During the model-building phase of the case study, four machine learning classification algorithms were configured based on time windows of various lengths so as to determine a suitable look-back period for historical feature generation. The algorithms were evaluated in terms of two performance evaluation metrics, namely AUC and classification accuracy. In this case, the AUC scores were determined as the average AUC score determined per class using a one-*versus*-rest configuration. The results obtained are summarised in Table 5. SMOTE was selected as the preferred sampling technique and Lasso (L1) regression was used during feature selection so as to ensure that the results are comparable.

As may be noted from the results in Table 5, the window size significantly influenced the performance of the various classification algorithms. In general, it was observed that the performance of the classification algorithms tended to deteriorate as the window size increases. This phenomenon may occur as a result of *concept drift* — a term often used in the realm of predictive analytics to explain the change in the statistical distribution of features as time passes. The best-performing classification algorithm was XGBoost, with window sizes of 1 and 2 months. The random forests classification algorithm performed second-best, with window sizes of 3 and 4 months. Interestingly, the performance of the random forest algorithm was not influenced as markedly as those of other classification algorithms when tested in conjunction with different window sizes.

The feature importance scores for the XGBoost and Random Forest models with window sizes 2 and 3 are summarised in Table 6. From the results in this table, it may be observed that both classification algorithms ranked the 'Days_To_Payment_Average' and 'Current' feature as the most important features. The feature importance scores for the other features, however, varied considerably for each algorithm and window size configuration.

Table 5: Machine learning model AUC and accuracy scores for different time windows.

		Time window (months)							
Model	**Metric**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Random Forest	AUC	0.85	0.86	0.87	0.87	0.86	0.86	0.86	0.86
	Accuracy	0.67	0.68	0.68	0.68	0.66	0.67	0.66	0.66
XGBoost	AUC	0.89	0.89	0.89	0.88	0.87	0.87	0.87	0.86
	Accuracy	0.72	0.72	0.70	0.69	0.67	0.68	0.67	0.65
Logistic Regression	AUC	0.82	0.83	0.82	0.81	0.81	0.81	0.81	0.81
	Accuracy	0.64	0.63	0.62	0.63	0.63	0.63	0.62	0.63
***k*-Nearest Neighbours**	AUC	0.76	0.77	0.78	0.77	0.77	0.77	0.77	0.77
	Accuracy	0.60	0.61	0.61	0.61	0.60	0.60	0.60	0.59

Table 6: Feature importance scores for the top-performing classification algorithms.

Feature	XGBoost (window = 1)	XGBoost (window = 2)	Random Forest (window = 2)	Random Forest (window = 3)
Days_To_Payment_Average	0.563	0.418	0.325	0.283
Current	0.181	0.200	0.236	0.221
MaxBucket	0.077	0.077	0.077	—
Status_FP_invamt_csum	0.054	0.158	—	0.062
Status_NP_invamt_csum	0.036	—	—	—
30 Days	0.027	0.012	0.067	0.083
60 Days	0.015	0.010	0.031	0.042
90 Days	0.012	—	—	—
Days_To_Payment_Std	—	0.147	0.209	0.202
Status_NP	—	—	—	0.055

Note: If no feature importance score is indicated for a feature, then the feature was not included in the top 10 ranked features.

4.4 Analysis of algorithmic results

After having developed an appropriate model during execution of the framework modelling component, a visualisation of the results could be constructed by invoking the analysis component. Consider the graphical illustration in Figure 2, representing the relationship between the days since the last payment was received from an account and the days to payment for a particular invoice, in order to illustrate the working of the analysis component.

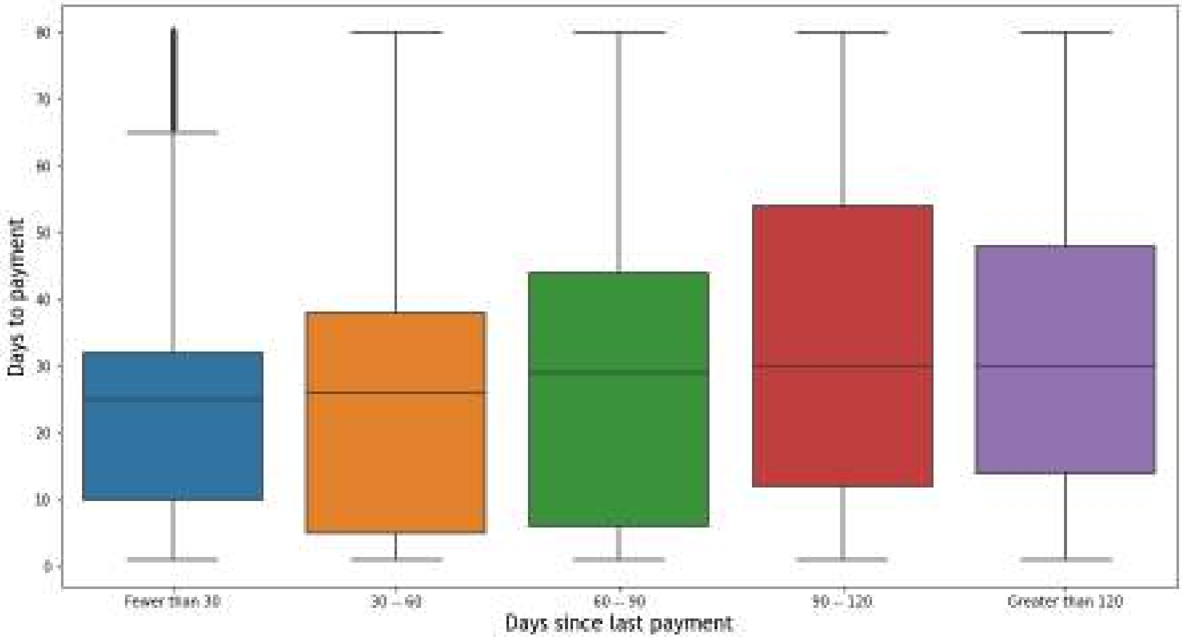

Figure 2: Days since the last payment was received from an account as a function of the days to payment for an invoice.

Upon studying the graphic in Figure 2, it was discovered that the days since the last payment was received from an account feature does, in fact, influence the time to payment of the account for a new invoice in some observations. This rule is, however, not sufficient to be applied in isolation, since a large number of observations did not follow this trend.

In order to gain the most value from the results produced by the analysis component, the framework user should iteratively study the relationships between various variables and underlying payment trends, so to arrive at actionable insights that may be implemented to improve the company's collection efforts.

At the time of writing, no productionised algorithm resulting from the case study had been implemented at the company. The management team is currently reviewing the proposal and planning the launch of such a project as part of their overarching data strategy.

5 CONCLUSION

A generic framework for modelling invoice payment predictions was presented in this paper. In order to describe the IPPP, for which resolution is facilitated by the framework, an introductory overview was first provided. An overview of similar research was presented next in an attempt to contextualise the framework within the existing literature. The various approaches that had been adopted in the literature to resolve instances of the IPPP, as well as their shortcomings, were outlined. A high-level overview of our framework was proffered next, after which a discussion followed on the various components of this framework, and their inner workings. A real-world case study based on a private education company was presented next to illustrate the practical working of the framework. Various machine learning classification algorithms were developed and evaluated as part of this case study, and the effects of adopting a rolling time window were demonstrated when calculating historical features. Potential future work for this study may involve testing the performance of ensembled survival analytical models and machine learning models, varying the classification threshold of the various algorithms in an attempt at improving the accuracy of the models, and performing a case study based on a company adopting an open-item accounting methodology (as opposed to a balance-forward accounting methodology).

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A MODEL FOR THE VEHICLE CREW SCHEDULING PROBLEM WITH STAFF CARS

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ABSTRACT

The simultaneous assignment of public transport vehicles and crew members to a set of timetabled trips is called the *vehicle crew scheduling problem* (VCSP). Various regulations and company rules typically determine the feasibility of duties thus formed. It is, for instance, required by some transport companies that transport be provided to some subset of the crew members between certain bus stations in order to facilitate their breaks, thereby ensuring the feasibility of the particular duties. This addition is referred to as the *staff transportation problem* (STP). In this paper, we propose a new model for integrating the VCSP and the STP, called the *vehicle crew scheduling problem with staff cars* (VCSPSC). We also propose a novel column generation procedure for solving the problem exactly, where the total cost due to trip-to-vehicle and trip-to-crew assignments is minimised. The proposed model and solution method are verified and validated in respect of real-world instances.

Keywords: Transportation, Vehicle scheduling, Crew scheduling, Column generation, Staff transportation

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1 INTRODUCTION

The management of a public transport system has traditionally been partitioned into three distinct sub-problems, the *multiple depot vehicle scheduling problem* (MDVSP), the *crew scheduling problem* (CSP) and the *crew rostering problem* (CRP). In the MDVSP, the aim is to assign a fleet of vehicles to perform a set of timetabled trips along which passengers are transported [1]. Similarly, the aim in the CSP is to assign crew members to the set of timetabled trips with a view to operate the vehicles [2]. The context in which transportation organisations need to solve each of the aforementioned problems, is collectively referred to as the transit network planning problem [3], as illustrated schematically in Appendix A.

The MDVSP and CSP are solved over a so-called *scheduling period*, typically a day, whereas the aim in the CRP is to assign crew members to timetabled trips spanning a so-called *rostering period*, which typically consists of several scheduling periods. Due to the considerable input and output dependency among these sub-problems [4], state-of-the-art solution approaches typically integrate the MDVSP and CSP, which is collectively known as the *vehicle-crew scheduling problem* (VCSP) [5].

The CSP, as it is studied in the literature, is aimed at establishing feasible crew schedules subject to a variety of labour and union regulations. Amongst other requirements, these regulations ensure that drivers are afforded sufficient break periods. Due to a variety of limitations in some transport systems, however, it has previously also been required that transport companies provide transportation for their crew members between bus stops to take breaks [6]. Perumal *et al*. [7] were the first to accommodate the practical consideration of transporting crew members who are responsible for the travel activities of the day in a CSP solution instance — in the process establishing a variation on the CSP called the *crew-scheduling problem with staff cars* (CSPSC).

Further required improvements related to staff transportation in a public transport system recently became apparent at a transport company in the Cape Metropole, South Africa, which serves as the industry partner attached to this research. In addition to vehicle and crew scheduling, the company requires integrated planning so as to provide transportation for its crew members to and from their homes in areas not covered by its transportation network as there are no other modes of transport available to these crew members by which to arrive at the company's depots.

The industry partner, in fact, desires to investigate whether it would be beneficial to utilise some of their available buses as staff cars to transport its crew members, as required. Existing models for the CSPSC are, however, not adequate for answering this question, because they do not take MDVSP considerations into account.

Our contribution in this paper is to provide a new model for the VCSP that takes staff transportation considerations into account, collectively referred to as the *vehicle crew scheduling problem with staff cars* (VCSPSC), as there is, to the best of our knowledge, only one model for the CSP that takes staff transportation considerations into account [6]. Our modelling approach consists of combining elements of the VCSP and the well-known *Dial-a-ride problem* (DARP).

The research approach we adopted started with an overview of the literature on the VCSP, the DARP and the CSPSC. A summary of the most important contributions may be found in Section 2. We then derived a mathematical model for the VCSPSC, which is described in Section 3, after which we designed an appropriate approach for solving instances of the VCSPSC. A description of this approach may be found in Section 4. We finally carried out a computational study in which the model and solution methodology were applied to real data, as discussed in Section 5. The paper closes with a brief conclusion and suggestions for future work in Section 6.

2 RELATED LITERATURE

The VCSP has been studied extensively in the operations research literature. Freling [8] and Huisman *et al*. [5] were among the first authors to suggest a fully integrated model and solution approach for the VCSP. In particular, Huisman *et al*. [5] based the vehicle scheduling considerations on a quasi-assignment model formulation and the CSP considerations on a set-covering model formulation. In addition, they included linking constraints between the vehicle scheduling variables and the crew scheduling variables. A column generation scheme was employed to solve VCSP instances in which the linear relaxation of the model was iteratively solved until there were no more negative reduced cost variables, after which a commercial *mixed-integer programming* (MIP) solver was used to generate a VCSP solution. Steinzen [9] used a time-space network to model the VCSP in order to reduce the number of vehicle scheduling variables, after which they adopted a similar solution approach to that of Huisman *et al*. [5] to solve instances of the VCSP. The reader is referred to Huisman [10] and Perumal [6] for good literature reviews on the VCSP.

The CSPSC was first introduced by Perumal *et al*. [7] who applied a matheuristic to generate solutions to real-world instances. The matheuristic alternates between an adaptive large neighbourhood search and invoking an MIP solver. Perumal *et al*. [11] suggested a column generation algorithm for solving instances of the CSPSC. This algorithm iterates between a master problem and two sub-problems. In one sub-problem, crew duties are generated while staff car variable values are generated in the other. Crew duties are generated by solving an *xxx* (SPPRC) instance by dynamic programming. In the CSPSC, crew members operate *staff cars* which transport other crew members between various bus stops whilst ensuring that each crew duty is feasible. This approach cannot, however, be built upon in the current paper since the authors do not take VSP considerations into account, and it is not necessarily the case that that there are staff cars available to transport crew members. Our approach differs from that of Perumal *et al*. [7] and Perumal *et al*. [11] in we allow for public transit vehicles to be utilised as staff cars while simultaneously incorporating VSP model considerations.

Research pertaining to the DARP is abundant. Cordeau *et al*. [12] employed a *branch-and-cut* (B&C) algorithm by which they were able to solve small, randomly generated DARP instances while Liu *et al*. [13] also employed the B&C algorithm to solve real-world instances. The reader is referred to Cordeau and Laporte [14], and also to Ho *et al*. [15], for excellent surveys on the DARP.

It has been shown by Bertossi *et al*. [16], Fischetti *et al*. [17] and Savelsbergh [18], respectively, that the MDVSP, the CSP and the DARP are all NP-hard.

3 MATHEMATICAL MODEL

This section is devoted to the derivation of a new mathematical model for the VCSPSC. A set $S = \{T_1, \ldots, T_n\}$ of timetabled trips is ordered according to non-decreasing starting times. Each trip in S must be assigned to some vehicle and crew member combination. The set of depots is denoted by $\mathcal{D}$, while the feasible duties associated with depot $d \in \mathcal{D}$ are indexed by the set $\mathcal{J}^d$. A depot in $\mathcal{D}$ can be considered as a location at which vehicles may be left without crew member attendance. Each depot $d \in \mathcal{D}$ has a vehicle storage capacity v_d associated with it.

The indices of the trips in S are captured in a set $\mathcal{N}^d \subseteq \{1, \ldots, n\}$. Furthermore, $\mathcal{O}^d(j)$ denotes the subset of duties that involve a (pull-out) trip from depot $d \in \mathcal{D}$ to the origin of (passenger) trip $j \in \mathcal{N}^d$. Similarly, $\mathcal{E}^d(i)$ is the set of duties that involve a (pull-in) trip from the destination of (passenger) trip $i \in \mathcal{N}^d$ to depot $d \in \mathcal{D}$. Finally, $\mathcal{F}^d$ denotes the set of all compatible trip pairs in the Cartesian product $\mathcal{N}^d \times \mathcal{N}^d$, and $\mathcal{J}^d(i,j)$ denotes the set of duties from depot $d \in \mathcal{D}$ that traverse the deadhead arc $(i,j) \in \mathcal{F}^d$. (Two trips are compatible if both trips can be serviced by the same vehicle and/or crew member.)

Decisions pertaining to the VCSP process of the VCSPSC may be represented graphically by means of a directed, weighted graph $G = (\mathcal{V}, \mathcal{A}^d)$, called the *VCSP graph*, which has the vertex set $\mathcal{V} = \mathcal{N}^d \cup \mathcal{D}$. The arc set of G is $\mathcal{A}^d = \mathcal{F}^d \cup (\mathcal{D} \times \mathcal{N}^d) \cup (\mathcal{N}^d \times \mathcal{D}) \cup_{d \in \mathcal{D}} \{(d,d)\}$. The set of arcs $\mathcal{F}^d$ is partitioned into two subsets $\mathcal{F}_\ell^d$ and $\mathcal{F}_s^d$, where the former denotes a set of so-called *long arcs*, while the latter denotes a set of *short arcs*. The set of long arcs contains arcs between two consecutive trips for which there is enough time to make a round trip from the destination of the first trip to the depot and then from the depot to the origin of the second trip before the start time of the second trip. The set of short arcs contains the arcs between two consecutive trips in the case where there is not enough time to perform a round trip of the type described above.

The aim in the DARP portion of our VCSPSC model is to transport a set of *users* from specified pick-up locations to drop-off locations by making use of staff cars dedicated to this purpose. A user is defined as a crew member who requests to be transported from a pick-up location to a drop-off location. The pick-up and subsequent drop-off must occur within a particular time window, as specified by the user. The pertinence of the DARP in the context of the VCSPSC is that, for each duty $\ell \in \mathcal{J}^d$ that can be assigned to a crew member, there are corresponding pick-up and drop-off locations which potentially must be visited by staff cars.

A *request* consists of a pick-up and drop-off pair, each duty in the VCSP portion of the model has a corresponding request associated with it, and all the requests are captured in the set $\mathcal{R} = \{1, \dots, R\}$. The pick-up and drop-off locations associated with each duty $\ell \in \mathcal{J}^d$ are captured in the sets $\mathcal{P} = \{1, \dots, R\}$ and $\mathcal{Q} = \{R+1, \dots, 2R\}$, respectively. The DARP portion of the model can therefore be formulated in terms of a complete directed graph $\bar{G} = (\bar{\mathcal{N}}, \bar{\mathcal{A}})$, with vertex set $\bar{\mathcal{N}} = \mathcal{P} \cup \mathcal{Q} \cup \{0, 2R+1\}$. The source and sink nodes 0 and $2R+1$ represent the depot from which the staff cars start and end their routes, respectively, while the set $\hat{\mathcal{J}}^d(i)$ contains those duties in $\mathcal{J}^d$ for which there is a request to be picked up at location $i \in \mathcal{P}$.

The staff cars are indexed by the set $\mathcal{W}$, and each staff car $w \in \mathcal{W}$ has a passenger capacity of v_w. It is assumed that the total duration of a staff car route may not exceed Δ. Each node $i \in \bar{\mathcal{N}}$ is equipped with a load ϱ_i and a non-negative service duration ρ_i, such that $\varrho_0 = \varrho_{2R+1} = 0$ and $\rho_i = -\rho_{2R+i}$ for each $i \in \mathcal{R}$. A time-window $[b_i, e_i]$ is also imposed on each node $i \in \bar{\mathcal{N}}$ during which it must be visited, where b_i and e_i denote the earliest and latest times at which node i must be visited by a staff car, respectively. A cost $c_{i,j}$ and a travel duration $t_{i,j}$ are also associated with each arc $(i,j) \in \bar{\mathcal{A}}$. Finally, the maximum allowable ride time of a user (in a staff car) is denoted by U.

The decision variables

$$z_{i,j}^d = \begin{cases} 1 & \text{if a public transport vehicle at depot } d \in \mathcal{D} \text{ is assigned to service trips} \\ & i \text{ and } j \text{ succession, with } (i,j) \in \mathcal{F}^d \text{, or} \\ 0 & \text{otherwise,} \end{cases}$$

$$z_{n+d,j}^d = \begin{cases} 1 & \text{if a public transport vehicle is assigned to depart from depot } d \in \mathcal{D} \\ & \quad \text{to service trip } j \in \mathcal{N}^d \text{, or} \\ 0 & \text{otherwise} \end{cases}$$

and

$$z_{n+d,j}^d = \begin{cases} 1 & \text{if a public transport vehicle is assigned to depart from depot } d \in \mathcal{D} \\ & \quad \text{to service trip } j \in \mathcal{N}^d \text{, or} \\ 0 & \text{otherwise} \end{cases}$$

are included in the model to describe the vehicle scheduling process of the VCSP, while the variables

$$\varpi_\ell^d = \begin{cases} 1 & \text{if duty } \ell \in \mathcal{J}^d \text{ associated with depot } d \in \mathcal{D} \text{ is selected for implementation, or} \\ 0 & \text{otherwise} \end{cases}$$

and

$$x_{i,j}^w = \begin{cases} 1 & \text{if a staff car } w \in \mathcal{W} \text{ is assigned to traverse arc } (i,j) \in \bar{\mathcal{A}}, \text{ or} \\ 0 & \text{otherwise} \end{cases}$$

are included for crew scheduling purposes. Decision variables $y_i^w \in \mathbb{R}^+$are also included in the model to keep track of the time at which staff car $w \in \mathcal{W}$ starts to service node $i \in \bar{\mathcal{N}}$. Also, $\vartheta_i^w \in \mathbb{Z}^+$denotes the number of passengers in staff car $w \in \mathcal{W}$ after having visited node $i \in \bar{\mathcal{N}}$. Decision variables $\varsigma_r^w \in \mathbb{R}^+$are included to keep track of how long the crew member associated with request $r \in \mathcal{R}$ is in staff car $w \in \mathcal{W}$. Finally, the decision variables

$$\gamma_i = \begin{cases} 1 & \text{if a pick-up location } i \in \mathcal{P} \text{ has to be visited, or} \\ 0 & \text{otherwise} \end{cases}$$

are included in the model to keep track of the set of pick-up nodes that must be visited.

Each trip in $\mathcal{N}^d$ must be assigned to exactly one public transport vehicle for a solution to an instance of the VCSP to be feasible. The set of constraints

$$\sum_{d \in \mathcal{D}} \sum_{j:(i,j) \in \mathcal{A}^d} z_{i,j}^d = 1, \qquad i \in S \tag{1}$$

is included in the model for this purpose. Constraint set (1) ensures that each trip is serviced either by a vehicle arriving from the destination of another trip or by a vehicle departing directly from a depot. Conservation of vehicle flows is ensured by including the constraint set

$$\sum_{i:(i,j) \in \mathcal{A}^d} z_{i,j}^d - \sum_{i:(j,i) \in \mathcal{A}^d} z_{j,i}^d = 0, \qquad j \in \mathcal{N}^d, \qquad d \in \mathcal{D}. \tag{2}$$

The set of constraints

$$\sum_{i \in \mathcal{N}^d} z_{n+d,i}^d \leq v_d, \qquad d \in \mathcal{D} \tag{3}$$

ensures that the vehicle capacity of depot $d \in \mathcal{D}$ is respected while the constraint sets

$$\sum_{\ell \in \mathcal{O}^d(j)} \varpi_\ell^d - z_{n+d,j}^d - \sum_{i:(i,j) \in \mathcal{F}_\ell^d} z_{i,j}^d = 0, \qquad j \in \mathcal{N}^d, \qquad d \in \mathcal{D} \tag{4}$$

$$\sum_{\ell \in \mathcal{J}^d(i,j)} \varpi_\ell^d - z_{i,j}^d = 0, \quad (i,j) \in \mathcal{F}_S^d, \qquad d \in \mathcal{D} \tag{5}$$

$$\sum_{\ell \in \mathcal{E}^d(i)} \varpi_l^d - z_{i,n+d}^d - \sum_{j:(i,j)\in\mathcal{F}_l^d} z_{i,j}^d = 0, \qquad i \in \mathcal{N}^d, \qquad d \in \mathcal{D} \tag{6}$$

serve as linking constraints between the variables pertaining to crew duties and those pertaining to vehicles. The set of constraints

$$\sum_{\ell \in \mathcal{J}^d(i)} \varpi_\ell^d - \sum_{j:(i,j)\in\mathcal{F}^d} z_{i,j}^d = 0, \qquad i \in \mathcal{N}^d, \qquad d \in \mathcal{D} \tag{7}$$

is included to ensure that a duty which services trip $i \in \mathcal{N}^d$ from depot $d \in \mathcal{D}$ is selected only if the same depot is responsible for servicing the trip. The constraint set

$$\sum_{w\in\mathcal{W}} \sum_{j\in\mathcal{N}} x_{i,j}^w - \gamma_i = 0, \qquad i \in \mathcal{P}, \tag{8}$$

in conjunction with the constraint set

$$\sum_{d\in\mathcal{D}} \sum_{\ell\in\hat{\mathcal{J}}^d(i)} \varpi_\ell^d \leq \left|\hat{\mathcal{J}}^d(i)\right|\gamma_i, \qquad i \in \mathcal{P}, \tag{9}$$

ensures that the requests associated with selected duties are each visited exactly once by a staff car, while the constraint set

$$\sum_{j\in\mathcal{N}} x_{i,j}^w - \sum_{j\in\mathcal{N}} x_{n+i,j}^w = 0, \qquad i \in \mathcal{P}, \qquad w \in \mathcal{W} \tag{10}$$

ensures that each pick-up and drop-off location pair is visited by the same staff car. The conservation of flow constraint sets

$$\sum_{j\in\bar{\mathcal{N}}} x_{0,j}^w = 1, \qquad w \in \mathcal{W}, \tag{11}$$

$$\sum_{j\in\bar{\mathcal{N}}} x_{j,i}^w - \sum_{j\in\bar{\mathcal{N}}} x_{i,j}^w = 0, \qquad i \in \mathcal{P} \cup \mathcal{Q}, \qquad w \in \mathcal{W} \tag{12}$$

and

$$\sum_{i\in\bar{\mathcal{N}}} x_{i,2R+1}^w = 1, \qquad w \in \mathcal{W} \tag{13}$$

ensure that each staff car transportation route starts and ends at its origin depot, while the set of constraints

$$y_j^w \geq \left(y_i^w + \rho_i + t_{i,j}\right) x_{i,j}^w, \qquad i \in \bar{\mathcal{N}}, \qquad j \in \bar{\mathcal{N}}, \qquad w \in \mathcal{W} \tag{14}$$

is included to keep track of the time at which staff car $w \in \mathcal{W}$ starts servicing node $j \in \bar{\mathcal{N}}$. Similarly, the set of constraints

$$\vartheta_j^w \geq (\vartheta_i^w + \varrho_j)x_{i,j}^w, \qquad i \in \bar{\mathcal{N}}, \qquad j \in \bar{\mathcal{N}}, \qquad w \in \mathcal{W} \tag{15}$$

is included to keep track of the load of staff car $w \in \mathcal{W}$ after having visited node $j \in \bar{\mathcal{N}}$. Constraints (14)–(15) are, however, non-linear. These constraints can be linearised by replacing them with the two sets of constraints

$$y_j^w \geq y_i^w + d_i + t_{i,j} - M_{i,j}^w(1 - x_{i,j}^w), \tag{16}$$

$$\vartheta_j^w \geq \vartheta_i^w + q_j - W_{i,j}^w(1 - x_{i,j}^w) \tag{17}$$

for each $i \in \bar{\mathcal{N}}^d$, $j \in \bar{\mathcal{N}}^d$ and $w \in \mathcal{W}$, where $M_{i,j}^w$ and $W_{i,j}^w$ are sufficiently large constants. The validity of constraints (16)–(17) can be ensured by setting $M_{i,j}^w \geq \max\{0, e_i + \rho_i + t_{i,j} - b_i\}$ for all $i, j \in \mathcal{N}^d$, and by setting $W_{i,j}^w \geq \max\{v_w, v_w + \varrho_i\}$ for all $i \in \mathcal{N}^d$ and $w \in \mathcal{W}$. The set of constraints

$$\varsigma_i^w = y_{n+i}^w - (y_i^w + \rho_i), \qquad i \in \mathcal{P}, \qquad w \in \mathcal{W} \tag{18}$$

is included to keep track of the total ride time of each crew member along a route, which is bounded from above by the set of constraints

$$t_{i,n+i} \leq \varsigma_i^w \leq U, \qquad i \in \mathcal{P}, \qquad \ell \in \mathcal{J}^d, \qquad w \in \mathcal{W}, \tag{19}$$

which ensures that the total duration spent by a crew member in a staff car does not exceed U. The duration of each staff transportation route is bounded from above by including the set of constraints

$$y_{2R+1}^w - y_0^w \leq \Delta, \qquad w \in \mathcal{W} \tag{20}$$

while the set of constraints

$$b_i \leq y_i^w \leq e_i \; i \in \bar{\mathcal{N}}, \qquad w \in \mathcal{W} \tag{21}$$

is included to ensure that each pick-up node is visited by a staff car within the specified time window. Furthermore, the constraint set

$$\max\{0, \varrho_i\} \leq \vartheta_i^w \leq \min\{v_w, v_w + \varrho_i\}, \qquad i \in \bar{\mathcal{N}}, \qquad w \in \mathcal{W} \tag{22}$$

ensures that the capacity of each staff car is respected. Finally, the sets of domain constraints

$$z_{i,j}^d \in \{0,1\}, \qquad (i,j) \in \mathcal{F}^d, \qquad d \in \mathcal{D}, \tag{23}$$

$$z_{i,n+d}^d \in \{0,1\}, \qquad i \in \mathcal{N}^d, \qquad d \in \mathcal{D}, \tag{24}$$

$$z^d_{n+d,i} \in \{0,1\}, \qquad i \in \mathcal{N}^d, \qquad d \in \mathcal{D}, \tag{25}$$

$$\varpi^d_\ell \in \{0,1\}, \qquad \ell \in \mathcal{J}^d, \qquad d \in \mathcal{D}, \tag{26}$$

$$x^w_{i,j} \in \{0,1\}, \qquad i \in \bar{\mathcal{N}}, \qquad j \in \bar{\mathcal{N}}, \qquad w \in \mathcal{W} \tag{27}$$

ensure the binary nature of the variables.

The model objective is to minimise the cost of performing the set of trips in S as well as the total cost incurred as a result of staff transportation. That is, to minimise

$$\sum_{d\in\mathcal{D}} \sum_{\ell\in\mathcal{J}^d} s^d_\ell \varpi^d_\ell + \hat{s} \sum_{d\in\mathcal{D}} \sum_{i\in\mathcal{N}^d} z^d_{n+d,i} + \sum_{w\in\mathcal{W}} \sum_{i\in\bar{\mathcal{N}}^-} \sum_{j\in\bar{\mathcal{N}}} c_{i,j} x^w_{i,j},$$

where s^d_ℓ denotes deadheading costs and costs associated with employing crew members, $\hat{s}$ denotes the fixed cost of a single vehicle and $c_{i,j}$ denotes the staff car cost of traversing the arc from node $i \in \bar{\mathcal{N}}$ to node $j \in \bar{\mathcal{N}}$.

4 MODEL SOLUTION APPROACH

The solution approach we propose for instances of our VCSPSC model of the previous section is based on a column generation procedure, as outlined in pseudo-code form in Algorithm 1 of Appendix B. The algorithm takes as input a set of timetabled trips and the set of all possible pick-up and drop-off locations, and it produces as output a feasible vehicle schedule, a crew schedule, and a set of routes for the staff cars. In particular, the first part of Algorithm 1, in lines 1–3, is initialised by constructing a set of pieces of work which are then used to generate the set of feasible duties $\mathcal{J}^d$. A crew scheduling sub-problem is next solved in lines 4–6, producing the set of duties for the VCSPSC column generation procedure, by invoking Algorithm 2, in Appendix B.

The column generation algorithm may be found in lines 12–28 of Algorithm 1. In particular, the restricted master problem is solved in line 13 and the dual information is stored. The pricing problem is then solved in line 18, after which a column management procedure is executed in line 21 if negative reduced cost duties are found. If, however, no negative reduced cost duties are found, $\mathcal{J}^d$ is set equal to the set of columns last considered in the restricted master problem, and the while loop is terminated. Finally, a feasible solution to the VCSPSC instance is produced in lines 30–32. Each of the solution method parts is discussed in more detail in the remainder of this section.

4.1 Algorithm initialisation

The purpose of the algorithm initialisation is to generate a set of pieces of work which can be used to generate a feasible set of columns $\mathcal{J}^d$, where a piece of work is defined as the set of trips assigned to a crew member whilst he or she is operating the same vehicle. This section is devoted to detailed discussions in Sections 4.1.1 and 4.1.2 on how pieces of work and feasible duties are generated, respectively.

4.1.1 Generation of pieces of work

Let the graph $\tilde{G} = (\tilde{\mathcal{V}}, \tilde{\mathcal{A}}^d)$, represent the network from which pieces of work are generated. Its vertex set is $\tilde{\mathcal{V}} = \mathcal{N}^d$ and its arc set is $\tilde{\mathcal{A}}^d = \mathcal{F}^d$, for each depot $d \in \mathcal{D}$ separately. The set of depot nodes and pull-in and pull-out arcs are thus omitted from the graph G of the previous section. It is assumed, during the generation of pieces of work, that the weight associated with an arc $(i,j) \in \tilde{\mathcal{A}}^d$ represents the time it takes to traverse the arc. Furthermore, it is assumed that each path in the graph $\tilde{G}$ can be used to formulate a feasible piece of work. The set of potential pieces of work is generated by producing a set of shortest paths between each pair of nodes, by invoking an all-pairs shortest path algorithm. The Floyd/Warshall method [19] may be used for this purpose. Pieces of work are generated for each depot $d \in \mathcal{D}$ where, for each piece of work, two additional arcs are then added: A pull-out arc is added from the respective depot to the first (passenger) trip of each piece of work and a pull-in arc is inserted from the last (passenger) trip of the piece of work back to the same depot. These pieces of work are used to generate the feasible set of duties $\mathcal{J}^d$.

4.1.2 Generation of feasible duties

A duty is feasible if it adheres to various requirements depending on the context of the problem instance. A duty therefore consists of a combination of pieces of work. In order to reduce complexity, it is assumed that the number of pieces of work assigned to any duty is limited to at most two, as was also assumed in the VCSP model proposed by Huisman *et al.* [5]. All the possible combinations of pieces of work (*i.e.* duty singles and doubles) are therefore simply enumerated. Each combination is referred to as a *duty*, and each duty is inspected to determine whether it adheres to the same feasibility requirements as outlined by Mesquita *et al.* [4]. A duty is discarded if it does not adhere to all these conditions. The set of remaining feasible duties then serves as input to the crew scheduling sub-problem in lines 4–6 of Algorithm 1 in Appendix B.

4.2 The crew scheduling sub-problem

The purpose of solving the CSP sub-problem before moving on to the VCSPSC is to generate an initial set of columns for the VCSPSC column generation procedure as well as to reduce the size of the set $\mathcal{J}^d$. One set of binary variables, ϖ_ℓ^d, defined in Section 3 for each depot $d \in \mathcal{D}$ and each duty $\ell \in \mathcal{J}^d$, is included in the sub-problem. The set $\tilde{\mathcal{J}}^d(i)$ denotes the subset of duties that cover trip $i \in \mathcal{S}$ from depot $d \in \mathcal{D}$. The constraint set

$$\sum_{d \in D} \sum_{\ell \in \tilde{\mathcal{J}}^d(i)} \varpi_\ell^d = 1, \quad i \in \mathcal{S} \tag{28}$$

is included to ensure that each trip $i \in \mathcal{S}$ is serviced by exactly one duty. Furthermore, the constraint set

$$\sum_{\ell \in \mathcal{J}^d} \varpi_\ell^d \leq v_d, \quad d \in \mathcal{D} \tag{29}$$

is included to ensure that the vehicle capacity of each depot $d \in \mathcal{D}$ is respected. The objective is to minimise the total cost incurred due to selecting duties — that is, to minimise

$$\sum_{d \in \mathcal{D}} \sum_{\ell \in \mathcal{J}^d} s_\ell^d \varpi_\ell^d. \tag{30}$$

The solution procedure adopted to solve instances of the CSP is presented in Algorithm 2 of Appendix C. An initial set of columns $\bar{J}_0$ is generated in line 2 in such a manner that each trip in S is assigned to only one duty, with all the duties in $\bar{\mathcal{J}}_0$ departing from and returning to the same depot. The set of duties $\bar{J}_0$ is constructed to serve as an initial set of columns for the column generation procedure during its first iteration. The initial set of negative reduced cost columns is captured in the set $\bar{\mathcal{J}}_t$ in line 4. A restricted master problem, which is the LP relaxation of the CSP, is solved in line 6, in respect of the current set of columns $\bar{\mathcal{J}}_t$. The dual variables are stored in the vector $\boldsymbol{\psi}$. In particular, $\psi_{0,i}$, contains the dual variables associated with constraint set (28) for each $i \in \mathcal{S}$, and the dual variables in $\psi_{1,d}$ are those variables associated with constraint set (29) for each $d \in \mathcal{D}$.

A pricing problem is then solved in line 11 by finding columns with negative reduced costs, where the reduced cost $\bar{s}_\ell^d$ of a duty $\ell \in \mathcal{J}^d$ for each $d \in \mathcal{D}$ is defined as

$$\bar{s}_\ell^d = s_\ell^d - \sum_{i \in \mathcal{J}(\ell)} \psi_{0,i} - \psi_{1,d}$$

with $\mathcal{J}(\ell)$ denoting the set of trips serviced by duty $\ell \in \mathcal{J}^d$. This procedure is iterated until no duties with negative reduced costs remain. If no negative reduced cost duties remain, the set $\bar{J}_t$ of columns considered during iteration t is returned to Algorithm 1 (and is then taken as the set of duties for the pricing problem), after which an integer solution $\bar{\mathcal{J}}^i$ is generated in line 22 by invoking an MIP solver (which serves as the initial set of columns for the VCSPSC master problem).

4.3 The VCSPSC column generation procedure

The master problem is the LP relaxation of the model derived in Section 3. The columns considered during the first iteration corresponds to the integer solution to the CSP, and the set of requests possibly visited is based on the columns in $\mathcal{J}^d$ (as initialised in lines 9–10 of Algorithm 1). The relevant dual variables are stored in $\boldsymbol{\pi}$. More specifically, the dual variables associated with constraint (4) are stored in $\pi_{0,j}^d$ for each $j \in \mathcal{N}^d$ and $d \in \mathcal{D}$. The dual variables associated with constraint set (5) are stored in $\pi_{1,i,j}^d$ for each $(i,j) \in \mathcal{F}_S^d$ and $d \in \mathcal{D}$, and the dual variables associated with constraint (6) are stored in $\pi_{2,i}^d$ for each $i \in \mathcal{N}^d$ and $d \in \mathcal{D}$. The dual variables associated with constraint (7) are stored in $\pi_{3,i}^d$ for each $i \in \mathcal{N}^d$ and $d \in \mathcal{D}$, and finally, the dual variables associated with constraint (9) are stored in $\pi_{4,i}$ for each $i \in \mathcal{P}$.

The pricing problem is solved in line 16 of Algorithm 1 by finding columns in $\mathcal{J}^d$ with negative reduced costs, similarly to the procedure described in Section 4.2. The reduced cost $\bar{s}_\ell^d$ of a duty $l \in \mathcal{J}^d$ in the VCSPSC is defined as

$$\bar{s}_\ell^d = s_\ell^d - \sum_{j \in \tilde{O}(\ell)} \pi_{0,j}^d - \sum_{(i,j) \in \tilde{\mathcal{F}}_S^d(\ell)} \pi_{1,i,j}^d - \sum_{j \in \tilde{\mathcal{E}}(\ell)} \pi_{2,j}^d - \sum_{i \in \mathcal{T}(\ell)} \pi_{3,i}^d - \sum_{i \in \tilde{\mathcal{P}}(\ell)} \pi_{4,i}$$

for each $d \in \mathcal{D}$, where $\tilde{O}(\ell)$ denotes the pull-out trip in duty $\ell \in \mathcal{J}^d$, $(i,j) \in \tilde{\mathcal{F}}_S^d(\ell)$ denotes the set of short arcs serviced by duty $\ell \in \mathcal{J}^d$, $\tilde{\mathcal{E}}(\ell)$ denotes the pull-in trip in duty $\ell \in \mathcal{J}^d$, $\mathcal{T}(\ell)$ denotes the set of trips serviced by duty $\ell \in \mathcal{J}^d$, and $\tilde{\mathcal{P}}(\ell)$ denotes the pick-up locations associated with duty $\ell \in \mathcal{J}^d$. Columns with negative reduced costs are added to $\bar{J}_t$ until no further negative reduced cost columns can be found in the set $\mathcal{J}^d$, after which the while loop spanning lines 10–26 of Algorithm 1 is terminated.

The final set of columns $\bar{\mathcal{J}}_t$ is used to generate an integer solution to the VCSP instance by invoking an MIP solver. More specifically, the VCSP consists of constraints (1)–(7) where the objective is to minimise

$$\sum_{d\in\mathcal{D}}\sum_{\ell\in\mathcal{J}^d} s_\ell^d \varpi_\ell^d + \hat{s}\sum_{d\in\mathcal{D}}\sum_{i\in\mathcal{N}^d} z_{n+d,i}^d. \tag{31}$$

The duties produced in line 28 of Algorithm 1 are then inspected so as to update the set of requests considered in the DARP, which contains constraints (10)−(22), and where constraint (8) is replaced with the constraint set

$$\sum_{w\in\mathcal{W}}\sum_{j\in\mathcal{N}} x_{i,j}^w = 1, \qquad i\in\mathcal{P}, \qquad \ell\in\mathcal{J}^d, \qquad d\in\mathcal{D} \tag{32}$$

since each request must be covered by exactly one staff car. The objective in the DARP is to minimise

$$\sum_{w\in\mathcal{W}}\sum_{i\in\mathcal{N}}\sum_{j\in\mathcal{N}} c_{i,j}x_{i,j}^w. \tag{33}$$

5 COMPUTATIONAL STUDY

A computational study was performed based on input data for the VCSPSC provided by the industry partner. The study involved a test instance of the VCSPSC with 246 timetabled trips serviced during weekdays, which was solved for vehicles departing from three depots. The input data for the VCSPSC instance are available online [20]. The model implementation and test data are discussed below in more detail.

5.1 Test data and model implementation

The fixed cost of acquiring a vehicle was assigned a value of 2 100 *monetary units* (m.u.), whereas the fixed cost associated with hiring a crew member (*i.e.* the cost of selecting a crew member duty), was assigned a value of 5 866 m.u. The variable cost per kilometre driven was assigned a value of 12 m.u. and the variable cost per hour worked overtime by a crew member was assigned a value of 200 m.u.

There are various regulations that dictate the feasibility of a duty, as outlined in Section 4.1.2. In particular, each duty must adhere to the following conditions to be deemed feasible:

- Maximum *spread*[1]: 720 minutes.
- Maximum driving time: 440 minutes.
- Minimum short break duration: 30 minutes.
- Minimum long break duration: 120 minutes.
- Maximum time without a break: 300 minutes.
- Multiple duty types: A duty can be categorised as being either a split duty[2] or a straight duty[3].

Furthermore, business rules at the industry partner dictate that drivers can only be relieved at depots and that each duty should start and end at a depot. It is required that transportation should be provided to crew members from locations near their homes to the relevant depots before the commencement of their first duties of the day, and from the depots back to the drivers' homes after the end of their last duties of the day. The industry partner suggested selecting bus stations in two neighbourhoods on the outskirts of the Cape Metropole (in Delft and in Gugulethu) where bus drivers typically reside. Each duty generated was assigned to one of these locations. The initial set of requests was constructed in such a manner that any driver would be guaranteed that each of the two home bus stations had to be visited once every hour by staff cars departing to any of the depots and that every depot would be visited once every hour by staff cars departing to any of the two home bus stations. Since there are three depots, this means that each home bus station has to be visited three times per hour, to depart to each of the corresponding depots. Similarly, each depot has to be visited twice per hour to depart to each of the home bus stations. The time-window of each pick-up node was set to the 60 minutes of the particular hour of the day. The set of duties was inspected and all the requests that were not required to be visited by any of the duties were removed.

Crew members were allowed to spend at most 500 minutes in a staff car. A total of three staff cars were available for assignment, and the maximum drive time for each driver of a staff car was set to 720 minutes. The maximum capacity of each staff car was set to 65 passengers.

The model (1)–(27) was implemented in Java, on an Intel i5 processor operating at 2.4GHz in a Windows 11.0 operating system and equipped with 16 GB RAM. The LP relaxation and integer solutions were generated using CPLEX 22.1.

5.2 The crew scheduling sub-problem

A total of $\sum_{d\in\mathcal{D}}\left|\mathcal{J}^d\right| = 8\,814\,011$ duties were generated according to the method described in Sections 4.1.1–4.1.2. The initial set of columns achieved an *upper bound* (UB) value of 1 935 127 m.u., whereas the set of duties during the last iteration achieved a UB value of 559 285 m.u., as shown in Figure 2 of Appendix D. The first 100 duties with negative reduced costs were again added to the set $\bar{\mathcal{J}}_t$ during each iteration.

Finally, an integer solution was generated by invoking the aforementioned MIP solver. A run-time limit of ten minutes was imposed during this step, when an integer solution was generated which achieved an optimality gap of 0.75%. This integer solution served as the

[1] The spread of a duty is defined as the time elapsed from the start of the duty to the end of the duty.

[2] A split duty is a duty comprising two pieces of work with a long break between the pieces of work.

[3] A straight duty is a duty which does not contain a long break between pieces of work.

initial solution for the column generation procedure described in the following section, which was aimed at finding columns with negative reduced costs while taking SCP considerations into account.

5.3 The VCSPSC

The set of feasible duties $\mathcal{J}^d$ was set equal to the set of duties $\bar{\mathcal{J}}_t$ of the last iteration of the CSP column generation procedure, as described in Section 4. At this point there where $\sum_{d\in\mathcal{D}}|\mathcal{J}^d| = 4\,698$ duties. The LP relaxation of the initial set of columns achieved a UB value of 639 284 m.u., whereas the set of duties during the last iteration achieved a UB value of 625 185 m.u., as shown in Figure 3 of Appendix E. The first 100 duties with negative reduced costs were again added to the set $\bar{\mathcal{J}}_t$ during each iteration of the column generation procedure.

The VCSPSC was partitioned into two separate problems, namely the VCSP and the DARP, so as to produce integer solutions for both cases, as described in Section 4. An integer solution with an optimality gap of 1.93% was generated for the VCSP within a run time of 12.2 hours and running out of memory, but achieving an objective function value of 639 284 m.u. The corresponding integer solution was then used to generate the problem instance for the DARP, which involved 38 requests.

We were, however, unable to generate an integer solution to the DARP instance within a reasonable time limit because of the large number of requests. Upon inspection it was, however, noted that the set of requests could be partitioned into two separate groups, namely those associated with early requests and those associated with late requests. Early requests comprised pick-up locations only at one of the two home bus stations and drop-off locations only at a depot in the morning. Late requests, on the other hand, comprised pick-up locations only at a depot and drop-off locations only at one of the two home bus stations in the afternoon.

The set of requests was therefore partitioned into a subset with a pick-up and drop-off time window before the 12AM, and a subset of requests with a pick-up and drop-off time window after 12AM. This was a reasonable step since the maximum drive time of a staff car driver was set to 12 hours. The DARP problem instance was thus partitioned into two separate sub-problem instances involving 18 early requests, and 20 late requests, respectively. For the instance with early requests, an optimal solution was obtained with an objective value of 4 728 m.u. within a run time of 9.9 hours. Similarly, for the instance with late requests, an optimal solution was obtained with an objective value of 6 132 m.u. within a run time of 13.7 hours.

The actual cost incurred by the industry partner when operating its timetable amounted to 676 701 m.u., disregarding any costs due to SCP considerations. When only considering the VCSP costs incurred due to our suggested solution method, a cost saving of 5.53% was therefore achieved. Furthermore, when including the costs due to the DARP as well, a total cost of 650 144 m.u. was incurred for the VCSPSC, which still amounts to a cost saving of 3.92% when compared to the *status quo* at the industry partner. Our VCSPSC instance solution is also available online [20] as a future benchmark.

6 CONCLUSION AND FUTURE RESEARCH

A mathematical model was derived in this paper for an integration of the VSP, the CSP, and the SCP. A model solution method based on a combination of heuristics, column generation, and integer programming techniques was suggested, which was able to outperform the *status quo* at the industry partner attached to this paper. In fact, our suggested solution approach provided results that resulted in a 4.17% cost saving over the manual assignment process of the industry partner whilst providing staff transportation for the crew members between their homes and the company's depots — considering that the industry partner currently does not provide such staff transportation for its crew members.

There are multiple possible avenues of future research that can be pursued which are related to the model presented in this paper. Most notably, the scalability of the DARP model seems problematic. The industry partner is, in fact, interested in implementing our suggested solution method while including more depots and timetabled trips. The problem of scaling the suggested solution approach for instances of the VCSPSC will become more acute if the numbers of timetabled trips and depots increase. Since the solution method for the VCSP part of the problem was, however, sufficiently fast, a matheuristic might well be a viable approach towards generating integer solutions for the entire VCSPSC.

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APPENDIX A

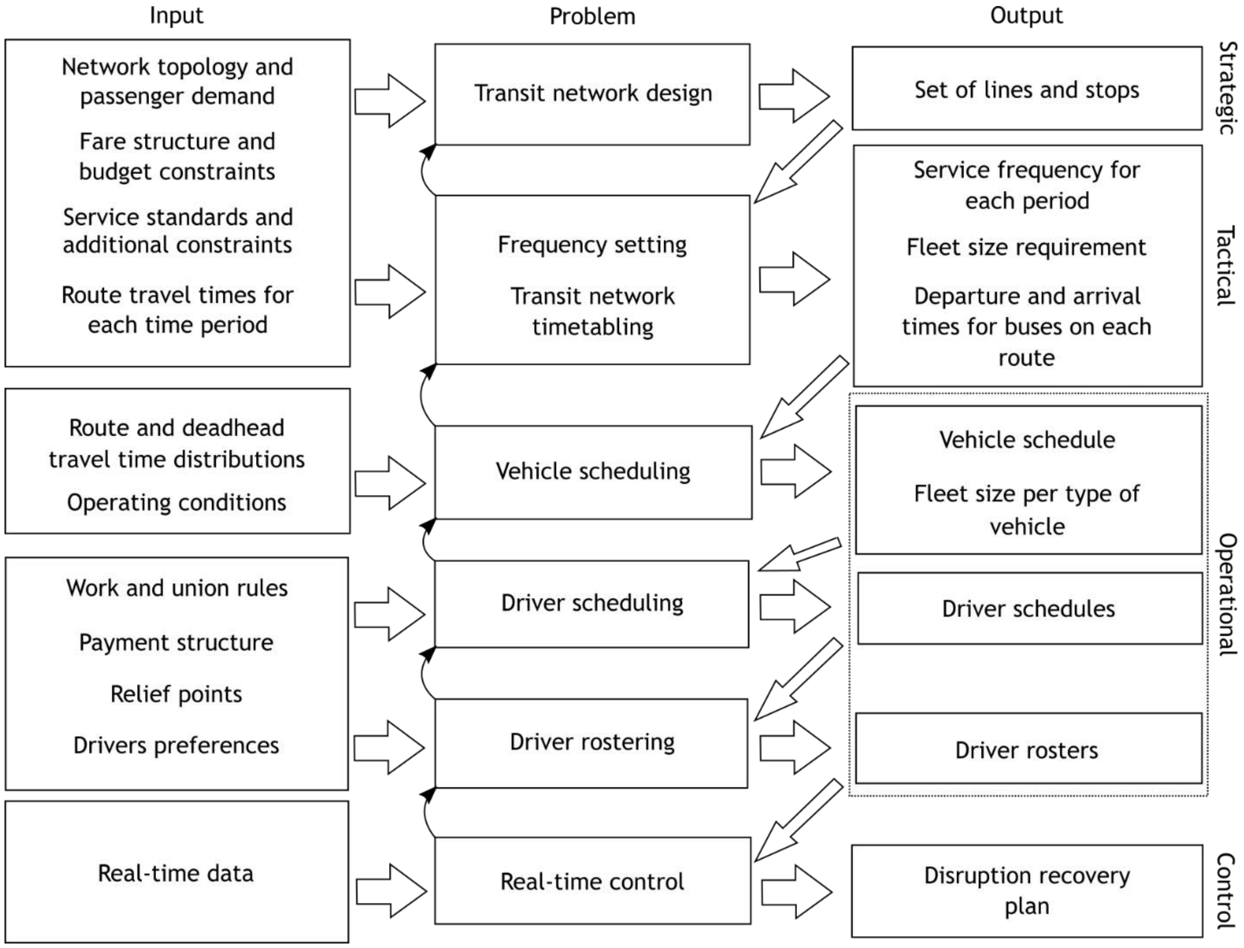

Figure 1: Phases of the TNNP (adapted from Ibarra-Rojas *et al.* **[3]**)

APPENDIX B

This appendix contains a pseudo-code description of our algorithm for solving instances of the VCSPSC.

Input : A set of timetabled trips S, a set of pick-up locations and a set of drop-off locations.

Output: A set of feasible vehicle schedules, crew schedules, and staff car routes.

Initialisation

  Construct pieces of work.

  Generate the feasible set of columns $\mathcal{J}^d$.

Produce a CSP solution by invoking Algorithm 2

  Store the final set of columns in $\mathcal{J}_t$.

  Store the integer solution in $\mathcal{J}^i$.

$t \leftarrow 0$.

Set $\mathcal{J}^d \leftarrow \mathcal{J}_t$.

Check each duty in $\mathcal{J}^d$ and update $\mathcal{R}$ accordingly.

Set $\mathcal{J}_0 \leftarrow \mathcal{J}^i$

Set $\mathcal{X} \leftarrow \mathcal{J}^i$.

while $\mathcal{X} \neq \emptyset$ **do**

  Solve the restricted master problem.

    Use the columns $\mathcal{J}_t$, to solve a linear relaxation of the VCSPSC.

    Store the dual variables in π.

    $\mathcal{X} \leftarrow \emptyset$.

  Solve the column generation pricing problem.

    Store negative reduced cost colums in $\mathcal{X}$.

  if $\mathcal{X} \neq \emptyset$ **then**

    Perform column management.

      $\mathcal{J}_{t+1} \leftarrow \mathcal{J}_t \cup \mathcal{X}$.

      $t \leftarrow t + 1$.

  end

  else

    $\mathcal{J}^d \leftarrow \mathcal{J}_t$

  end

end

Generate a feasible solution.

  Use the columns $\mathcal{J}_t$, produce an integer solution for the VCSP.

  Update the set of pick-up and drop-off locations based on the integer solution of the VCSP.

  Generate an integer solution for the DARP.

Algorithm 1: Solution method for solving instances of the VCSPSC.

APPENDIX C

This appendix contains a pseudo-code description of our algorithm for solving instances of the crew scheduling sub-problem.

Input : A set of timetabled trips S and the set of feasible duties $\mathcal{J}^d$.
Output: An integer solution for the CSP, $\bar{\mathcal{J}}^i$, and a set of feasible duties, $\bar{\mathcal{J}}_t$.
Set $t \leftarrow 0$.
Generate an initial set of columns $\bar{\mathcal{J}}_t$.
Initiate columns with negative reduced cost $\mathcal{X}$.
$\mathcal{X} \leftarrow \bar{\mathcal{J}}_t$.
while $\mathcal{X} \neq \emptyset$ **do**
  Solve the CSP restricted master problem.
    Use the columns $\bar{\mathcal{J}}_t$, to solve a linear
    relaxation of the CSP.
    Store the dual variables in ψ.
    $\mathcal{X} \leftarrow \emptyset$.
  Solve the column generation pricing problem.
    Store negative reduced cost colums in $\mathcal{X}$.
  if $\mathcal{X} \neq \emptyset$ **then**
    Perform column management.
      $\bar{\mathcal{J}}_{t+1} \leftarrow \bar{\mathcal{J}}_t \cup \mathcal{X}$.
      $t \leftarrow t + 1$.
  end
  else
    $\mathcal{J}^d \leftarrow \bar{\mathcal{J}}_t$
  end
end
Generate an integer solution for the CSP, and store it in the variable $\bar{\mathcal{J}}^i$

Algorithm 2: Solution method for solving instances of the CSP.

APPENDIX D

This appendix contains a graphical illustration of the progression of the CSP column generation procedure.

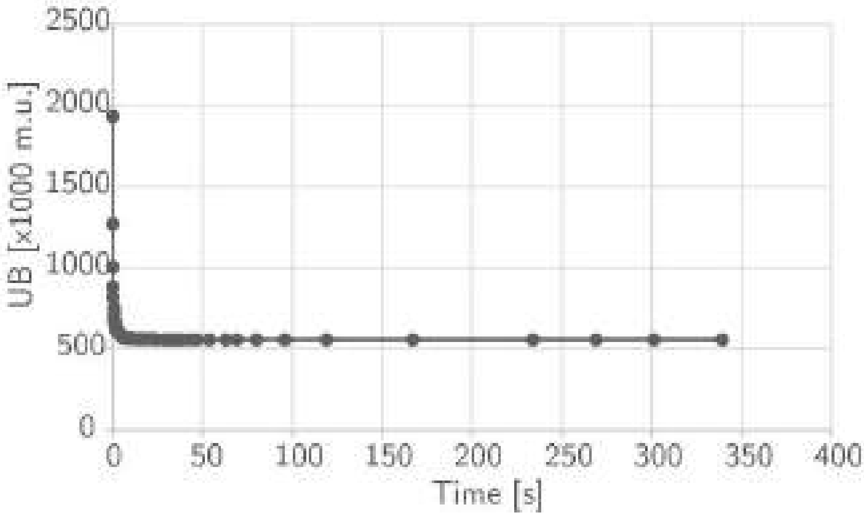

Figure 2: The progression of the CSP column generation procedure. Each encircled value represents an LP relaxation upper bound value associated with the current set of columns considered during that iteration.

APPENDIX E

This appendix contains a graphical illustration of the progression of the VCSPSC column generation procedure.

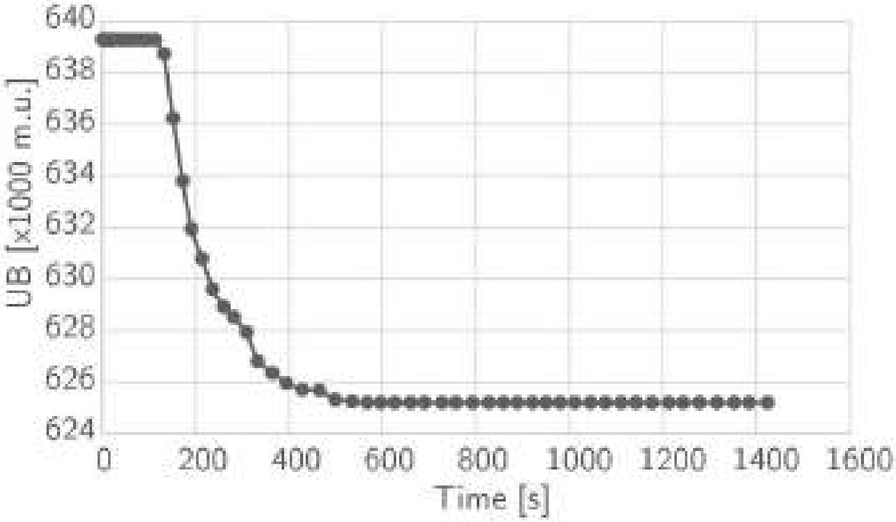

Figure 3: The progression of the VCSPSC column generation procedure. Each encircled value represents an LP relaxation upper bound value associated with the current set of columns considered during that iteration.

DETERMINING BARRIERS WHICH IMPEDE GREEN INFORMATION AND COMMUNICATION TECHNOLOGY ADOPTION IN SMALL AND MEDIUM ENTERPRISES

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ABSTRACT

Green information and communication technology (GICT) is a set of initiatives organisations undertake to reduce carbon emissions and their carbon footprint produced by their Information and Communication Technology (ICT). This study addressed the problem of the low adoption rate of GICT encountered in Small and Medium Enterprises (SMEs) by determining the context from a developing country's perspective. The primary objective of the study on which this paper is based was to identify the barriers which impede GICT adoption in SMEs. A comprehensive literature review was conducted to identify certain barriers which were then used as indicators for the compilation of the measurement instrument. A census study was conducted with data being collected via a self-administered, web-based questionnaire and exploratory factor analysis was employed. The findings indicated a lack of funding, awareness, legislation, skills, knowledge based on uncertainty and complexity as the reasons why SMES are reluctant to adopt GICT. A lack of funding being the most prominent barrier to low GICT adoption. It is recommended that SMEs align themselves with GICT initiatives such as cloud computing, and that policy makers consider offering tax benefits and rebates for SMEs that adopt GICT.

Keywords: Green information and communication technology (GICT), barriers, SMEs.

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1. INTRODUCTION

The reduction of industry pollution whilst simultaneously making a profit should be in the forefront of any managerial mind. Industrial waste from organisations is inevitable [1]. There are several ways to ensure this and one of the ways of doing this is through the adoption of green information and communication technology (Green ICT) by organisations. Organisations have control over how GICT is introduced, but are reluctant to exercise this option, with a low GICT adoption rate being a problem identified from literature [2]. Information communication technology (ICT) consists of hardware and software, both of which enable the distribution of information and simplify the sharing of digital communication among individuals and organisations [9].

Hankel, Heimeriks and Lago, [3] introduced the practice of effectively managing the negative effect of ICT by reducing the amount of carbon dioxide (CO_2) released into the environment. Hence, GICT aims to improve ICT such that it has the minimum effect on the environment and promotes environmental and economic sustainability [4]. Globally, the awareness of environmental issues has increased over the past decade. Suryawanshi and Narkhede, [5] state that most organisations are willing to implement GICT initiatives. This is primarily due to the significant environmental and cost benefits, such as carbon footprint and hazardous e-waste minimisation, environmental sustainability, reduction in energy cost, compliance with institutional legal regulations and the fulfilment of corporate social responsibility.

In developing countries, small and medium enterprises (SMEs) do not have sufficient resources to ensure compliance, unlike the large organisations who have policies and procedures in place enabling them to comply with GICT requirements. Due to these limited resources SMEs are slower on the uptake in their adoption of GICT [6], [7]. Mukonza [8] emphasises that a possible factor contributing to the low GICT adoption rate could be the lack of regulation and legislation in South Africa (SA).

This paper addresses the problem of the low adoption rate of GICT encountered in SA SMEs by determining the context from a developing country's perspective. According to Buchalcevova and Gala [7], compared to larger companies SMEs are being constrained in their adoption of GICT due to limited resources such as cloud computing. The primary objective of the study on which this paper is based was to identify the barriers which impede GICT adoption in SMEs. It is envisaged that by determining the main barriers and recommending strategies, the risks associated with not introducing GICT may be avoided.

The aim of the research was to investigate the different barriers resulting in low adoption rate of GICT in SMEs. The essential contribution of this paper is to contribute towards understanding GICT principles that may result in the low rate of adopting green technology in regulations to protect the environment and fill the void in literature regarding the limited research in this field [10].

2 PROBLEMS INVESTIGATED AND THE RESEARCH OBJECTIVES

The problem is the low GICT adoption rate by SMEs in South Africa. A review of the literature revealed a lack of specific research providing insight into the low rate of adoption of GICT practices in developing countries [10], [11], [12], [13]. The study endeavoured to examine the problem of the low rate of adoption of GICT by SA SMEs. Once greater insight has been obtained, tailored recommendations can be made to SMEs and possibly those in other developing countries.

The focus of the research was to examine the fundamental aspects contributing to the low adoption rate of GICT to achieve sustainable business practices. Moreover, the specific barriers resulting in the low adoption rate of GICT in operation practices. South Africa is viewed as the 13th largest emitter globally with an estimated 468 metric tons of CO_2 based on 2016 statistics [14]. This provided justification to investigate the barriers identified in the literature influencing the low adoption rate of GICT. The problem, therefore, is the low adoption rate of GICT in South Africa. The primary objective of this paper was therefore to identify the barriers which impede GICT adoption in SMEs.

3 LITERATURE REVIEW

The theoretical framework for this paper consists of an overview of a background on GICT, a general understanding on the definition of GICT, and the benefits of GICT. The review concludes with a detailed discussion about the different drivers and barriers resulting in the low adoption rate of GICT.

3.1. Background on Green ICT

Here the background on GICT is contextualised to corroborate where the problem regarding the low GICT adoption rate has emerged from. Sustainability generally consists of three essential pillars which include economic, social, and environmental factors whereby the aforementioned has become a key factor in preventing the exploitation of resources [15]. Garg and Singla [16] state that SMEs in the information technology (IT) industry has increased but these enterprises are unaware of the significance in terms of environmental sustainability. This is taken further by Corrocher and Solito [17] that state big corporations tend to invest more towards environmental sustainability through green research and development (R&D) whereas SMEs attempt to some degree with limited resources. SMEs therefore play an important role towards the sustainability of society.

Dezdar [18] points out that sustainable development is a global concern and GICT is considered as an essential eco-friendly practice to adopt. This idea has been built upon by Muafi [19] that green IT consists of “environmental sustainability, the economics of energy efficiency, and the total cost of ownership, which include the cost of disposal and recycling”. The latest statistics revealed that the ICT industry is now liable for 3% CO2 emission globally including other toxins and GICT is viewed as one of the ways through which SMEs can reduce the impact on the environment [16]. Andreopoulou [20] describes GICT for sustainability as “an approach of efficient and effective design, manufacturing, use and disposal of computers, servers, and associated sub-systems in order to achieve reduction of energy, emissions, and consumption resources”. Therefore, it can be said that different concepts are being used synonymously for GICT which leads to the enhancement of more green business processes.

Nizam and Vilhi [21] indicate that a positive attitude of employees towards GICT in a corporation from the bottom to top of hierarchy increases the adoption rate of GICT. GICT is multifaceted and should be effectively used to impact the business operations and procedures in companies such as the organisational culture while decreasing the ecological footprint [3]. Sub-Saharan Africa has been rated amongst the world’s ten rapidly developing economies on the rise [22]. In parallel to this, De Wet and Koekemoer [23] stated that South Africans are shifting towards a position where ICT has become an extensive part of life through constant connectivity. Hence, this research provides an overview about the current state of the GICT adoption rate in SA SMEs. Against this background, this research study can be considered imperative due to the low GICT adoption rate specifically evident within SA SMEs.

3.2. Green ICT defined

Green technology is defined as an eco-friendly technology used to protect the ecosystem and natural resources by lessening the negative effect of human actions, with the intent of diminishing waste [24]. ASSAF (2014:53-61) place emphasis on five foremost sectors based on National Policies which direct green technologies namely: energy, water, waste, buildings, and information and communication. However, this study will focus on ICT related sectors as it doesn’t only impact the ICT industry but other sectors at large as well. Prior to the 2017

ASSAF [25] reported that the ICT industry is accountable for 2% of CO_2 emission globally but could decrease the outstanding 98% released by non-ICT sectors.

It is highlighted by Malison and Thammakoranonta [26], that people are becoming more familiar with green terminologies but a low degree of awareness regarding the term GICT still exists especially from a developing country's viewpoint. Dezdar [18] explained that the concept "green IT", "green computing" or "ICT sustainability" was created due to the high number of energy usage that has turn into a serious concern from an ecological or economic viewpoint. Thus, some unclearness still exists regarding the definition of GICT despite the important role it plays due to the similarity in concepts used.

Malison and Thammakoranonta [26] refer to Green of ICT as a process that takes into consideration the effect of ICT on environmental conditions both from an implicit or explicit, and favourable or unfavourable perspective. A similar stance is taken by Deng, Ji, and Wang [27] that GICT can be differentiated between an internally approach based on practices within the IT sector or external approaches which focus on improvement of sustainability in other industries. It is therefore clear that a variety of concepts regarding GICT exists. These concepts can be seen as collective activities directed at decreasing the harmful impact of technology on the environment. Even though the ICT industry contributes towards CO2 emission, it has the potential to decrease this negative impact through technological tools.

3.3. Benefits of Green ICT

Hojnik and Ruzzier [28] indicate that predominantly 80.4% of eco-innovations lead to the reduction of costs and has an estimated throughput rate of 32% more. Green products use less resources, have lower impacts and risks to the environment, and prevent waste generation already at the "conception stage" Fraccascia, Giannoccaro & Albino [29]. Based on the above, the importance to incorporate GICT within SMEs is reaffirmed as numerous Green ICT practices are beneficial to enterprises and the environment. Table 1 reflects the different benefits related to GICT practices-based information generated from existing literature.

Table 1: Benefits of Green ICT

Benefit	Description of benefit
a) Protecting the environment	Lessening GHG released, support the reusability and the usage of material with a minimum negative effect.
b) Provides cost-effective and energy efficiency ways	Better quality performance of processes, decreases in costs, enhance partnerships, lessen energy usage, decrease space utilised, lessen CO2 released.
c) Enhance environmental protection activities	Decrease the impact on environment through efficient ICT operation processes and development of advanced information systems create a shift towards a more environmentally sustainable attitude.
d) Saving of costs	The adoption of cloud computing reduces expenditure, increase competitiveness in the market, offer recovery solutions including automatic system updates and maintenance.
e) Fewer resources are utilised through the production green products	Minor effect on the environment and prevent wastage as early as the beginning phase of production.

From Table 1, the most noticeable benefit of GICT is the shift towards the enhancement of more sustainable practices resulting in a positive impact on SMEs and the environment. Different factors can hinder the adoption of GICT, but it can clearly be seen that the benefits have a far greater positive effect in the long run.

In contrast to these benefits identified from existing literature, Abiola, Ashamu and Yekini [30] reported that 42% of non-adopters SMEs in Nigeria indicated that ICT does not provide benefits. This view may be linked to various reasons such as the barriers already addressed. Even though this is from a non-adopter's point of view about ICT and not GICT, it still provides insight on how developing countries are lacking behind on development of GICT practices. However, the benefits of GICT predominantly overshadow the aforementioned view as it enables companies to keep up to date with the latest and most advanced technology trends in the market.

It is evident that there are numerous benefits which SMEs can benefit from through the adoption of GICT. At the same time, GICT practices could enhance an enterprise's operational efficiency by aligning it with organisational strategies. Considering these benefits, it can be concluded that it is important for SMEs to engage in GICT practices to ultimately gain profitable benefits and shift towards a more sustainable environment.

3.4. Drivers and barriers of Green ICT adoption

ICT has become increasingly more convenient and popular to a broad-spectrum of the public and business users globally. Currently, the universal policies of a green economy are challenging countries to move towards eco-friendly innovation to secure a green world for the future generations to come [31]. Hence, the origin of GICT emerged due to the increasing demand of technology devices and overall impact on the environment making it highly important for SMEs to adopt GICT.

To understand industry and the problem of the low GICT adoption rate, the study envisaged to obtain a more in-depth understanding on the key drivers and barriers impacting stainable green practices in SMEs. These key drivers and barriers have been identified as the most important factors when considering the adoption of GICT based on previous literature reviewed. The four key drivers that were identified from information collected are: reduction on cost, competitive advantage, product life cycle and environmental conditions.

Upon the revision of existing literature, five key barriers were identified as hindering factors of GICT adoption from a variety of research articles. The five barriers which emerged are: lack of awareness, lack of knowledge, lack of expert ICT skills, legislative regulations, and lack of funding. GICT adoption can thus be classified into two groups, namely, the drivers pushing towards advancing the adoption of GICT and the barriers pulling from the adoption of GICT. GICT therefore consist of a combination of push and pull factors resulting in the low adoption rate.

3 RESEARCH METHODOLOGY

The primary objective of the study on which this paper is based was to identify the barriers which impede GICT adoption in SMEs. The secondary research objectives were (a) to determine the barrier that is perceived as the most prominent regarding low rate of GICT adoption in SA SMEs, and (b) to recommend strategies for improving the rate of GICT adoption in SA SMEs.

4.1. Research design and instrument

The research design consisted of a quantitative, non-experimental, and descriptive research design to explore the rate of GICT adoption in SMEs. The research instrument used was a self-administered questionnaire. To achieve the research objectives, the following were carried out: (a) an intensive review of the literature, (b) the administration of questionnaires, representative of a descriptive quantitative research method, and finally (c) exploratory factor analysis (EFA). This enabled the researcher to come to conclusions and to make recommendations regarding the identification of the barriers which impede GICT adoption in SMEs. The data collection technique consisted of a questionnaire survey.

The questionnaire was e-mailed to all the possible participants (owners and managers) in the research study to collect data from SMEs registered with Council for Scientific Research's (CSIR) Innovation Hub. Respondents received a link via e-mail to a questionnaire that was administered through SurveyMonkey®. The questionnaire was compiled based on the barriers identified in the literature, namely, lack of awareness, lack of knowledge, lack of expert ICT skills, legislative regulations, and lack of funding.

4.2 The population and sampling in the study

The target population of the study included all SMEs registered with The Innovation Hub, located in Gauteng. There was a total of 400 registered organisations at the time of the research, with at least one contact person for each organisation. The SMEs registered with the Innovation Hub were selected based on its focus on high-end innovative solutions that create a cutting-edge ICT platform for entrepreneurs.

The census was viewed as the appropriate sampling technique due to small population size (entire 400 SMEs registered with The Innovation Hub) including budget and time constraints in this situation. The unit of analysis of the survey measured the collective perceptions of SME owners and managers relating to the low rate of GICT adoption. Of the 400 targeted participants, a total of n=100 answered the questionnaires successfully, realising a response rate of 25%.

4.3 Data collection and analysis

The primary data was collected by means of a self-administered questionnaire which was sent via an email link to the participants to determine the impact of constructs in study. The collected data was interpreted, and information gathered from the literature study helped the researcher to report on the findings of the study [32]. The questionnaire was utilised to elicit responses as to identify the barriers which impede GICT adoption in SMEs. The pilot-test was conducted using two experts from The Innovation Hub as well as two academics. To ensure validity the researcher obtained items from the literature that were included in the questionnaire to measure the proposed constructs that the study intended to measure [33].

Descriptive statistical analysis was used to identify and show patterns in the data. Multivariate statistical techniques (both univariate and bivariate analysis) were also used to examine several measurements of variables under investigation simultaneously; these included a factor analysis. The collected data was coded electronically and analysed by a statistician by means of the IBM SPSS, Version 25 statistics software program.

The descriptive, multivariate, and statistical measures used to analyse the data included the following two steps, namely, exploratory factor analysis comprising Bartlett‘s test of sphericity, the Kaizer-Meyer-Oklin (KMO), Cattell’s scree test and statistical outcomes (mean, standard deviation and Cronbach alpha). Summaries of constructs (ratings) (mean value and standard deviation) were presented for all the six factors identified (legislation, skills, funding, awareness, knowledge based on complexity, and uncertainty). This is followed by discussions and recommendations.

From Table 2 it is evident that the KMO and Bartlett’s test are statistically significant, as a value greater than the minimum ($p < 0.05$) is deemed a valid factor analysis [34]. The chi-square approximation is therefore significant for the barriers resulting in low GICT adoption.

Table 2: KMO and Bartlett's test

Kaizer-Meyer-Oklin measure of sampling adequacy		0.722
Bartlett ‘s test of sphericity	Approx. Chi-Square	1158.338
	df	253
	Sig.	0.000

**Df = Degree of freedom*

***Sig = Significance*

Subsequent to the above, the Cattell's scree test was used to plot the eigenvalues and identify a maximum number of factors greater than 1.0 extracted before the curve starts to straighten [1]. The eigenvalues of the components extracted showed only six values above 1 (5.85, 2.76, 2.53, 2.12, 1.62, 1.07), of which the total variance was 67.65%. In Figure 1 a scree plot with the variance between the components extracted is shown.

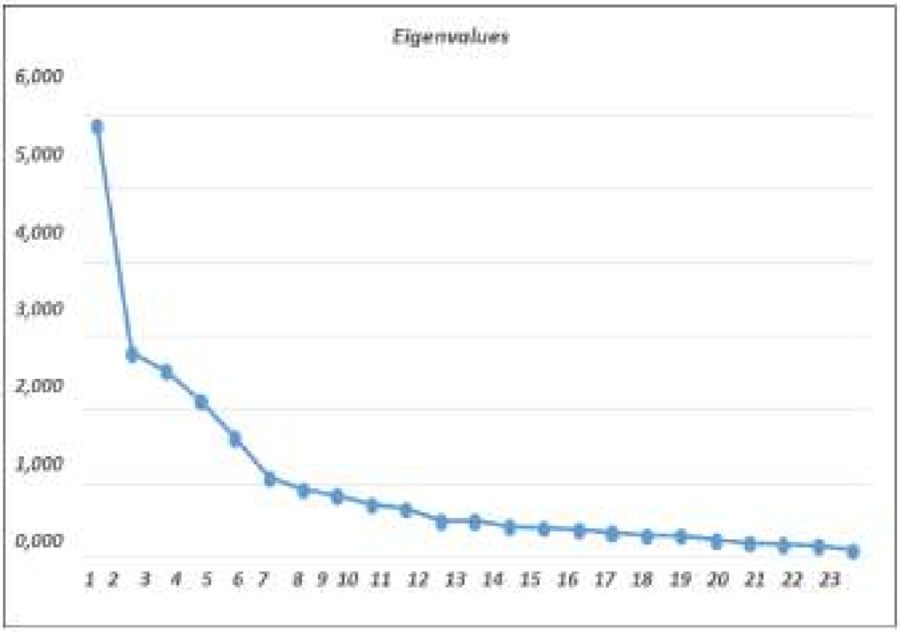

Figure 1: Cattell's Scree test

Figure 1 revealed a much greater variance between components 1 and 2 in comparison with the other components. On the plot, a clear break is indicated between components 2, 3, 4, 5 and 6, which will be explored. In all, six factors were identified from Cattell's scree test to be retained for further exploration and validity.

The next step was to report on the statistical outcomes to meet the primary objective. The perception of respondents regarding the low GICT adoption rate was tested. With the collected data having been analysed, the mean scores indicate the prominence of each barrier perceived by SMEs. In Table 3, the ranking of mean scores for barriers is shown.

Table 3: Statistical outcomes

Ranking	Barrier	Item	Item Mean/SD	Construct Mean/SD
First	Funding	Insufficient capital	4.01 (1.07)	3.94 (0.76)
		High research and development costs	3.87 (1.02)	
		Uncertainty about return on investment	3.91 (1.07)	
		Continuous investment required	3.84 (0.96)	
		High initial investment required for operational costs	4.06 (1.00)	
Second	Awareness	Unsureness about the implementation of GICT	3.85 (0.83)	3.94 (0.67)
		Unawareness of GICT to improve sustainability	3.96 (0.83)	
		Unawareness of GICT in the marketplace	3.96 (0.89)	
		Unawareness about GICT operation processes	4.00 (0.80)	

Third	Legislation	Insufficient government subsidies	3.87 (1.10)	3.88 (0.88)
		Unpredictable changes in government laws	3.69 (1.07)	
		Inadequate capabilities by government	3.81 (1.04)	
		Unclear government policies	3.93 (1.08)	
		Insufficient government support for green initiatives	4.09 (1.06)	
Fourth	Skills	Q4.3.a: Lack of qualified employees	3.72 (0.99)	3.78 (0.75)
		Q4.3.b: Lack of skills to enhance green initiatives	3.85 (0.93)	
		Q4.3.c: Inadequate technical capabilities	3.72 (0.90)	
		Q4.3.d: Poor expertise about GICT operation processes	3.61 (0.91)	
		Q4.3.e: Lack of GICT training	4.02 (0.97)	
Fifth	Knowledge-uncertainty	Lack of shared knowledge collaboration	3.62 (1.01)	3.68 (0.94)
		Uncertainty about GICT benefits	3.73 (1.04)	
Sixth	Knowledge-complexity	Too complex	3.22 (1.09)	3.18 (1.00)
		Risk of failure	3.14 (1.15)	

Table 3 indicates that participants rated lack of funding as the foremost barrier hindering the adoption of GICT with (mean = 3.94; SD = 0.76). This implies that the respondents (owners and managers of SMEs) perceived a lack of funding to be the key barrier preventing the adoption of GICT. The high initial investment required for operation costs (mean = 4.06; SD =1.00) was identified as the item with the highest agreement among respondents, followed by insufficient capital (mean = 4.01; SD = 1.07). The next highest perceived item was uncertainty about return on investment (mean = 3.91; SD = 1.07), high research and development costs (mean = 3.87; SD = 1.02) and finally continuous investment required (mean = 3,84; SD = 0.96).

5 FINDINGS AND RESULTS

5.1 Presentation of findings

The analysis indicated that most participants (60%) were owners of SMEs, while 38% were managers. The problem investigated was the low GICT adoption rate in SA SMEs.

5.1.1. Primary objective:

The primary objective of the research study was to determine what are the most prominent barriers resulting in the low adoption rate of GICT in SA SMEs

Six constructs extracted through an exploratory factor analysis reaffirmed that barriers identified through literature do result in a low GICT adoption. Although five constructs were originally discussed in literature, the overall eigenvalues extracted showed six components whereby knowledge is distinguished between complexity and uncertainty. Having analysed the data collected, the mean values indicate the prominence of each barrier perceived by SMEs. In general, respondents indicated that they agree with statements about the barriers of GICT. In Table 4, the results of the overall ratings and ranking of mean values for barriers resulting in the low adoption of GICT is shown.

Table 4: Mean values for barriers of Green ICT

Ranking	Barrier	Mean	Standard Deviation
First	Funding	3.94	0.760
Second	Awareness	3.94	0.667
Third	Legislation	3.88	0.878
Fourth	Skills	3.78	0.746
Fifth	Knowledge - uncertainty	3.68	0.936
Sixth	Knowledge – complexity	3.18	0.999

Table 4 indicates that respondents rated lack of funding as the foremost barrier in hindering the adoption of GICT with a mean score of 3.94 and standard deviation of 0.760. According to these findings from the results of the survey, the primary objective was achieved.

5.1.2. Secondary objective 1:

The secondary objective 1 of the research study was to determine the barrier with strongest underlying correlation resulting in the low adoption rate of GICT in SA SMEs.

A Pearson Product-moment coefficient was used to determine the correlation between legislation, skills, funding, awareness, and knowledge based on complexity and uncertainty respectively. Based on the findings, it can be deduced that there is a perfect positive correlation between constructs. This implies that these constructs are significant and influence each other either with a small or medium effect size. The correlational analysis showed positive correlations of legislation with skills (.26 - small), funding (.33 - medium) - and knowledge – uncertainty (.28 – small) exist. This indicates that these constructs affect one another when deciding to adopt GICT in SMEs.

In general, the findings indicated that awareness linked to knowledge-uncertainty about GICT adoption significantly impacting SMEs decision making processes. Based upon the collective shared views by respondents, the significant relationship between awareness and knowledge - uncertainty was indicated as the barrier with the strongest underlying correlation resulting in the low adoption rate of GICT. Overall, the data indicated that the uncertainty linked to knowledge and lack of awareness about GICT adoption (benefits and shared knowledge) greatly influenced by SMEs decisions. According to these findings from the results of the survey, the secondary objective 1 was achieved.

5.1.3. Secondary objective 2:

The second secondary objective of the research study was to recommend strategies on how to improve the adoption rate of GICT in SA SMEs.

Based on the barriers identified, is it clear that the respondents of SA SMEs perception were that they had a lack in awareness, knowledge, skills, funding, and legislation regulation regarding GICT. Considering this, business owners and managers of SMEs should attend training workshops and initiate GICT practices in the workplace by raising awareness amongst employees. SA SMEs should commit towards enforcing GICT strategies and engage in different environmental activities to create an environmental culture in the workplace. It is also evident that strategies regarding GICT should enable policy makers to make valuable contributions towards decision-making processes and prioritising the adoption of GICT practices. Apart from this, business owners and managers of SMEs with a higher level of education may require more information on advantages than business owners and managers with a lower level of education to consider GICT adoption. According to these findings from the results of the survey, the secondary objective 2 was achieved.

6 LIMITATIONS OF THE RESEARCH

Certain limitations regarding the study existed due to constraints related to budget and time as well as the unavailability. The literature review indicated that GICT is a fairly new concept, especially in developing countries. Within this context, certain delimitations can be expected from the research study such as a smaller population size though it would be acceptable to test the theory. The questionnaire was distributed to all participants but not everyone could participate resulting in a low response rate. Lastly, the study mainly considered SMEs located in Gauteng and the viewpoint on barriers of GICT by high technology-based SMEs due to budget and time constraints. Due to this, it must be noted that the findings of the study cannot be generalised, however, it is deemed sufficiently representative to be applied to developing economies like South Africa.

7 MANAGERIAL IMPLICATIONS

The research makes a managerial contribution by suggesting possible strategies enabling SMEs to overcome funding barriers. Recommendations are made to both owners/managers of SMEs and policy makers such as the South African government. The Innovation Hub, which functions as an existing platform to aid SMEs, would be an important vehicle in the context of implementing GICT.

8 SIGNIFICANCE OF THE STUDY

The significance of the study is that it to contributes to the body of knowledge on the low adoption rate of GICT in SA SMEs. This research study envisaged to fill the void in the literature regarding the limited research on the low adoption rate of GICT [11]. This study also examined the GICT principles that could influence the low rate of adopting green technology in terms of regulations to protect the environment [10]. South Africa is the largest emitter of carbon dioxide in Africa producing 24% of all Africa's emission [10]. It is therefore imperative to understand the reasons for the reluctance of SA SMEs to adopt GICT practices.

9 FURTHER RESEARCH

As further research, this study could be replicated in other countries to determine the compliance with and/or deviations from the findings reported on in this study. Furthermore, the study focused purely on the barriers to the adoption of GICT; future research could well focus on the drivers of GICT to compile a stronger case study in its favour. Various authors have proposed further research on the development of greener technologies.

10 CONCLUSIONS AND RECOMMENDATIONS

The conclusions of this study are based on the research findings in line with the objectives of the study. The following note-worthy conclusions were drawn from the findings. The GICT barriers identified were a lack of funding, awareness, legislation, skills, knowledge based on uncertainty and complexity respectively. Hence, all objectives of the study were achieved as the most prominent barriers resulting in the low adoption rate of GICT in SA SMEs were identified. The study determined that the most prominent barrier to GICT adoption was lack of funding. It is noteworthy to look at innovative ways to overcome this barrier, otherwise SMEs will not benefit from the numerous advantages offered by GICT. In general, it can be concluded that the respondents agreed with statements about the barriers of GICT.

It is recommended that SME owners could consider partnerships with other SMEs to share GICT resources, resulting in cost savings and to achieve economies of scale. SME owners/managers are also encouraged to adopt cloud computing initiatives which is more cost effective for SMEs while at the same time offering a bouquet of functionalities from the cloud [33]. It is also recommended that policy makers assist SME owners/managers through the offering of GICT development programmes, awareness raising, the inculcation of knowledge specifically addressing complexity and uncertainty, skills provision, and funding.

The Innovation Hub is an effective platform for expanding support offerings to SMEs and the expansion of the Innovation Hub to a national platform might be beneficial for SMEs for initiatives such as GICT uptake.

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A SYSTEMATIC LITERATURE REVIEW ON QUALITY PROCEDURES WITHIN A CITRUS PACKHOUSE

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ABSTRACT

Adequate quality procedures in a citrus packhouse assist in decision-making to enable optimal value-add to the business. Citrus accounts for more than a third of the total fruit production in South Africa, and it also accounts for half of total fruit export revenue. Citrus production is affected by a variety of factors, including the following but not limited to entomological, climatological, grading, and physiological factors. This study aims to investigate the existing literature on quality procedures within an agricultural packhouse. The categories investigated in this study include different quality systems and their implementations within the agricultural industry. This paper will contribute to research by identifying the potential research gap in agricultural quality procedures.

Keywords: Quality Procedures, Agriculture, Packhouse

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1 INTRODUCTION

According to [1] , effectively managing quality procedures within agricultural packhouses is vital for optimising business outcomes and ensuring the delivery of high-quality products to consumers. This is particularly relevant in the context of citrus production, which holds a prominent position in South Africa's fruit industry. With citrus accounting for over a third of the total fruit production and half of the country's fruit export revenue, robust quality procedures become paramount.

Citrus production is subject to numerous factors that can impact quality measurements, including and not limited to entomological threats, climatological conditions, grading processes, and physiological factors. Packhouses rely on well-defined quality systems and procedures to mitigate these challenges and ensure optimal product quality.

Historically, packhouses in South Africa were initially basic structures where fruits and vegetables were manually sorted, graded, and packed for distribution [2]. However, with the growth of the agricultural industry and the need for improved efficiency, technological advancements transformed packhouses into modern facilities equipped with state-of-the-art machinery and quality control systems [3].

Establishing the Citrus Marketing Board in South Africa in 1924 significantly shaped the development of packhouses. The board introduced standardised grading and packing practices, which led to increased consistency in product quality and increased product quality consistency [4]. Over the years, implementing quality control measurements and adopting innovative technologies have become essential components of packhouse operations in South Africa.

One notable development in packhouse technology is the adoption of sorting and grading systems. Such advancements have significantly improved the efficiency and accuracy of packhouse operations. The following technological advancements and domains have been applied to improve the packhouse operations in South Africa:

- **Data analytics:** Data analytics plays a pivotal role in driving innovation within packhouses in South Africa. By harnessing the power of data, packhouses can gain valuable insights into production processes, quality trends, and customer preferences. Advanced analytics techniques, such as predictive modelling and machine learning algorithms, enable the identification of patterns, anomalies, and optimisation opportunities. Data-driven decision-making empowers packhouse managers to make informed choices, optimise resource allocation, and continually improve operational performance [5].
- **Industry 4.0:** The emergence of Industry 4.0 technologies has revolutionised packhouse operations by leveraging automation, connectivity, and data analytics. South African packhouses have embraced advanced technologies such as robotics, Internet of Things devices, and cloud computing to optimise production processes [6]. These technologies enable real-time monitoring, data-driven decision-making, and predictive analytics, improving operational efficiency, reducing costs, and enhancing product quality. Integrating cyber-physical systems within packhouses facilitates adaptive and agile production, ensuring the industry can respond to changing market demands.
- **Lean management:** The concept of lean management, derived from the Toyota Production System, focuses on eliminating waste, improving efficiency, and maximising value. In the context of packhouses, lean management principles and practices have been adopted to streamline operations, reduce costs, and optimise resource utilisation [7]. Lean methodologies, such as value stream mapping, just-in-time inventory management, and continuous improvement initiatives, have been implemented in South African packhouses to enhance productivity and minimise operational inefficiencies.

- **Quality control:** Effective quality control practices are crucial for ensuring the delivery of high-quality products from packhouses. Quality control measures enhance product quality and increase customer satisfaction and market competitiveness. In South Africa, packhouses have embraced various quality control techniques and technologies, such as optical sorters, weight sorters, and colour sorters. These advancements enable accurate sorting and grading of agricultural products based on size, colour, and defects, resulting in consistent product quality and reduced waste [3].

Understanding the current state of research on quality procedures within agricultural packhouses is essential for further advancements within this field. For this reason, this paper explores the existing literature on quality procedures within agricultural packhouses, explicitly focusing on citrus production. By analysing scholarly articles, research papers, and industry reports published since 2018, the paper aims to explore the range of quality systems utilised in agricultural packhouses and evaluate their effectiveness. The results obtained from this study may pave the way for academics and industry partners to enhance and improve packhouse operations in South Africa. The systematic literature review is outlined and conducted in Section 2. The results are discussed in Section 3, followed by conclusions and valuable future recommendations in Section 4.

2 A SYSTEMATIC LITERATURE REVIEW

A systematic literature review represents a meticulous and methodical approach to comprehensively gathering, assessing, and synthesising existing research literature about a specific subject or research query [8]. It encompasses a systematic exploration of numerous databases and sources, meticulous selection of pertinent studies based on predetermined criteria, critical appraisal of their quality, extraction of pertinent data, and synthesis of the findings to furnish a comprehensive overview of the prevailing evidence.

2.1 Research Method

The systematic literature review conducted in this study on quality procedures within a citrus packhouse followed the guidelines outlined and proposed by Kitchenham et al. [9] and Du Plessis and Bisset [10].

2.1.1 Research Questions

To achieve the aim of this study, the following four research questions, as shown in **Table 1**, were formulated.

Table 1: Research Questions

Research Question 1	Research Question 2	Research Question 3	Research Question 4
How many studies contain the research keywords in the (Title, abstract or keywords) “Quality” AND “Packhouse” AND “Operations”?	How many studies focus on each of the following domains within packhouse operations: • Data Analytics • Industry 4.0 • Lean Management • Quality Control	How many studies focused on Quality Control within packhouse operations?	Which Quality Procedures, Systems or Technology are applied in each study?

2.1.2 *Search Process, Data Collection and Analysis*

A search process was developed to ensure that all relevant studies were included in this systematic literature review. **Table 2** below shows the appropriate steps that were followed to achieve this.

Table 2: Steps Followed in the Search Process

Step 1	Step 2	Step 3	Step 4
Identify all the studies containing the specified keywords.	Remove all duplicate literature.	Identify studies that contain the following keywords in the (Title, abstract or keywords) "Quality" AND "Packhouse" AND "Operations".	Identify all the studies that focus on each of the following domains within packhouse operations: • Data Analytics • Industry 4.0 • Lean Management • Quality Control

Tables 3 and 4 indicate the keywords, databases, inclusion, and exclusion criteria used in this systematic literature review.

Table 3: Keywords and Databases Used in the Search Process

Keywords	Databases
"Quality" AND "Packhouse" AND "Operations"	• Science Direct • Scopus • Web of Science • EBSCO Host (*Academic search complete, Applied Science & Technology Source, Business Source Complete, E-Journals, Environment Complete*) • Emerald Insight

Table 4: Inclusion and Exclusion criteria used in the Search Process

Inclusion Criteria	Exclusion Criteria
1. Studies that contain the following keywords in the (Title, abstract or keywords) "Quality" AND "Packhouse" AND "Operations". 2. Timeframe (2018 -2022)	1. Non-English Literature 2. Books

Table 5 shows the data categories collected during the systematic literature review. This data was analysed accordingly to answer the research questions formulated in Section 2.1.1. The research was conducted for the period from 2018 to 2022.

Table 5: Data Collection and Analysis

Data Collection	Data Analysis
• Research Title, • Year of publication (Studies that were published between 2018 – 2022), • Database, • Abstract,	1. How many studies contain the research keywords in the (Title, abstract or keywords) "Quality" AND "Packhouse" AND "Operations"? (Research Question 1) 2. How many studies focus on each of the following domains within packhouse operations: (Research Questions 2) • Data Analytics

• Keywords, • Application Domain, and • References.	• Industry 4.0 • Lean Management • Quality Control 3. How many studies focused on Quality Control within packhouse operations? (Research Question 3) 4. Which Quality Procedures, Systems or Technology are applied in each study? (Research Question 4)

2.2 Discussion of Research Results

The search outcomes, as well as the results following each research protocol step, are illustrated in **Table 6**.

Table 6: Research Results

Research Protocol	Research Results
Step 1: Identify all the studies containing the specified keywords. **Keywords:** "Quality" AND "Packhouse" AND "Operations" **Timeframe:** 2018-2022 Excluding: • Non-English Literature • Books	Science Direct - 30 Scopus - 3 Web of Science - 3 EBSCO Host - 35 Emerald Insight - 3 **Total - 74**
Step 2: Remove all duplicate literature	Science Direct - 28 Scopus - 1 Web of Science -2 EBSCO Host - 34 Emerald Insight - 3 **Total after removing duplicates - 68**
Step 3: Identify studies that contain the following keywords in the (Title, abstract or keywords) "Quality" AND "Packhouse" AND "Operations".	Science Direct - 16 Scopus - 1 Web of Science -2 EBSCO Host - 32 Emerald Insight - 1 **Total after removing duplicates - 52**
Step 4: Identify all the studies that focus on each of the following domains within packhouse operations: • Data Analytics • Industry 4.0 • Lean Management • Quality Control	Science Direct - 7 Scopus - 1 Web of Science - 2 EBSCO Host - 22 Emerald Insight - 1 **Total - 33**

From **Table 6**, it is evident that a total of 33 studies were identified. These studies are provided in **Table 7**.

Table 7: Results of the systematic literature review

No.	Title	Year	Database	Domain	Reference
1	smAvo: Packhouse optimization using smart avocadoes in South Africa	2021	Scopus	Data Analytics	Broekman, and Steyn [11]
2	Harvest and Postharvest Factors Affecting Bruise Damage of Fresh Fruits	2020	Web of Science	Quality Control	Hussein et al. [12]
3	Mechanized Blueberry Harvesting: Preliminary Results in the Italian Context	2021	Web of Science	Industry 4.0	Brondino et al. [13]
4	Future research methodologies of lean manufacturing: a systematic literature review	2021	Emerald Insight	Data Analytics	Evangelos [14]
5	Mapping the postharvest life of imported fruits from packhouse to retail stores using physics-based digital twins	2021	Science Direct	Data Analytics	Kanah et al. [15]
6	Influence of harvest method on the Quality and Storage of highbush blueberry	2022	Science Direct	Industry 4.0	Brondino et al. [16]
7	Identifying temperature breaks in table grape export cold chains from South Africa to the United Kingdom: A Western Cape case	2022	Science Direct	Data Analytics	Fedeli et al. [17]
8	Unveiling how ventilated packaging design and cold chain scenarios affect the cooling kinetics and fruit quality for each single citrus fruit in an entire pallet	2019	Science Direct	Industry 4.0	Wu et al. [18]
9	Carbon intensive but decarbonizing quickly? Retrospective and prospective Life Cycle Assessments of South African pome fruit	2019	Science Direct	Lean Management	De Kock et al. [19]
10	Linking smallholder vegetable producers to markets - A comparison of a vegetable producer group and a contract-farming arrangement in the Lesotho District of Tanzania	2018	Science Direct	Quality Control	Gramzow et al. [20]
11	Toward sustainable primary production through the application of lean management in South African fruit horticulture	2021	Science Direct	Lean Management	Pearce et al. [21]
12	Differential evolution with reinforcement learning for multi-objective assembly line feeding problem.	2022	Applied Science and Technology	Data Analytics, Industry 4.0	Lue et al. [22]
13	Domain Feature Mapping with YOLOv7 for Automated Edge-Based Pallet Racking Inspections.	2022	Academic Search Complete	Industry 4.0	Hussain et al. [23]
14	The integrated order line batching, batch scheduling, and picker routing problem with multiple pickers: the benefits of splitting customer orders.	2022	Applied Science and Technology	Data Analytics, Quality Control	Haouassi et al. [24]
15	Optimizing payment schemes in a decentralized supply chain: A Stackelberg game with quality investment and bank credit.	2022	Applied Science and Technology	Data Analytics	Cao et al. [25]

No.	Title	Year	Database	Domain	Reference
16	A bi-objective humanitarian logistics model considering equity in the affected zones: application to a recent earthquake in Mexico.	2022	Business Source Complete	Data Analytics, Lean Management	Hernández-Leandro et al. [26]
17	Mathematical Modelling of Inventory and Process Outsourcing for Optimization of Supply Chain Management.	2022	Academic Search Complete	Data Analytics	Alkahtani [27]
18	Applying Integrated QFD-MCDM Approach to Strengthen Supply Chain Agility for Mitigating Sustainable Risks.	2022	Academic Search Complete	Data Analytics	Hsu et al. [28]
19	Integrating vehicle scheduling and open routing decisions in a cross-docking centre with multiple docks.	2022	Applied Science and Technology	Data Analytics	Cota et al. [29]
20	Evolving a bi-objective optimization model for an after-sales supply chain in the presence of information asymmetry and service level requirements.	2022	Business Source Complete	Data Analytics	Goswami et al. [30]
21	A state-based multi-agent system model of taxi fleets.	2022	Applied Science and Technology	Data Analytics, Industry 4.0	Ribas-Xirgo [31]
22	The Piggyback Transportation Problem: Transporting drones launched from a flying warehouse.	2022	Applied Science and Technology	Industry 4.0	Wang et al. [32]
23	Operations Research Algorithms Drive Intelligent Warehouse Robots to Work.	2022	Applied Science and Technology	Data Analytics, Industry 4.0	Qin et al. [33]
24	Robot Scheduling for Mobile-Rack Warehouses: Human-Robot Coordinated Order Picking Systems.	2022	Business Source Complete	Data Analytics	Wang et al. [34]
25	Analytical Assessment of Stochastic Spread of Demand for the Port Storage Capacity.	2022	Academic Search Complete	Data Analytics	Kuznetsov et al. [35]
26	Assessing construction material manufacturers' warehouse processes from a customer satisfaction perspective.	2021	Academic Search Complete	Data Analytics	Alumbugu et al. [36]
27	Analytical Assessment of Stochastic Spread of Demand for the Port Storage Capacity.	2020	Academic Search Complete	Industry 4.0	Kuznetsov et al. [35]
28	ASSESSMENT OF TRANSPORTATION EFFICIENCY FOR THE DELIVERY OF CONSTRUCTION MATERIAL IN NORTH-CENTRAL NIGERIA.	2020	Academic Search Complete	Data Analytics	Alumbugu et al. [37]
29	REPLENISHMENT POLICIES FOR IMPERFECT INVENTORY SYSTEMS UNDER NATURAL IDLE TIME AND SHORTAGES.	2020	Applied Science and Technology	Quality Control	Jaggi et al. [38]
30	A disaster relief operations management model: a hybrid LP-GA approach.	2020	Applied Science and Technology	Data Analytics	Molladavoodi et al. [39]
31	Urban Transportation Network Design for Fresh Fruit and Vegetables Using GIS-The Case of Bangkok.	2019	Applied Science and Technology	Data Analytics	Suraraksa and Shin [40]

No.	Title	Year	Database	Domain	Reference
32	A web mining-based case adaptation model for quality assurance of pharmaceutical warehouses.	2019	Business Source Complete	Quality Control	Tang et al. [41]
33	An Integrated Metaheuristic Routing Method for Multiple-Block Warehouses with Ultranarrow Aisles and Access Restriction.	2019	Applied Science and Technology	Data Analytics, Industry 4.0	Chen et al. [42]

Each study is identified based on the title, abstract, year of publication, database, domain, and reference. Based on the results in Table 7, the research questions are addressed.

2.2.1 Research Question 1: How many studies contain the research keywords in the (Title, abstract or keywords) “Quality” AND “Packhouse” AND “Operations”?

Table 7 indicated that a total of 52 studies contained these keywords in each study's title, abstract and keywords. The number of publications per database is provided in **Figure 1**.

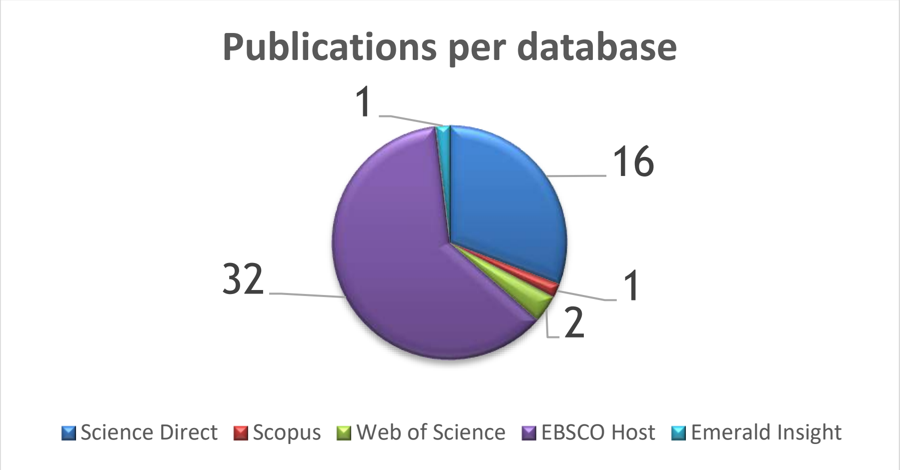

Figure 1: Publications per database

Figure 1 illustrates that a total of 16 studies were identified in EBSCO Host, 16 in Science Direct, 2 in Web of Science, 1 in Scopus and 1 in Emerald Insight. The publications per year are demonstrated in **Figure 2**.

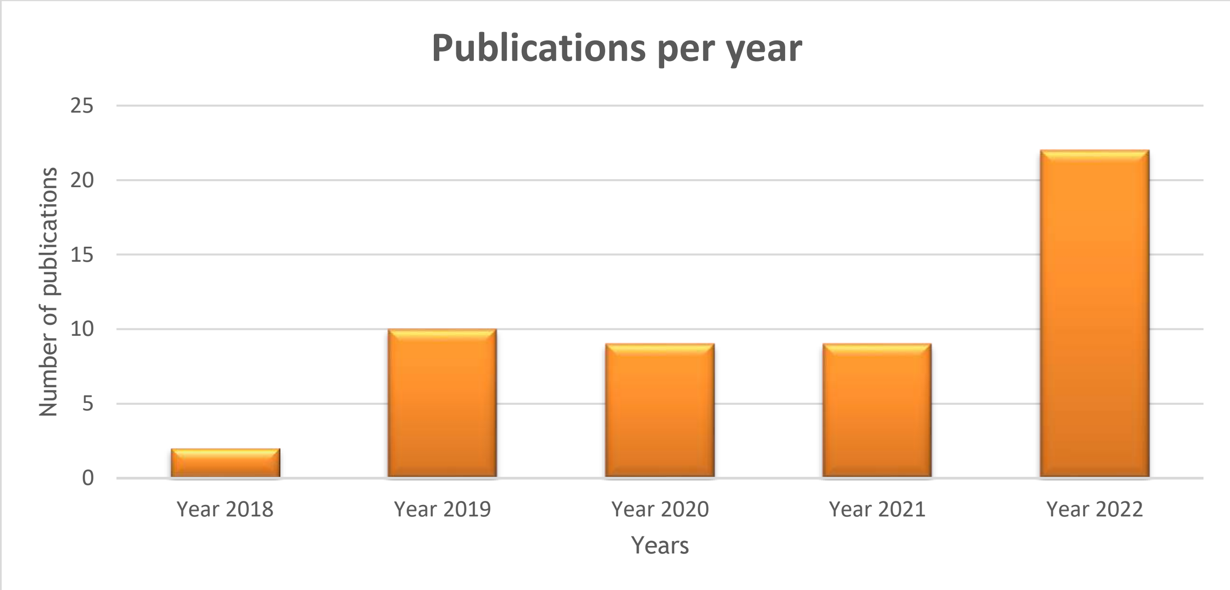

Figure 2: Publications per year

Figure 2 shows that two studies were published in 2018, ten in 2019, nine in 2020, nine in 2021 and 22 in 2022. This shows that the research interest in the agricultural sector increased with time and provides more future research opportunities.

2.2.2 Research Question 2: How many studies focus on each of the following domains within packhouse operations: Data analytics, industry 4.0, lean management and quality control?

The number of publications or studies per domain is demonstrated in **Figure 3**.

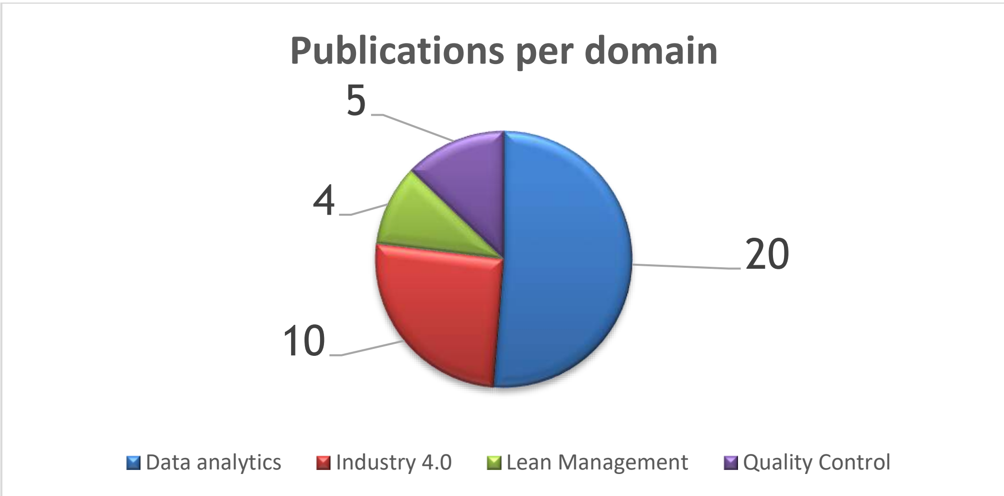

Figure 3: Publications per domain

Figure 3 illustrates that 20 studies focused on data analytics, 10 on Industry 4.0, 4 on lean management and 5 on quality control. There are 39 studies identified in **Figure 3**, this is because 6 studies focused on more than one domain. One study focused on data analytics and quality control, four studies focused on data analytics and industry 4.0 and one study focused on data analytics and lean management.

2.2.3 Research Question 3: How many studies focused on Quality Control within packhouse operations?

From the results, it is evident that a total of five studies focused on quality control.

2.2.4 Research Question 4: Which Quality Procedures, Systems or Technology are applied in each study?

This study focuses specifically on quality control measures and procedures within a packhouse. For this reason, each study that focused on quality control is discussed in detail in **Table 8**.

Table 8: Research Question 4 results

No.	Title	Year	Overview	Quality Procedures, Systems or Technology	Limitations & Future research opportunities	Reference
1	Harvest and Postharvest Factors Affecting Bruise Damage of Fresh Fruits	2020	This article investigates the factors related to harvest and postharvest practices that contribute to bruise damage in fresh fruits. The study focuses on understanding the causes of bruising and explores potential solutions to minimize damage while handling and storing fruits. This article highlights the importance of implementing appropriate quality procedures, systems, and technologies to mitigate bruise damage in citrus packhouse operations.	**Mechanized Harvesting:** To reduce bruise damage in fresh fruits, such as automated fruit-picking machines. It investigates the technical specifications, operating parameters, and optimization strategies of these machines to ensure gentle fruit handling and minimize impact-induced bruising. **Packaging and Transportation Technologies:** The research focuses on advanced packaging technologies and transportation systems that mitigate bruise damage during fruit transit. It examines the use of shock-absorbing materials, protective cushioning, and optimized packing configurations to minimize vibrations and impacts, ensuring the preservation of fruit quality. **Postharvest Handling Protocols:** Precise postharvest handling procedures to minimize bruise	**Varietal Differences:** Citrus varieties' characteristics and susceptibility to bruising for targeted mitigation strategies could be investigated for future research. **Impact of Environmental Factors:** The interaction between environmental conditions and bruise damage in citrus packhouse operations could be future researched to establish its direct effects on Quality Procedures in the packhouse operations. **Development of Innovative Packaging Materials:** Further research opportunity on packaging solutions with enhanced shock-absorbing properties for minimizing bruise damage. **Automation and Robotics:** Further concentrated research into the application of automation technologies in citrus packhouses to enhance efficiency and reduce bruising could be beneficial.	[12]

No.	Title	Year	Overview	Quality Procedures, Systems or Technology	Limitations & Future research opportunities	Reference
				damage. It explores sorting and grading technologies, including computer vision systems and machine learning algorithms, to identify and segregate bruised fruits.		
2	Linking smallholder vegetable producers to markets - A comparison of a vegetable producer group and a contract-farming arrangement in the Lushoto District of Tanzania	2018	This article compares two different approaches, a vegetable producer group, and a contract-farming arrangement, in linking smallholder vegetable producers to markets in the Lushoto District of Tanzania. The study examines the effectiveness of these market linkage models in improving market access, income generation, and livelihoods for smallholder vegetable farmers. This article offers insights into market linkage models for smallholder vegetable producers and their relevance to citrus packhouse operations.	**Producer Group Organizational System:** The research explores the use of digital platforms, communication technologies, and database management systems to facilitate collaboration, information sharing, and collective decision-making among smallholder vegetable producers. **Contract-Farming Arrangements:** It explores the integration of information systems, such as enterprise resource planning (ERP) software and traceability systems, to monitor and ensure adherence to quality standards and facilitate efficient supply chain coordination.	**Scaling up and Replication:** Further Investigation on the scalability and replicability of successful market linkage models in citrus production could be done. **Market Linkage Strategies:** Identify innovative strategies to enhance market access and competitiveness for smallholder citrus producers. **Quality Assurance and Certification:** Examine the role of quality assurance systems and certifications in citrus packhouses to ensure compliance with international standards that could be researched for future benefits.	[20]
3	The integrated order line batching, batch scheduling, and picker routing problem with multiple pickers: the benefits of splitting customer orders.	2022	This article focuses on the optimization of order-picking operations in e-commerce warehouses to achieve fast delivery and maintain high	**Optimization Algorithms for Order Picking:** The research develops optimization algorithms and mathematical models to address order-picking challenges. The	**Scalability and Real-World Implementation:** Future studies could explore the integration of the algorithm with existing packhouse systems and evaluate its performance	[24]

No.	Title	Year	Overview	Quality Procedures, Systems or Technology	Limitations & Future research opportunities	Reference
			service quality. Specifically, the study explores the impact of splitting customer orders and introduces a route first-schedule second heuristic to solve the integrated order line batching, batch scheduling, and picker routing problem. The proposed algorithm divides orders into clusters and constructs picking tours using a split-based procedure, followed by assigning the tours to pickers while satisfying order deadlines.	study utilizes mathematical programming techniques, heuristics, and algorithms like genetic algorithms and ant colony optimization. **Route First-Schedule Second Heuristic:** The heuristic employs graph theory, network optimization, and algorithms like the nearest neighbour algorithm or the travelling salesman problem to optimize picker routing.	under varying operational conditions. **Consideration of Other Factors:** The article primarily focuses on the reduction of picking time and meeting order deadlines. Future research could expand the scope to consider additional factors relevant to citrus packhouse operations, such as quality control. **Comparative Analysis:** While the results show the benefits of splitting customer orders using the proposed algorithm, further comparative analysis with other optimization methods or heuristics specific to citrus packhouse operations could provide more insights into the effectiveness and efficiency of different approaches.	
4	REPLENISHMENT POLICIES FOR IMPERFECT INVENTORY SYSTEMS UNDER NATURAL IDLE TIME AND SHORTAGES.	2020	This article explores replenishment policies for retailers who operate their businesses for only a portion of the day and face challenges related to imperfect quality items and shortages. The study investigates the impact of natural idle time, which occurs during the closing period when no demand is fulfilled. The retailer conducts	**Rigorous Inspection Process:** The article focuses on the implementation of an inspection system within the inventory management process. It employs quality control techniques, such as statistical process control (SPC), Six Sigma methodologies, and automated inspection technologies, to identify imperfect inventory items. The system utilizes computer vision, sensors, or statistical analysis	**Real-Time Implementation:** The article presents a model under specific assumptions and scenarios. Future research can focus on implementing and validating the proposed replenishment policies in real-world citrus packhouse operations to assess their practicality and effectiveness. **Quality Control Techniques:** The study primarily focuses on the inspection process to ensure perfect	[38]

No.	Title	Year	Overview	Quality Procedures, Systems or Technology	Limitations & Future research opportunities	Reference
			a thorough inspection process to ensure only perfect quality items are used to fulfil customer demand. The model assumes fully backlogged shortages and aims to maximize profit. Sensitivity analysis is performed to gain managerial insights and assess the robustness of model parameters.	tools to detect defects or quality deviations. **Shortage Management Strategies:** It investigates techniques such as demand forecasting models, safety stock optimization algorithms, and reorder point calculations to minimize the impact of shortages.	quality items. Future research could explore different quality control techniques, such as statistical process control or automated inspection systems, that could apply to citrus packhouses for efficient quality management. **Sustainable Inventory Management:** The article does not specifically address sustainability aspects in inventory management. Future research could incorporate sustainability considerations, such as optimizing resource utilization into the replenishment policies for citrus packhouse operations.	
5	A web mining-based case adaptation model for quality assurance of pharmaceutical warehouses.	2019	This article proposes a web mining-based quality assurance system (WMQAS) for pharmaceutical warehouses. The quality assurance (QA) of pharmaceutical warehouses is crucial for ensuring compliance with regulations and minimizing errors and quality problems. The current QA planning process, which relies on human experience, can lead to increased rejection and recall rates. The WMQAS integrates case-	**Web Mining-Based Quality Assurance System:** The research proposes a system that integrates web mining techniques to enhance quality assurance processes. It employs web scraping, data mining, natural language processing (NLP), and machine learning algorithms to extract relevant information from web sources, such as regulatory databases, scientific literature, or adverse event reporting systems. The system assists in quality control decision-making, root cause analysis,	**Data Availability and Reliability:** The effectiveness of the proposed WMQAS relies on the availability and reliability of web information. Future research can explore methods to ensure the accuracy and relevance of web-mined data for decision-making in the context of citrus packhouse quality assurance. **Integration of Real-Time Data:** Future research can investigate the integration of real-time data streams from citrus packhouse operations to enhance the accuracy and timeliness of	[41]

No.	Title	Year	Overview	Quality Procedures, Systems or Technology	Limitations & Future research opportunities	Reference
			based reasoning (CBR) and a hybrid web mining technique to enhance decision-making in QA operations and improve product quality.	and knowledge sharing. **Case-Based Reasoning (CBR):** The study utilizes case-based reasoning as a knowledge representation and problem-solving technique in quality assurance. It involves capturing and storing past quality-related cases in a database, indexing them based on attributes, and retrieving similar cases to guide decision-making. The system leverages similarity metrics, case adaptation algorithms, and reasoning engines to provide recommendations, solutions, and lessons learned from previous quality assurance cases.	decision-making in QA processes. **Optimization of QA Processes:** The article does not explicitly address the optimization of QA processes. Future research could explore optimization techniques and algorithms to streamline and improve the efficiency of quality assurance operations in citrus packhouses.	

3 CONCLUSIONS AND FUTURE RECOMMENDATIONS

The systematic literature review investigated existing research and identified research gaps in agricultural quality procedures within citrus packhouses. Focusing on four research questions, the review analysed 33 relevant studies from databases such as Science Direct, Scopus, Web of Science, EBSCO Host, and Emerald Insight. These studies covered various aspects of packhouse operations, including data analytics, industry 4.0, lean management, and quality control. The findings demonstrated a diverse range of quality procedures, systems, and technologies applied in packhouse operations. The review provides valuable insights into the current state of research, emphasizing the significance of data analytics, industry 4.0, lean management, and quality control in optimizing packhouse operations for citrus production. Future research in this field should explore the integration of these approaches and technologies to develop comprehensive and efficient quality procedures within packhouse operations. It would be beneficial to investigate the effectiveness and practical implementation challenges of these approaches, supporting industry practitioners and researchers. In conclusion, the systematic literature review identified a range of quality procedures, systems, and technologies utilized in citrus packhouses. This knowledge can guide future research and facilitate continuous improvements in quality procedures within agricultural packhouses.

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A NOVEL ENTERPRISE ENGINEERING METHOD TO MAKE ARCHITECTURE PRACTICAL

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ABSTRACT

A novel, practical, logical, and proven method is introduced to engineer an enterprise. The method utilizes a sequence of architecture reference models and enforces order in a cascading effect to create a fit-for-purpose enterprise that amongst others, considers legacy, politics, and hidden agendas. The concept of this method is explained using a Performance Reference model, Organization Reference Model, Business Reference Model, Service Reference Models, Information Reference Model and Technology Reference Model. The proposed method is based on heuristic techniques, frameworks, and self-discovery. The method has the potential to provide significant benefits for organisations seeking to achieve their strategic and operational goals through effective architecting. This paper highlights the value of the proposed method in an enterprise context and can enable a unique capability in addressing business and solution architectures. While the method is not entirely new, it has never been published before, but has a reputable track record in practice.

Keywords: Enterprise Engineering, Enterprise Architecture, Business Architecture, Solutions Architecture, Reference Models, Controls; Measures; Risks; Governance

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1 INTRODUCTION

It is long overdue that the essentials and benefits of Enterprise Architecture (EA) be introduced in an applied way that will reconstruct the way we define an enterprise. This paper is not about EA, but its fundamentals are entrenched in what is being proposed in this paper. It is noticeable that EA fundamentals are not incorporated properly in projects, and not evident in operations that we conduct, and it becomes notoriously obvious when witnessing things go wrong, if no-one knows what others are doing, and the reason and objectives of what is being done is not realized, defined, or understood. These are but a few symptoms that manifests that we see evidence of, justifying what are being proposed here within.

One might get the idea that EA concepts are mere natural intrinsic manifestation and applied unknowingly, but consider it intrinsic to eat dinner, yet one have to know what you are going to eat, when it is dinner time, who will prepare and who will eat the dinner, what utensils you will need to eat it with, where are dinner going to be at, and if it is really necessary to eat at all? Suddenly one must think, and it is not that apparent anymore. This is where EA must help to make sense. The field of EA was specifically chosen due to its fundamental value proposition to describe a capable enterprise. It is not only EA, but a combination part of skillsets within the disciplines of Research, Systems Engineering (SE), and even Software Engineering (SoE).

A novel Enterprise Architecture method is herewith introduced, termed the Framework for Enterprise Architecture Focus Plus (FEAF+). The FEAF+ appears to be unique in the research publication world, but it has good, applied reputations and references in many corporate and large enterprises, of which applied examples exists. It is more than an approach, it is an established capability (people, tools, processes) but needs to obtain a research presence, so that continuous improvement initiatives of this concept and its approach can eventually be included and integrated with other disciplines.

This paper introduces a practical EA application based on vocabulary that is common to understand. It outlays an approach and its elements and commences in a structured, but formal way to obtain the best possible result when applied.

Conclusion: "*You don't have to do it, but one day, you will wish you did, in excruciating detail*", else consequences is predictable [17].

2 BACKGROUND

In the quest of identifying ways that keeps us honest to the goal, resist legacy and politic agendas, and providing a re-usable approach, lead to the FEAF+. This proposed approach is based on heuristic techniques that is a culmination of experience, frameworks, and self-discovery in the designing of an offering that is not currently available in empirical format relating to its content, structuring, adoption, and configuration, and the approach is therefore deemed one-of-its kind.

It recognizes the fact that there must be order in how we approach things, so it underpins the concept of following a logical life cycle, or steps, with exceptions if you deviate or overstep. It incorporates the notion of concept vs. instantiation and must help one to define both. This mean it aligns and bridges the ideal world with physical things or situations that must be considered. It includes knowing what the business requirements are before mitigating it with solutions. This is especially apparent now days where the 4th Industrial Revolution (4IR) wave enforces solutions without understanding the value proposition it will bring to the business, if any. It promulgates the concept of cascading-of-goals, ensuring that abstractions, aggregation, and associations are guided by the boundary it was derived from. It ensures the spectrum of interrogatives (why, what, where, when, how, who) as defined in [17], is addressed to make sure everything that describes an enterprise is incorporated. In fact, many EA fundamentals as described by the Zachman framework is incorporated by FEAF+. It is based on the belief that what you experience is probably by design, even unintendedly, and therefor proper design is necessary to steer the desired outcome. This makes it a dynamic and evolving approach, not due to the approach, but due to the content and sequence defined in the approach.

This explicit format of the approach makes it possible to culminate principles of Research Design, Enterprise Architecture, Systems, and Software Engineering, and in doing so formulates the establishment of an Enterprise Engineering and Architecture capability.

The scope of this approach is to define the context that would serve the development of skills. In the author's current organisation, the adoption of this approach turns out to be a multiyear intervention, staggered and leveraged according to available capacity and capability of the resources that can develop, conduct training, and receive the training. This alludes to the magnitude of this approach and provides forewarning in this paper's ability to cover the full extent of the FEAF+ and suggest covering the balance in a subsequent submission.

Ultimately, the purpose is to establish capability that is capacitated by resources, supported, and proven in its instantiation, with measurement-of-effectiveness being the value added.

3 FRAMEWORK FOR ENTERPRISE ARCHITECTURE FOCUS PLUS (FEAF+)

3.1 EA Overview

FEAF+ has an Enterprise Architecture (EA) foundation and it is stimulating to know that EA has its origin in the 1960s, born from various architectural manuscripts on Business Systems Planning (BSP) [2], [9]. According to the Enterprise Architecture Book of Knowledge (EABOK), John. A. Zachman, one of Walker's students, helped formulate those documents into a more structured format of EA [16], and since then is considered the father of Enterprise Architecture **Error! Reference source not found.**. This approach will not be justified without referencing the Zachman Enterprise Architecture Framework principles that sculptured part of the approach, because it sets the foundation of what we consider being architecture.

EA has its own vocabulary, frequently using terms that are common between disciplines, but having a unique perspective and definition in the context of EA. It will serve the reader if these are contained and reserved to present a linguistic intrinsic (belonging naturally) meaning. This activity would suggest an ontology (the science of what is) library consisting of terms, definitions, and set of principles that will set the values that guide the EA behaviour. For this reason, the following terms are fundamental to list:

Enterprise Architecture is an analytical discipline that provides methods to comprehensively define, organize, standardize, and document elements that are used to describe an enterprise [14]. EA is furthermore considered a discipline because it consists of a practice that obey rules or a code of behaviour. It is depicted as information about the architecture for an enterprise across architecture domains with the purpose to provide transparency for operational alignment and decision making, but also to enable tactical and long-term planning.

An enterprise is seen as an interconnected set of a capabilities and needs to balance processes, ICT, facilities, structure, cost, technology, and other factors such as culture, narratives, and motivation for a common goal [8]. An enterprise could be an ecosystem, company, business, department, section, or even a project, whatever you consider being the boundary of what you want to describe.

Contradicting earlier believe, although the stigma persist, EA is an approach that does not only focus on ICT but on all types of architectures, referred to as architecture domains. EA domains are partial representations of an entire enterprise architecture of its components that shares commonalities, or area of knowledge [3]. Domain as a term refer to work specialization. Specialist architects usually develop domain architectures independently. When the domain architectures are put together, a complete architecture exist. A viewpoint is comprised of domains, which represent a more detailed breakdown of the elements of that viewpoint [10].

As an overview, many frameworks, approaches, and methods are widely used under the banner of EA. Although many may be applicable, appropriate, or conceivable, it is the intend to highlight and make the reader aware of the predominant frameworks associated with EA, that impacted the FEAF+ approach and to allude to their purposes to manage expectations.

Three well known enterprise architect references have been consulted being The Open Group Enterprise Architecture Framework (TOGAF), Zachman Framework and the Federated Enterprise Architecture Framework (FEAF). From these, an approach was tailored to define an architecture to provide a fit-for-purpose design, promoted by:

- Cascading-of-goals, ensuring all architectural outputs are identified and related directly to the primary objective with non-repudiation. It relates to defining reference and sequence principles that guides an applied approach (adopted from FEAF) [6], [7].
- The architectural outputs relate to interrogatives, i.e. Who, What, When, Where, Why, and How (adopted from the Zachman Framework) [17].
- A suitable architectural design method (ADM) to identify and measure the gap to achieve the output through considering the As-Is of the outputs and analyse the To-Be considerations in order to achieve the intended architectural output (adopted from TOGAF) [11], [12].

3.2 FEAF+ Composition

Based on the principle of natural laws of classification, life is governed by interrogatives and reification [17]. We extract that there is a sequence how enterprises are defined, based on the concept of applying order, and this order is architecture. FEAF+ provides a logical way for that.

The FEAF+ approach originated by deriving various architecture domains in a specific sequence to ensure interrelated appropriateness, completeness, and accuracy. It is formulated as reference models, meaning it refers to a predefined structure used as references to derive appropriate content. It is highly entrenched in the following principles:

<u>Fit-for-Purpose</u>: Legacy and politics have caused a lasting persisting negative effect in what we do. It is intrenched everywhere and in everything. FEAF+ allows getting rid of legacy, political agendas, and redundancy, with a caveat that it is possible to make legacy, politics, or redundancy an expected criterion, but then it was deliberately designed.

<u>Cascading-of-goals</u> effect: FEAF+ forces to keep affiliated to the preceding concept through association, as a hierarchy (abstraction), breaking down, or building up, or extending to other components according to the affiliation, up to the level that makes sense.

3.3 FEAF+ References

The concept of reference models was adapted from FEAF, applied Zachman theory and TOGAF ADM to accommodate the various architectural domains in a method of sequence and logic to obtain the minimum set of parameters to explain an enterprise [13]. Subsequently, the architecture is contained within architectural references as models: Performance Reference Model (PRM); Organisation Reference Model (ORM); Business reference Model (BRM); Service reference Model (SRM); Information reference Model (IRM) and Technology Reference Model (TRM) [6]

Performance references – It becomes imperative to know what the objectives are to which the enterprise design needs to conform to. Objectives are referred to in a generic sense, and it represents any need, hope, goal, mission, vision, objective, requirement, plan, idea, wish, future that dictates the result hoped to be achieved. It recognises the concept that objectives can represent various levels of hierarchy, and various types, spanning vertically and horizontally. Every reference referred below stems from the performance reference. It is in this reference that one should caution the objectives selected to refrain from legacy, political agendas, or irrelevancy.

Organisation references – Identifies the organisational requirement, which entails the defining of accountability and responsibility requirement. This will inform the capacitation that an organisation, or enterprise, must establish to ensure the objectives are achieved. The capacitation of the organisation requirement will identify the factors dictating the quantification of the line organisation. The organisation reference is fundamental to the success of the architectural implementation because it represents the human aspects that will perform and be accountable for achieving the objectives. For every expectancy not allocated with appropriate organisational design, failure of achieving that objective will be predictable.

Business references – Identifies the expected business domain, function, processes, activities, steps that must be catered for to fulfil the preceding reference model requirements. It is the intension that the business reference designs will be in conjunction with the systems thinking decisions outcome. This includes the analysis of proposed solutions, the design thereof and the response expectancy when a process events occur. It also has a direct cascading association to the organisational references, meaning, no business reference should exist if it cannot be associated to the appropriate organisational reference design. Failing doing so will reside in business not being conducted, or business conducted which is not necessary, typical legacy businesses.

Service references – Describes the applications or system interventions required to mitigate the business events (Business reference outputs). The scope of this reference is to address the alignment of current or known systems capabilities with the architectural requirements derived from the preceding reference models. Where misalignments exist, alludes to gap identification. By the nature of this reference, it starts suggesting the solution on how the business references will be mitigated.

Information references – Describe the information that will be identified during an operations context and integration requirement to ensure realisation.

Technology references – Identifies the infrastructure, hosting, network, device and all other technologies and their interrelationship to provide an appropriate solution.

Through contextualising the various references in models, provides the consistency and re-usability that ultimate defines the FEAF+ approach, illustrated by the following:

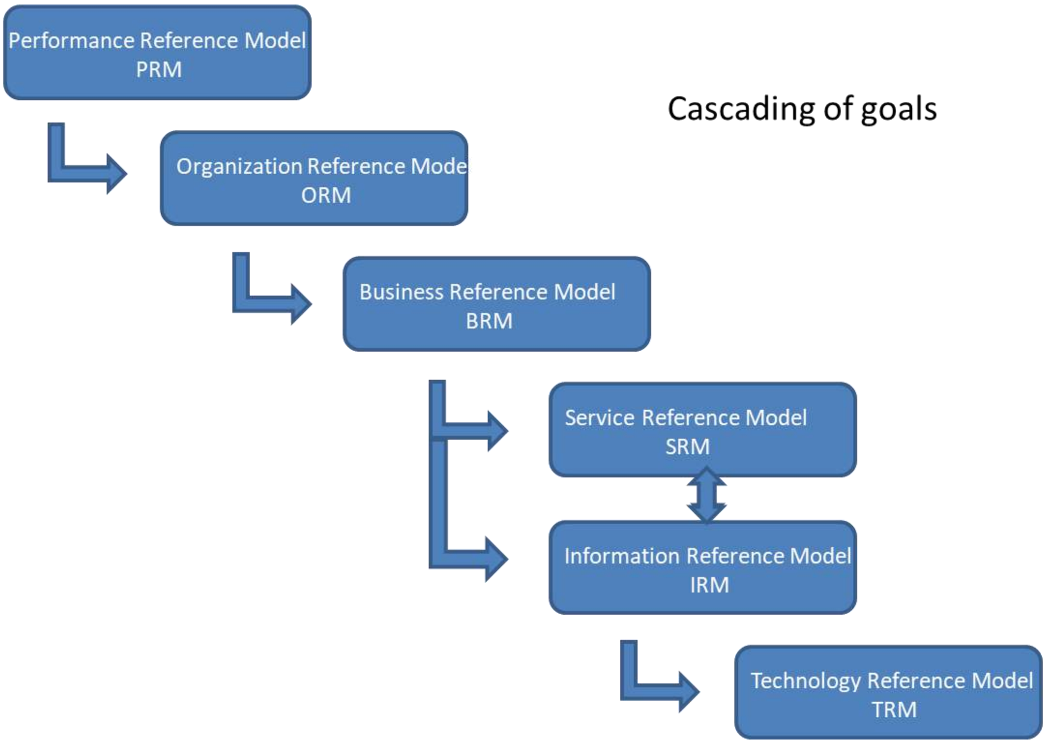

Figure 1: FEAF+ Reference Models (adapted from [7])

Coincidently (or not), it also promulgates the belief that one need to define the business need (Business Architecture) before considering the solution (Solution Architecture), and that the opposite will cause having solutions for which you do not have a need for, or a solution for which your organisation (enterprise) cannot accommodate. This notion is illustrated by the following:

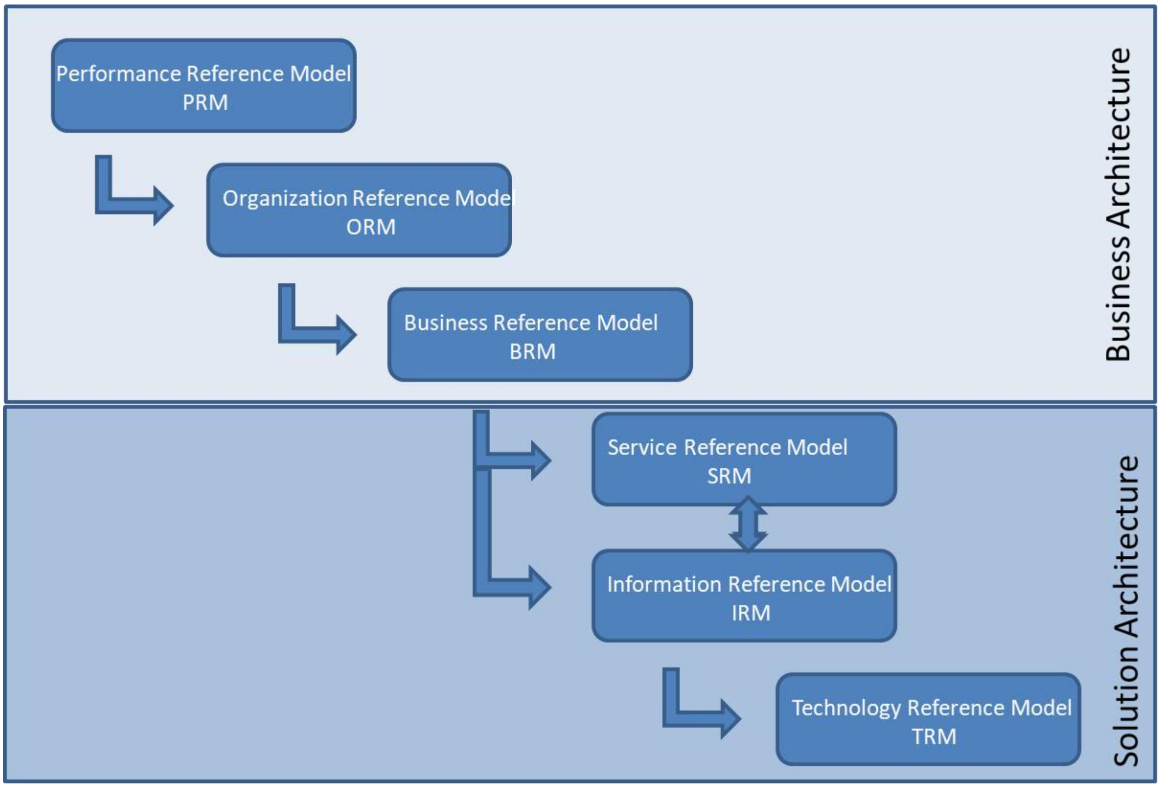

Figure 2: FEAF+ Business and Solutions Architecture principle

3.4 FEAF+ Process of Process

Fundamental to understand is that the reference models follow and are dependent on each other. It is referred to as Line-of-Site (LOS). If the line-of-sight is broken, the architecture design is broken, meaning one will end up with things in your architecture that you can't justify. This also ensures a fit-for-purpose principle.

Each of the various reference models, has a specific method how it is facilitated and derived, persistently ensuring the cascading-of-goals effect, i.e., Performance References relates and associates and derives the Organisation References. The Organisation References relates and associates and derives the Business References, and the same pattern continues...

If one assumes a life cycle process that evolves from a business concept to a high-level design, to a detail level design, to a physical implementation in a simplistic representation, the following example illustrates the typical cascading effect that will apply:

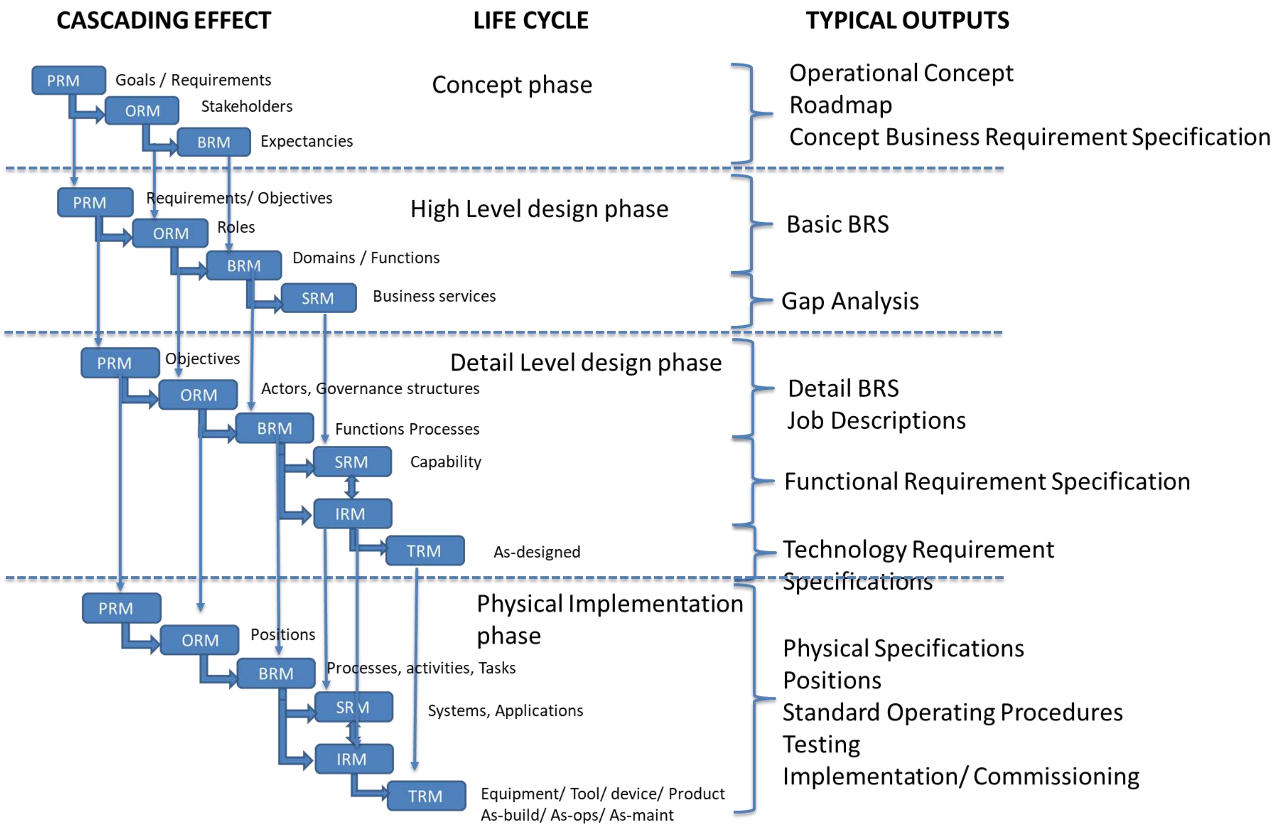

Figure 3: FEAF+ Process of Process

4 PERFORMANCE REFERENCE MODEL (PRM)

The objectives (as interpreted in the performance reference section) are captured in Performance Reference Model (PRM). It identifies objectives to be considered in the form of Goals, Objectives, Controls and Risks. These elements were typically used in Process Control Manuals when defining processes [5] but used in a different context in this method to track benefit, and to measure appropriate results, keeping in mind the governance that will control it, and the risk that may influence it. Essentially, selecting the incorrect Performance Reference will cause a ripple effect and cause un undesired performance outcome. This is because of the cascading-of-goals effect that a design is either an appropriate or an incorrect performance objective.

4.1 PRM Structure

The PRM structure is illustrated by the following:

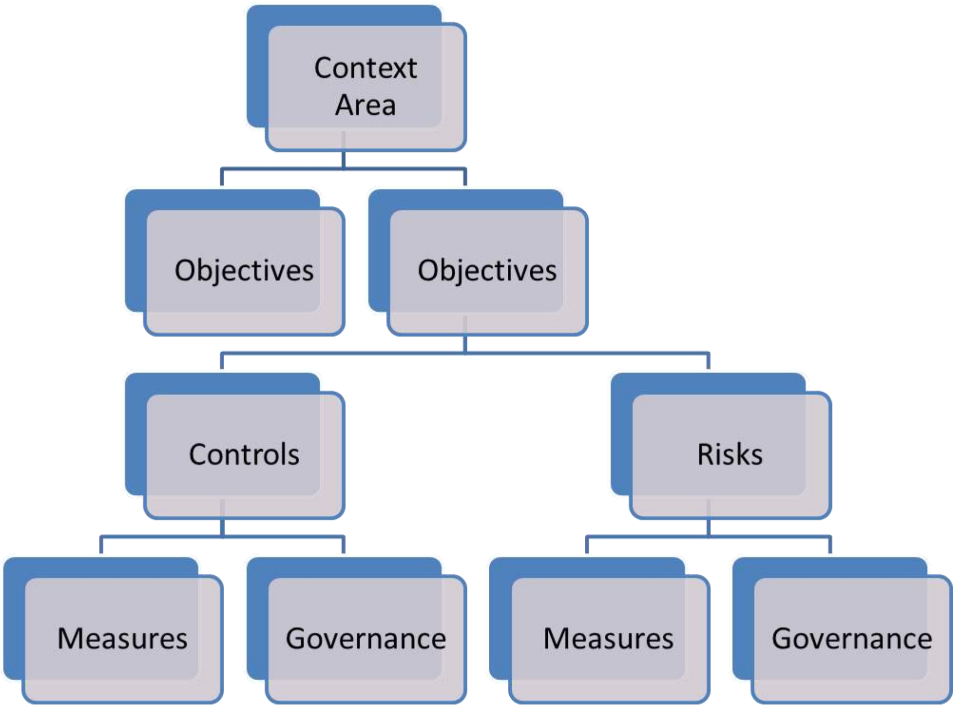

Figure 4: FEAF+ PRM Structure

4.1.1 Context Area

A context area is an unstructured shared understanding of impacting factors that influences the scope of focus area within the enterprise, for which a segregation or group has a logical relevance. This typically resides in a form of a narrative description.

Typical question to consider: What are the AREA boundaries that are in play and must be described?

Examples that may assist determining a context area: concept diagram; operation model; operational concept; power map; value chain; key performance area; business case, program, project, strategy, goals, among other.

4.1.2 Objectives

Objectives (as interpreted in the performance reference section) are derived from the context area focus, stating what the intentions are hoped to be achieved. The objectives should generally be a performance statement that is SMART (Specific, Measurable, Achievable, Relevant, Time-bound) to the appropriate level of abstraction.

Typical question to consider: What would be considered the main objectives within a context AREA boundary.

Examples that may assist determining objectives are strategic objectives; operational objectives; performance objectives, key performance indicators, discipline focusses, milestones.

4.1.3 Controls

Controls are event points for an objective (or a risk mitigation) with the power to make relevant decisions about expectancy, responsibilities, and reporting. Many controls can be defined for an objective. The accumulated set of controls defined per objective would be deemed meaningful if the successful outcome thereof justifies the objective being achieved. It identifies the end state “controls” that need to be in place for the objective to be met.

Typical question to consider: What must have been achieved to consider the objective being met?

Examples that may assist determining controls are: Past tense verb and descriptive noun, e.g.: Timesheets approved; SMMEs registered, 5% profit achieved; quality points checked, quantifiable unit of measure, achievement, decision gates, deliverables, outputs, phases, cycles.

4.1.4 Measures

Measures describes how the control will be qualified and the evidence to proof achievement. Many measures can be defined for a control, but at least one measure per control is required. It should revert from defining non-indicative measures and must be in compliance with governance.

Typical question to consider: How will one know the control was successful?

Examples that may assist determining controls are achievements, quality gates, targets, evidence, quantifiable and qualifiable parameters.

4.1.5 Governance

Governance is not just about compliance, but assurance, sustainability and relevance of the controls defined, or may act as a mitigation against risks defined. This may be in the form or rules, policy, procedures, guides, specifications, standards or relating form. Controls and Risks should require governance that will ensure compliance to the performance of activities. Governance relates to the need to constrain the controls providing the best chance of success. Many Governances can relate to a control(s), or risk(s).

Typical question to consider: What exists that will rule, guide, list, or govern the assurance of achievement of the control, or mitigation against risks?

Examples that may assist determining controls are rules; criteria; considerations; principles; catalogue of things, compliancy requirements.

4.1.6 Risks

Risks identifies the probability of a control, objective or measure not being achieved, or what will hamper its achievement.

Typical questions that will be answered by this are: What will prevent me to achieve a control or an objective, or a measure?

Examples that may assist determining risks are consequences; impact; concerns; gaps; risk; problem, cause, pain points; bottleneck, issue, feasibility.

4.2 PRM Hierarchical Structure

Continuing the pattern of goal cascading, the PRM can/should be applied in a hierarchical structure. The level of cascading is determined by the instantiation level sufficient for the level of expectation. I.e., it is determined by the beholder, illustrated as follow:

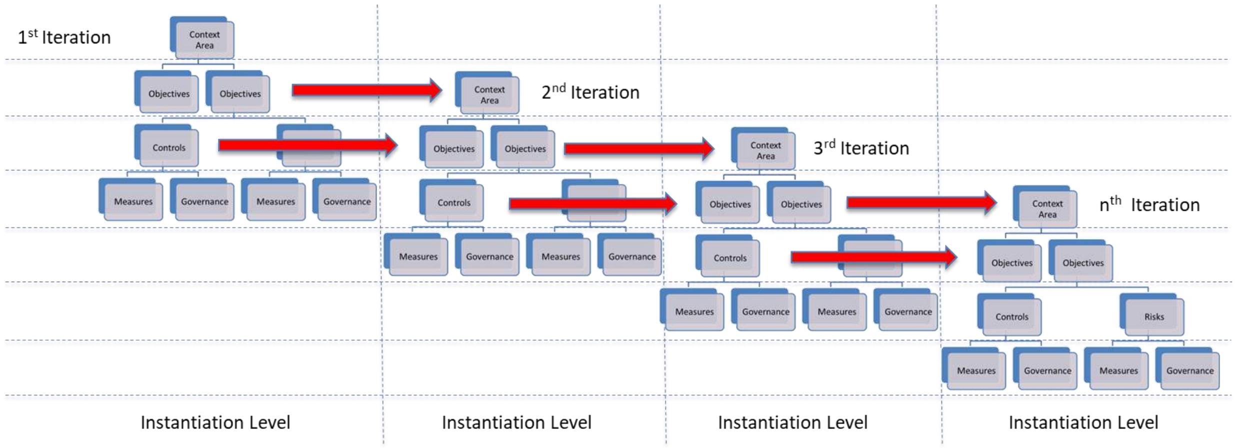

Figure 5: FEAF+ PRM Hierarchical Structure

The following principle is applied: An "objective" of a specific PRM level, is considered the "Context Area" of the next abstraction PRM level, and the "context area" perspective is applied to what was previously the "objective" in the previous PRM.

Similarly, the "control" of a specific PRM level, is considered the "objective" of the next abstraction PRM level, and the "objective" perspective is applied to what was previously the "control" in the previous PRM.

Subsequently, new instantiation of the governance, risks and measures are derived based on the cascaded effect applied.

The next PRM level will follow a new iteration of the above, and so it continues until the appropriate relevant level was defined.

4.3 PRM Structure Template

The PRM described has a specific meta schema involved, and a PRM template will assist the facilitation and application of the PRM. Accordingly, a template is suggested to guide and record the resulting design. By applying the principles and perspectives as defined in the previous sections will assist in instantiating the PRM. The following template is suggested:

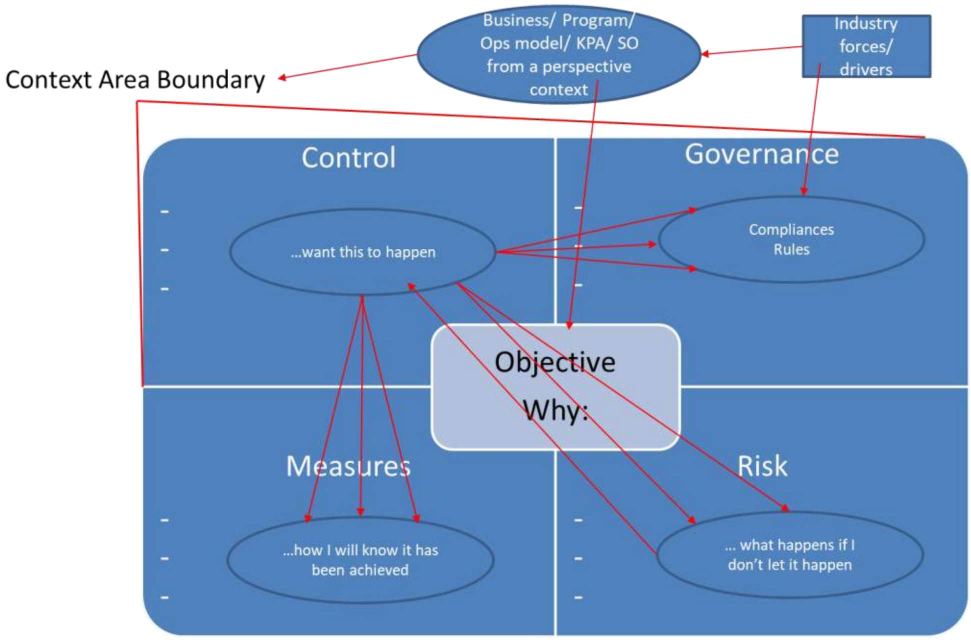

Figure 6: FEAF+ PRM Template

4.4 PRM Structure Cascading

As defined in the section describing the PRM Hierarchical Structure, the following effect using the PRM template will result:

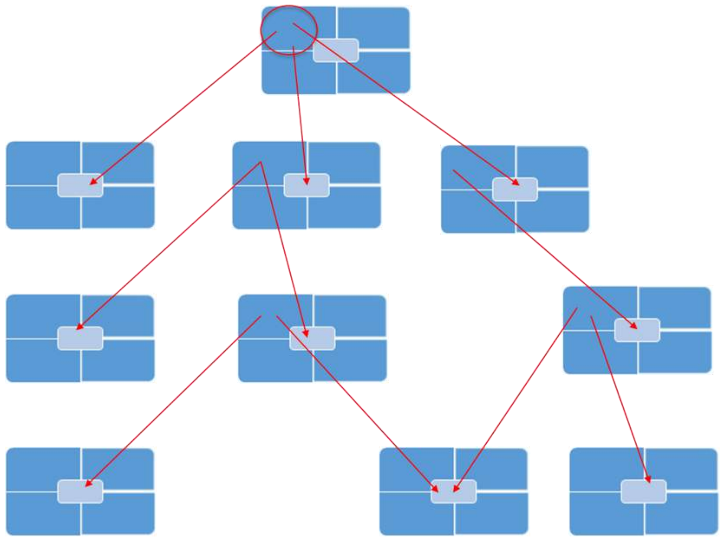

Figure 7: FEAF+ PRM Template Hierarchical Effect

5 ORGANISATION REFERENCE MODEL (ORM)

5.1 ORM Structure

An organisational design is needed to capacitate the human requirement to achieve the expectancies defined in the PRM. Representative organization structures are accordingly derived to address the objectives in the PRM in a cascading effect. The ORM distinguishes between a functional organisation (defined as roles) vs. a line organisation (usually defined as positions) in an existing organisation. This allows to address it in the following perspectives: Perspective 1: An ideal organisational structure can directly and specifically be defined in a functional perspective to fulfil the PRM obligations – referred to as the Functional Organisation Structure (FOS) – "creating system". Opposed to Perspective 2: An existing Line or reporting Organisation Structure (LOS) that may already exist in an organisation – "created system". The two perspectives need to be aligned incorporating the functional organisation with the line organisation. This is referred to as capacitation. Capacitation also includes the notion of location and quantity, i.e., where capacitation needs to happen, and with how many. This includes the elements of skill, competency, experience, and accreditation. It evolves further if vetting and authorisation is required for instance in the case of top-secret clearance requirements, or accreditation requirements.

5.1.1 Accountable vs. Responsible

Another fundamental aspect relates to the concept of accountability vs. responsibility. To be successful, both accountability and responsibility structures needs to exist within the Functional Organisation Structure (FOS) to have a successful outcome. The FOS comprises of an accountability structure and a separate, but corresponding responsible organisation structure. Both needing capacitation from the LOS.

Accountability describes answerability, meaning the necessity and expectation to explain one's actions for whatever they are accountable for. It implies that the accountable role representative must be able to give account of what has been done (objective measure), indicate why it was done (objective) and how it was done (control). It relates to accountability that is measurable after the fact and usually portrayed as a directorial, managerial, or strategical position. By nature, this role defines the process and outcomes envisaged necessary to achieve an objective for which one is accountable for, dispositioned to the responsibility role to ensure it happens, to cover any answerability that may arise.

Responsibility describes the insurance of realisation. This implies the execution and monitoring of the process and the outcomes to achieve a defined objective. This role is responsible for the root cause behind whether a process succeeds, fails, lives, or dies. This is usually portrayed as a supervision or operational position in obligation of the accountable role's requirement. Responsibility is measured before and/or after a task.

5.1.2 Cultural and social aspects

Cultures and social aspects also impact the organisational design, and as the saying goes, "*Culture eats strategy for breakfast*" [4] may be a component that needs addressing. This will not be the focus in this paper but acknowledge it becoming a fundamental aspect that needs to be considered. It is proposed to deal with this in a subsequent paper that introduces the concept of "power maps" and using "sensors and triggers" [1] to steer organisational behaviour in a timely matter in the right direction, effectively.

5.1.3 Created system vs. Creating system.

Perspective (1), implied above, relates to the "Creating" system opposed to perspective (2), relating to the "Created" system. The Created system informs the instantiation of the creating system = Design system. The creating systems formulates the basis of the created system and enables one or more created systems = System under design. The purpose of this paper is to define the governance, management and execution expectancy of the original creating system intent.

The ORM therefor serves the establishment of a functional organisation structure that is capacitated with "creating system" entities, defined within a line organisational structure, to ensure activities are performed by entities mandated and assigned with the appropriate capability and capacity.

5.2 Functional Organisation

The functional organisation is derived by identifying accountability and responsibility that must address the objectives in the PRM and seen as addressed if it was possible to measure the achieved controls. And, if all the controls were achieved, result that the objective have been fulfilled. Entities accountable for the controls ensures the execution thereof by ensuring the appropriate functional roles are established to execute and monitor the operation that ensure realisation.

5.3 Line Organisation

The line organisation represents the organisational structure for which positions have been defined and staffed, in addition to reporting and delegation nodes that may exist. These must be considered and transformed in such a way that the functional organisation expectation is capacitated, else the objectives may not be achieved. The parameters considered relates to Human Resource (HR) positions that have been established, and the reporting structures to which these positions report to.

5.4 Capacitation

Capacitation suggests mapping the LOS to the FOS. The mapping may imply that the FOS requirement may be mapped by one or more organisational position in the LOS. Capacitation is also implicated by measures of effectiveness. If the control expectation and measures thereof relates to a high magnitude of events, or its governance relate to a specific skill expectation, this may result in one-to-many relationships, meaning more than one position from the LOS may be needed to comply with the FOS role expectation defined in the ORM. Gaps identified during the capacitation may lead to organisational transformation requirements, or re-consideration of objectives in the PRM may be needed.

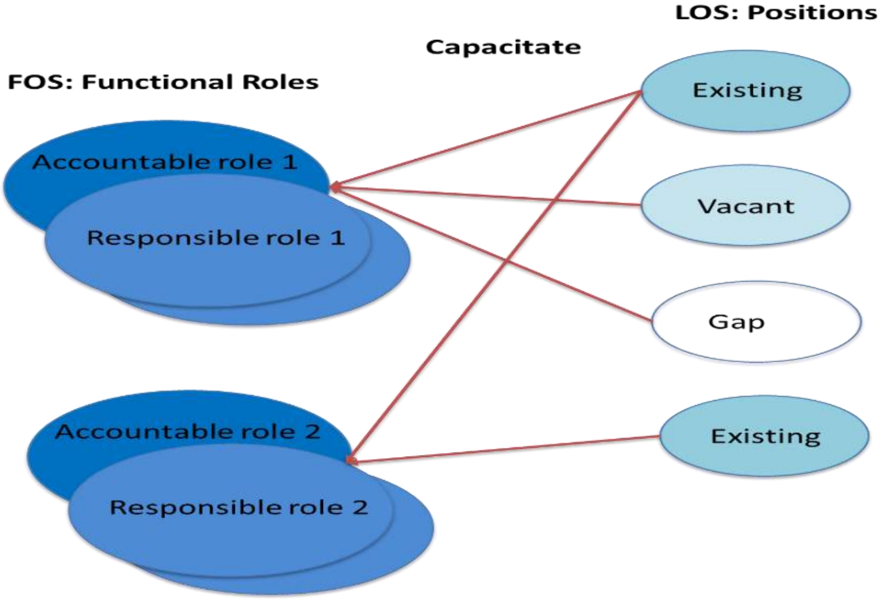

Figure 8: Functional Role Capacitation

5.5 Organisation gap

From the FOS, an attempt must be made to identify how the LOS would be able to capacitate these roles with HR positions. The degree of mapping success will determine the capability and capacity of an enterprise to achieve the defined objectives. I.e., if the degree of mapping is low, the probability is high that the enterprise will not be able to achieve the objectives.

5.6 ORM Cascading

The summation of the ORM cascading effect is illustrated in, Figure **9**. It illustrates that for the PRMs, a corresponding ORM needs to be derived directly from the controls that where defined. The principle of a corresponding ORM for each control is applied, ensuring the controls will be achieved, and in turn ensures the fulfilment of the objectives.

The ORM is established based on the functional expectation to be executed and transformed into functional roles. A Functional Organisational Structure (FOS) is thereby formulated defining the sum of human intervention roles required to directly achieve the PRM.

Assuming an existing Line Organisation Structure (LOS) exist, or if a green-field scenario exists, it provides opportunity to uniquely define the organisational positions and reporting nodes of the physically staffed organisation structures. Without capacitating the FOS with the physical human positions defined in the LOS, the probability of the PRM failure is predictable.

Capacitation therefor needs to be conducted to define the gaps. This requires mapping of positions, with skills, experience, accreditation, and factors necessary to ensure complete coverage of the FOS. Capacitation is not necessarily a one-to-one mapping and may indicate a culmination of positions for a role.

Only by complete capacitation of the FOS will PRM success be achieved. If capacitation positions lead to vacancies, it may indicate a transformation requirement. The author is aware of the labour implication this may cause, which is a story for another day. The fact remains that the PRM success will be quantifiable and qualifiable.

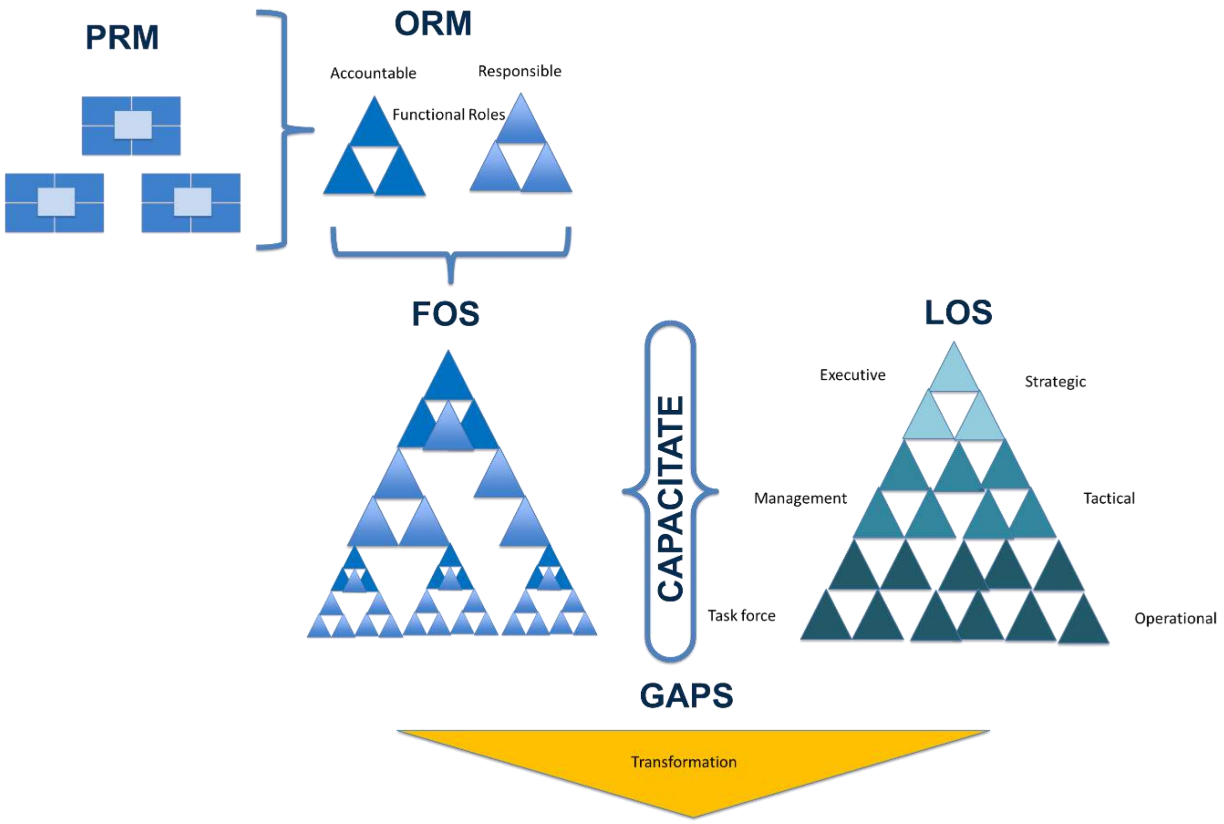

Figure 9: ORM Cascading

6 CONCLUSION

Limitations on this paper prevents the opportunity to describe the full extent of the FEAF+, and therefor only described the Performance and Organisation Reference Models but hope to have entice the research community of a method that deserves exploring. Although this approach does not currently have a research presence, this paper serves as the initiation thereof. It is not to say that due to lack of explicit references that it is not a tried and proved method. Many practical references of its use exist, and they are not mere small enterprises in magnitude scope or size, but effectively utilised by Government Departments, Energy and Mining Industries, among other.

Future consideration may suggest to further explain and describe the remaining FEAF+ reference models. Although the PRM and ORM is a fundamental start, it falls short of defining an effective Enterprise Reference.

Subsequently, an enterprise still need to be described in terms of the process, technology, applications, information, elements that are addressed in the remaining reference models consisting of the Business Reference Model (BRM), Service Reference Model (SRM), Information reference Model (IRM) and the Technology reference Model (TRM). Only then would a well-defined and complete reference architecture exist that can materialise an implementation solution. Further, the approach needs a solution realisation approach. This too can be explored in future papers.

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A FRAMEWORK TO IMPROVE INVENTORY MANAGEMENT SYSTEMS USING SIMULATION-DRIVEN OPTIMISATION TECHNIQUES.

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ABSTRACT

In today's cutthroat business world, effective inventory management is one of the critical factors in determining an organisation's success. Simulation models enable testing with different conditions and methods, assisting in risk assessment and objective performance measurement by simulating complex inventory systems. This paper aims to contribute to inventory management by developing a simulation model framework that enables more accurate inventory management decisions while considering supply chain performance and collaboration. This research paper may guide organisations looking to improve their inventory management practices by developing a thorough methodology that includes a literature review, data analysis, simulation model development, verification, performance evaluation, and inventory policy optimisation. Furthermore, the research conducted in this study offers firms seeking to improve their inventory management systems a thorough and trustworthy resource. Organisations may improve their long-term profitability, increase competitive advantage, and make informed decisions by implementing simulation-driven optimisation strategies.

Keywords: Inventory Management, Simulation-driven optimisation techniques, Vertical Supply Chain

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1 INTRODUCTION

Inventory management is one of the most critical factors determining an organisation's success [1]. Relying exclusively on management instincts and intuition is no longer adequate for making decisions in today's competitive corporate environment. Inventory management's complexity and dynamic behaviour have led to the successful emergence of simulation modelling for facilitating the design and evaluation of these operational management strategies.

According to Lateef [2], simulation models enable testing with various situations and strategies since they correctly mimic intricate inventory systems. The primary purpose of using a simulation model is to reduce the costs associated with impractical implementation in the existing inventory system [2]. Subsequently, simulations aid in risk assessment and objective performance measurement. Attributes such as supply chain collaboration and inventory policies influence the simulation model used within an organisation [2].

The purpose of a simulation model is to evaluate or alter a system before it is put into use, lowering the likelihood of failure. Simulations are beneficial for identifying problems within an existing inventory system or choosing the best design for a new approach [3]. For this reason, finding and using the best simulation model for an inventory management system is crucial for businesses to obtain their full potential.

This study aims to contribute to inventory management by developing a simulation model framework that enables more accurate inventory management decisions while considering supply chain performance and collaboration. This paper may contribute to research and industry by providing a thorough approach and particular insights for simulation-driven optimisation strategies.

Optimisation, in the context of this study, involves refining inventory management through a simulation model framework. This approach enhances decision-making precision while considering supply chain performance and collaboration. The study contributes to research by offering insights and a comprehensive simulation-driven optimisation strategy. Moreover, it provides practical guidance for implementing these methods in manufacturing, aiming to boost productivity, reduce waste, and increase profits.

Optimising operational efficacy, cost-effectiveness, and overall supply chain performance all depend on proper inventory management [4]. The use of simulation modelling techniques for inventory optimisation is a sophisticated strategy that deals with difficult problems in a methodical and data-driven way.

Some relevant inventory examples include:

1. **Raw Materials Inventory:** Maintaining the ideal quantity of raw material inventories is a frequent challenge. Understocking or overstocking issues can affect production continuity and cost management due to fluctuating demand, supplier lead times, and production schedules. [5]
2. **Work-in-Progress (WIP) Inventory:** It's critical to maintain a steady workflow throughout a production process. Increased lead times, greater carrying costs, and potential production line bottlenecks can all result from excessive WIP inventory. [5]
3. **Finished Goods Inventory:** Finding the ideal balance between finished product inventory levels and demand forecasting is a never-ending issue. Underestimating the demand can result in stockouts and unhappy customers while overestimating it can result in extra inventory expenses. [5]

Through Mulya's analysis of inventories like the above-mentioned, it is known that their intricate challenges can be addressed via simulation modelling in inventory optimisation [6]. It incorporates dynamic trends and spikes to address complicated demand patterns.

Robust planning considers supply chain uncertainties including lead times and production delays. Through thorough testing, the best reordering procedures are developed, and production capacity restrictions and service level trade-offs are successfully controlled. Simulation models are also useful for distributing inventories among several sites and analysing the effects of unknown lead times. This strategy improves decision-making accuracy, agility, and supply chain overall optimisation.

Furthermore, this paper offers practical guidance by providing suggestions for applying simulation-driven optimisation methodologies in the manufacturing industry. The conclusions and suggestions made in this article can help organisations in a competitive business climate with their decision-making processes, cut expenses, and improve their long-term profitability. This will allow for more precise inventory management decisions to reduce safety stock quantity while considering supply chain performance. By concentrating on using simulation modelling explicitly in the context of inventory management in manufacturing facilities, the research fills a gap in the body of open-source literature that follows a methodical approach.

The work done within this paper is a good contender for approval due to the overall relevance, strict methodology, real-world applications, and contribution to the body of research within the inventory management academic industry. A detailed literature review will be conducted on supply chain collaboration in Section 2. Section 3 provides an overview of inventory simulation methodology, and an implementation framework in Section 4. Conclusions are provided in Section 5, followed by valuable future recommendations.

2 EXISTING APPROACHES TO ADDRESS INVENTORY CHALLENGES

Jenkins [7] has highlighted the numerous strategies that have been developed in the areas of supply chain coordination and inventory management to address the difficulties involved in preserving ideal inventory levels and effective distribution.

2.1 Traditional Inventory Management Approaches

Traditional inventory management techniques have been used for a long time to control stock levels and guarantee a constant flow of commodities throughout supply networks. The Economic Order Quantity (EOQ) model is one such strategy that determines the ideal order quantity by balancing holding costs and ordering expenses. Agarwal [8], expressed that although EOQ offers a straightforward and uncomplicated solution, it frequently assumes static demand patterns and may find it difficult to adjust to changing market conditions and client demand.

2.2 Collaborative Planning, Forecasting, and Replenishment (CPFR)

Fliedner [9] has expresses that CPFR encourages supply chain participants to collaborate on planning and share information. CPFR attempts to increase the accuracy of demand forecasting and decrease excess inventory by aligning predictions, exchanging real-time data, and coordinating replenishment actions. However, strong levels of cooperation and trust amongst partners are necessary for successful implementation.

2.3 Just-In-Time (JIT) Inventory System

From Mukwakungu [10] it is learnt that by placing a strong focus on reducing waste and carrying costs by maintaining low inventory levels, the Just-In-Time (JIT) inventory system has become well-known. JIT strives to match supply with demand, resulting in shorter lead times and better responsiveness. The focus on JIT, however, calls for intense coordination between supply chain participants and offers little opportunity for production or supply chain interruptions.

2.4 Addressing Limitations

To overcome the limitations of traditional approaches in inventory management, simulation appears as a powerful solution proposed by Schwartz *at al*. [11] In comparison to other modelling tools, its extraordinary granularity captures complex business rules, regulations, and production requirements. Through simulation, which highlights interdependencies between supplier and internal stocks while taking demand variations, manufacturing cycles, and transportation wait times into account, the complexity of the multi-tiered supply chain is made more understandable. [11]

The stochastic component of simulation makes it the best option for service-level analysis. The conundrum of limitless policy-parameter combinations is resolved by combining simulation and optimisation. The ideal inventory strategy is improved by the effective exploration of various scenarios during simulation optimisation. This comprehensive approach clarifies "why" particular policies succeed, fostering openness and confidence. [11]

The simulation's capacity to depict variability, which ensures conservative inventory objectives based on stochastic demand, is one of its distinguishing strengths. Additionally, simulation is excellent in explaining inventory dynamics. This viewpoint enhances strategic understanding by considering several impacts. Simulation transforms inventory planning thanks to its accuracy, versatility, and ability to work well with optimisation. [11]

3 SUPPLY CHAIN COLLABORATION

Supply chain collaboration is when multiple organisations achieve mutual advantages [12]. Horizontal collaboration is an inter-organisational system relationship between two or more organisations at the same level or stage in the supply chain to enable greater ease of work and cooperation towards achieving a common objective. Vertical collaboration is where two or more organisations from different levels or stages in the supply chain share their responsibilities, resources, and performance information to serve relatively similar end customers [13]. More vertical supply chain collaborations exist than horizontal ones [14]. This is due to vertical cooperation's increased prevalence and simplicity [7].

Two different inventory management supply chains have been considered for this study. These inventory policies will be based on vertical supply chain collaboration to be more applicable to existing industries. The inventory policies for conceptual models of vertical supply chains are discussed in the following sub-sections.

3.1 Vertical supply chain: (s, S) Inventory policy

A (s, S) inventory policy is applicable for vertical supply chain collaboration when a quantity is immediately purchased to raise the level to ‘S’ (maximum inventory level) if the end-of-period stock is less than ‘s’ (minimum inventory level or reorder point). No replenishment occurs if the end-of-period stock reaches ‘s’ [15].

3.2 Vertical supply chain: (s, Q) Inventory policy

A continuous review (s, Q) inventory policy can alternatively be implemented for vertical collaboration in which a purchase order for ‘Q’ (order quantity) spares is placed as soon as the inventory position falls below ‘s’ (minimum inventory level or reorder point) [15].

4 SIMULATION METHODOLOGY

The simulation methodology section of the paper provides a detailed explanation of the technique used to analyse inventory management in the context of this research.

4.1 Modelling approach:

For an inventory simulation to be effective, some measures must be taken. The method used to carry out the simulation is constant regardless of the problem and goal. The modelling approach can be broken down into steps, as displayed in Figure 1.

The following describes the dependent steps within the simulation approach:

1. **Define the problem.**

The defined inventory problem will not always be correct. It will be necessary to take the iterative steps and formulate the model again. Such cases can be avoided by defining the scope and objectives of the simulation. The efficacy of different inventory system configurations can be tested by calculating necessary performance measures [16]. Finally, verifying that a simulation model is the correct method of resolving the defined inventory problem is necessary.

2. **Formulate a model.**

Understanding the behaviour of the current inventory system and determining the underlying needs are essential for formulating an accurate simulation model. It is necessary to choose between controlled and uncontrolled inputs. A model structure can be developed by defining a goal function and a system performance metric [17]. This structure can be connected to the defined inputs and the performance metrics.

3. **Collect data.**

The type of data to be collected must be determined first. Demand patterns, lead times, inventory levels, sales and profit data, and product characteristics are all examples of such data [18]. Historical data is obtained before fitting them into theoretical distributions.

It is important to note that for realistic inventory simulations, the type of historical data and its temporal span are crucial. Customer demand, inventory levels, lead times, orders, supplier performance, and external factors should all be included in the data. The temporal horizon should include business cycles, lead periods, and demand trends. It must be long enough to cover a range of situations while remaining current. Multiple seasons should be considered when describing seasonal goods. Granularity and relevance to the business cycle of the data are critical. Insights into inventory management are improved with the right data and time horizon, enhancing decision-making and supply chain effectiveness. [19]

4. **Translate the model.**

The translation of the model involves converting it into a programming language, which can be a general-purpose language like R or a specialised simulation program like FlexSim or Anylogic. Choosing a language that best suits the inventory problem at hand is essential [18].

5. **Verify the model.**

Verification ensures the model performs as anticipated through animation or debugging. A model can be verified but remain invalid. Several procedures can be used to verify the inventory simulation. Implementing a "Structured Walk-through" policy, which involves many people assessing the model, can help verify it. Verifying the simulation model's output using various input combinations might also be advantageous [20]. It is always an excellent strategy to compare the simulation's outcomes to the analytic counterparts.

6. **Validate the model.**

There are a few steps to ensure that a validated model is obtained. Maintaining contact with the client is crucial to ensure the simulation content can be supervised. Applying assumption data to the model and quantitatively testing it will help validate and evaluate its assumptions.

It is possible to see how significant changes in the input data would affect the outcomes by conducting a sensitivity analysis [21]. After validation, the model must be transformed into a more intricate model for simulation-based testing before being converted into an executable form for physical implementation.

7. **Scenario generation.**

It is essential to create several different states of the inventory system within a validated simulation model [22]. These other states entail different input parameters. These input parameters can include a change in demand, inventory, costs, and times. This will allow users to access various scenarios' impact on the inventory. It is crucial always to estimate the different input parameters from historical data. This would ensure that the model remains valid.

8. **Experimentation and output analysis.**

Creating alternative models, running simulations, and statistically evaluating the performance of the alternative inventory systems with the natural systems are all steps in the experimentation process. Analysing the simulation output makes it possible to conclude how well the inventory management system performs [23]. Crucial factors to analyse include inventory costs, service standards, stockout rates, and order fulfilment rates.

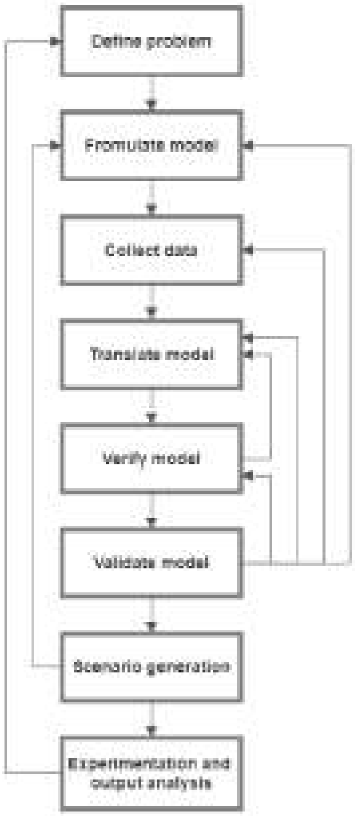

Figure 1: Inventory management simulation approach [24]

4.2 Simulation arguments:

The simulation model must be prepared once the collaboration supply chain has been identified to be vertical. The logical arguments used within the simulation model include the following variables:

- D_i : Distributor inventory - This refers to the quantity of goods or products held by a distributor at a specific point in time. It represents the stock available for distribution to retailers or customers.
- R_i : Retailer inventory - This signifies the number of products that a retailer currently possesses. It reflects the stock available for sale to end consumers.
- M_i : Manufacturer inventory status - This indicates the inventory level of a manufacturer, representing the quantity of finished goods or components awaiting distribution.
- S_i : Supplier inventory status - This term denotes the inventory status of a supplier, representing the quantity of raw materials or components available for production or distribution.
- C_d : Customer demand (daily) - This represents the daily quantity of products or goods that customers require or purchase. It reflects the market demand for a particular item daily.

Demand signals are employed to predict future demand and assist businesses in making choices regarding production capacity, inventory control, and marketing campaigns. Businesses may optimise their operations and provide better service to their consumers by analysing patterns in client demand [25]. These signals are used throughout the inventory simulation model.

The variables relating to simulation demand signals are defined as follows:

- R_d : Merchant demand
- D_d : Distributor demand
- M_d : Manufacturer demand
- S_R : Maximum inventory
- Q_R : Merchant order quantity

Figure 2 presents the simulation framework for vertical supply chains that work with different inventory policies. It is therefore important to note that the simulation arguments are strictly relevant to businesses falling under the vertical supply chain branch, as outlined in section 3.

The figure shows the flow of activities and interactions between various entities participating in the supply chain process using a simulation or logical model of a linear supply chain. The coordination and flow of operations among various organisations to meet consumer demand while abiding by inventory regulations are demonstrated in this model, which offers a structured picture of how a linear supply chain functions.

4.2.1 Simulation demand signals: (s, S) Inventory policy

$$R_d = S_R - R_i \quad (1)$$

$$D_d = S_D - D_i \quad (2)$$

$$M_d = S_M - R_M \quad (3)$$

4.2.2 Simulation demand signals: (s, Q) Inventory policy

$$R_d = Q_R \quad (4)$$

$$D_d = Q_D \quad (5)$$

$$M_d = Q_M \quad (6)$$

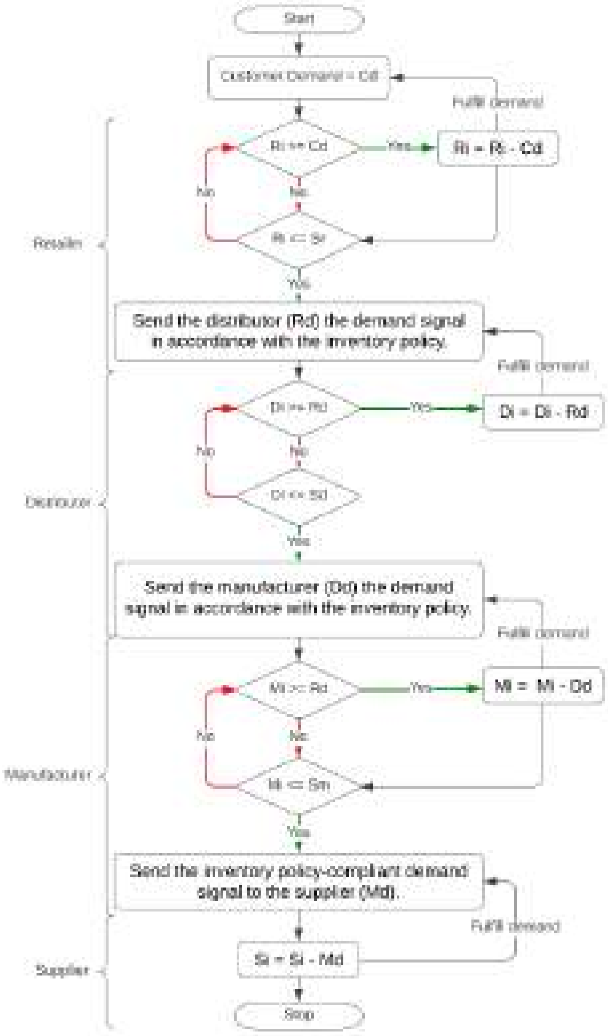

Figure 2: Vertical collaboration simulation arguments [26]

4.3 Simulation Validation and Verification:

The model's configuration can be adjusted to align with the existing inventory system. This will allow for comparing the models and actual outcomes observed in the real system. Various techniques can be used for verifying and validating the simulated inventory management model.

4.3.1 Data Validation:

Using incorrect data can significantly compromise the accuracy of the simulation model [27]. Sargent [28] expresses that it is essential to ensure that simulation data is as accurate as possible by making diligent efforts.

1. **Historical Data Validation:** Historical data gathered from demand, inventory levels and seasonal patterns all impact the simulated inventory management system. The simulation model is created using some of this data. The simulation accuracy and variability can therefore be validated using the remaining data.
2. **Sensitivity Analysis:** The influence of independent variables on dependent variables can be examined by performing a sensitivity analysis on the simulation model.

3. **Continuity testing:** Continuity testing can be performed by iteratively running the inventory simulation model with slightly altered input parameter values. Shifts in the output will then be considered an indication of a possible error that requires investigation.

4.3.2 Model Verification:

It is necessary to apply verification throughout the model continuously. Robinson [29] ensures that verified simulation models will be accurate to the inventory model.

1. **Code Verification:** Particularly in areas that need a lot of reasoning, the modeller should evaluate the code to guarantee correct data and logic. A second person who knows the current inventory management model must read the code. The code can be expressed in a non-technical format if the advisor lacks coding knowledge. The logic of the model must equate to the advisor's logic.
2. **Visual Verification:** The model's logic and conformance to real-world occurrences may be verified by running the simulation model and carefully monitoring the behaviour of each constituent. This validation procedure can benefit from a variety of strategies. One method entails going through the model event by event and carefully assessing each step to ensure it meets expectations. Another method involves pausing the model, making predictions about the subsequent sequence of events, starting the simulation again, and then comparing the results to the predictions. [30].
3. **Output Verification:** The output from a simulation run may be examined to compare the actual and predicted results. It is necessary to compile the output in a simulation report. This report should contain a detailed account of every action throughout the inventory run. Examining this report can assist in identifying and fixing any issues.

4.3.3 Conceptual Model Validation.

Conceptual model validation is carried out when a simulation either has not or cannot be evaluated by directly comparing simulation results with an acceptable reference. Determining if the simulation can support the planned purposes is the primary purpose of conceptual model validation. Interface testing, proof of correctness, inference, cause and effect graphing, induction, and alpha testing can be used to validate the conceptual inventory model.

4.4 Inventory Simulation Methods.

It is vital to briefly review the most popular simulation techniques after highlighting the different arguments that should be included in the simulation study. Four popular techniques can be used for simulating an inventory management system [31].

4.4.1 Monte Carlo Inventory Simulation.

A Monte Carlo (MC) simulation can be utilised to develop several inventory policies to optimise inventory levels and minimise inventory costs. MC simulations are a favoured technique for inventory forecasting. MC simulations are ideal for production size estimates, determining the amount of raw material (inventory) needed at a given time [32].

An MC simulation that manages the high inventory cost may be applied using Microsoft Excel, R, Workspace, or similar tools. Regardless of the computer program used, the same four steps are followed when applying MC simulations to inventory management [33].

1. **Identification of Transfer Function:** To create an MC simulation, you require a quantitative model of the inventory model that you wish to investigate. It is necessary to establish a transfer function for the mathematical model.

2. **Defining Input Parameters:** After establishing the transfer function, it is necessary to determine the data distribution for each factor in the equation. Some inputs may have a triangular or uniform distribution, while others may follow a normal distribution. The appropriate techniques should therefore be used to determine the distribution parameters for each input, such as the mean and standard deviation.
3. **The set-up of the Simulation Model:** To ensure the simulation's authenticity, generating a significantly large and random dataset is necessary. These data points represent the values observed for each input over a prolonged inventory period.
4. **Statistical Analysis of Process Output:** Once the simulated data is obtained, the transfer function can be utilised to calculate the outcomes of the simulations. By considering the anticipated volatility in the inputs, running a substantial amount of simulated input data through the inventory model will yield a precise prediction of the process's long-term outputs.
5. **Optimisation of Input Parameters (Optional):** For each input, it is required to define a search range to do parameter optimisation. This can be done by setting a +/- standard deviation range for each input parameter that the MC simulation search.

It is possible to translate a system into transfer function notation when it is represented by a single nth-order differential equation. Consider a third-order differential equation, where x(t) stands for the input and y(t) for the outcome, to get started on this. The first step is to apply the Laplace Transform to the differential equation while assuming initial conditions of zero to get the transfer function. It is crucial to remember that differentiation inside the temporal domain is the same as multiplying by the Laplace domain variable "s." The transfer function then appears as the output-to-input quotient, sometimes abbreviated as H(s), capturing the core of the system's behaviour in the Laplace domain. [34]

A case study presented by Ghafoor, shows that Monte Carlo simulations can be considered when given the responsibility of managing a supply chain and faced with the challenge of maximising inventory levels for a certain product. The determination of the needed inventory level that simultaneously reduces costs and diligently upholds excellent service standards is the primary goal at hand. Utilising the Monte Carlo simulation technique enables you to examine a wide range of demand scenarios, allowing wise choices that will optimise inventory levels. [35]

The results of the subsequent simulation are meticulously examined, providing crucial information on performance measures such as fill rates, occurrences of stockouts, and mean costs, all of which are beautifully displayed for comparison. Sensitivity analysis follows, in which input parameters are repeatedly changed to assess trade-offs and, finally, identify the ideal inventory level that strikes a peaceful balance between financial concerns and service benchmarks. [35]

The created MC simulation follows a process flow logic, as seen in Figure 3 [36]. The process flow begins by determining which period is being modelled. The opening stock is the sum determined for the reorder level if the procedure is for the first period. Based on this assumption, a purchase order may be issued in the first period. The closing stock for the prior cycle will serve as the starting stock for all other cycles. The inventory is updated with any upcoming delivery. Orders decrease the resultant supply. The amount on hand and the level of reordering are compared. A purchase order is increased if the amount on hand falls short of the reorder threshold. The procedure is completed by calculating the backlog and closing stock for the following period.

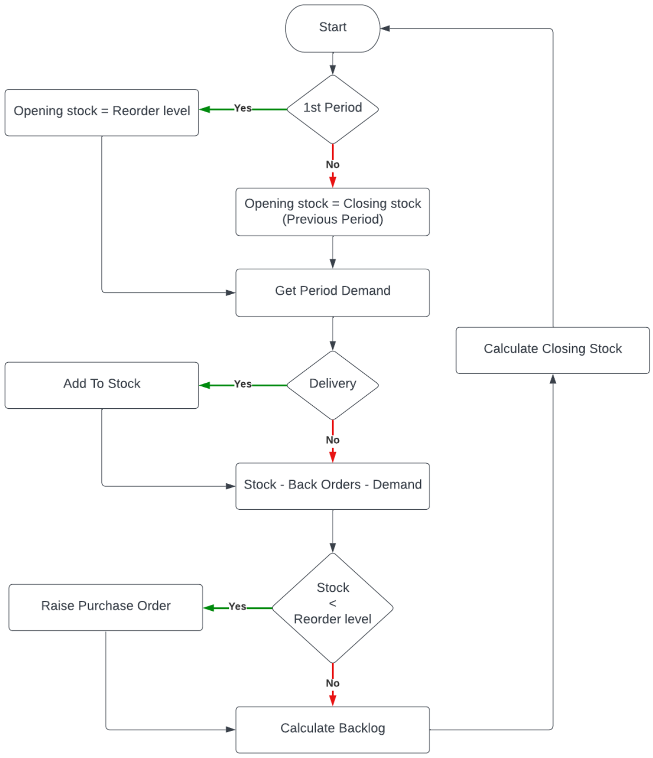

Figure 3: Monte Carlo Inventory Process Flow [36]

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4.4.2 Agent-Based Inventory Simulation:

Discrete-event simulation (DES) represents a system's evolution over time through a model where the state variables undergo instantaneous changes at various time points. The amount of data that must be kept and managed for most real-world systems prevents discrete-event simulations from being done by hand computations, even though it is theoretically possible [16].

Figure 4 represents the process flow followed throughout a DES inventory fulfilment model. The flow depicted in the figure outlines the dynamic interplay of inventory management, order processing, and supply chain activities within a discrete event simulation. It visually portrays the steps involved in fulfilling customer demand, managing inventory levels, and ensuring timely order shipments. The model provides insights into the various stages of the inventory fulfilment process, helping to identify potential bottlenecks, optimise workflows, and enhance overall supply chain efficiency.

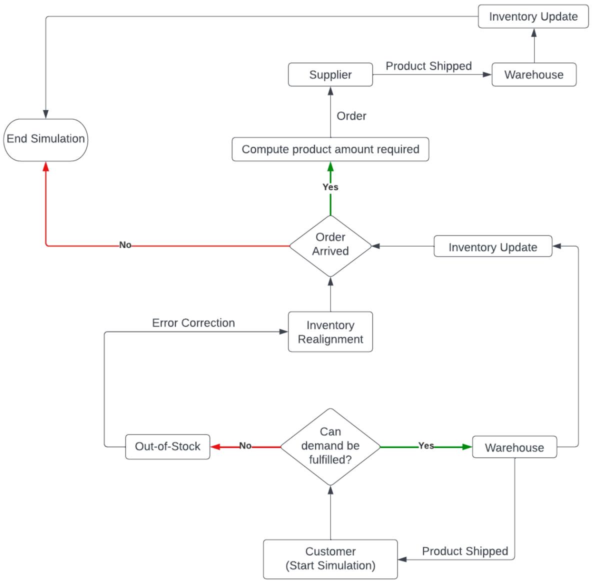

Figure 4: Decision process implemented for inventory fulfilment in a DES model [37]

4.4.3 Continuous Event Inventory Simulation:

Continuous simulation models represent inventory systems by expressing an inventory system's state variables as constantly changing regarding time. Differential equations, which create links between the rates of change of the state variables and time, are used in this kind of simulation. Given defined initial values for the state variables, numerical analysis techniques are often used to integrate the differential equations for most continuous simulation models numerically. A crucial distinction between taking note of is that DES models schedule events to update the state variables, whereas continuous simulation employs equation-computed updates to the state variables. Combining discrete and continuous components in one model concurrently is an additional benefit of these two simulation tools [16].

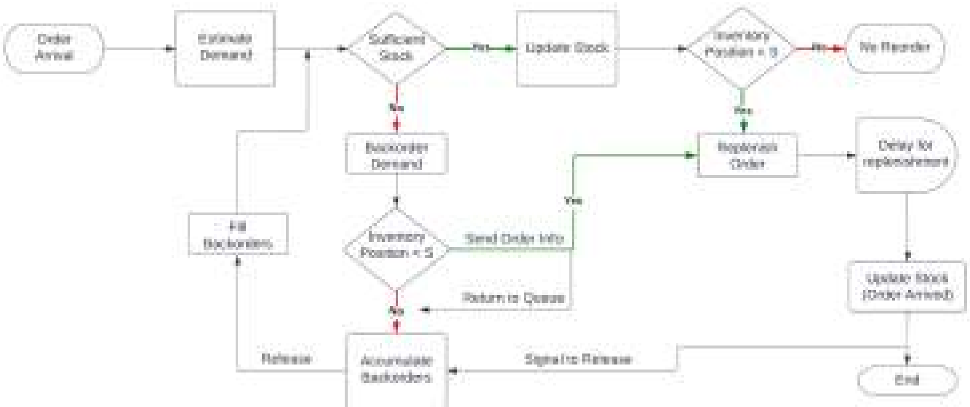

Figure 5: Inventory flow ideal for continuous simulations [38]

A continuous event simulation is beneficial for simulating a multi-echelon inventory model. A continuous model is perfect since multi-echelon inventory models always want the right amount of stock at the right location and time [38]. Figure 5 represents the inventory production flow ideal for implementing a continuous event inventory simulation. The figure stands as a comprehensive representation of the inventory flow meticulously tailored to harmonise the intricacies of continuous event inventory simulations. Through its intricate interplay of stages and decision points, this figure encapsulates a sophisticated blueprint for optimising inventory management dynamics, paving the way for streamlined and efficient operations within the engineering domain.

4.4.4 Combined Continuous-Discrete Event Inventory Simulation:

There are three main types of interactions between variables that undergo discrete changes and those that undergo continuous changes [16]:

1. The value of a continuous state variable can undergo discrete changes when a discrete event occurs.
2. A discrete event can cause a specific moment to change the relationship governing a continuous state variable.
3. A discrete event can cause a specific moment to change the relationship governing a continuous state variable.

By considering these interactions, it is expected of the modeller to determine if a combined inventory simulation is necessary.

5 IMPLEMENTATION FRAMEWORK

The implementation framework of an inventory simulation model consists of several steps. These steps are in the flowchart, as demonstrated in Figure 6. A thorough implementation structure for an inventory simulation model is shown in the figure. It entails analysing the body of research, identifying supply chain collaboration, choosing an appropriate simulation type, describing simulation arguments, validating data, verifying the model, and putting the model into practice. This systematic methodology guarantees the creation of a solid inventory management simulation model, enabling informed decision-making and a detailed comprehension of inventory dynamics. Following and implementing each step will lead to a conclusive inventory management simulation model.

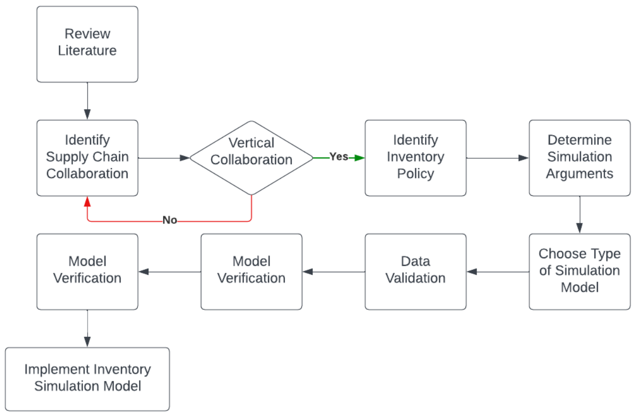

Figure 6: Implementation Methodology

The business owner and modeller should start by reviewing all the literature in this report. This can be done by thoroughly examining the literature on verification and validation methods, inventory simulation methodology, and supply chain collaboration. This phase will assist the reader in comprehending all the necessary knowledge required to implement a simulation-based approach. This paper was developed around vertical collaboration. Therefore, it is vital to identify the correct type of supply chain collaboration. Renko [39] advises that failure to do so will lead to incorrect implementation of inventory policies within the model.

Determination of collaboration and policies should be followed with statistical analysis of the pertinent data that the inventory management system provides. Data on demand trends, lead times, inventory levels, sales, profit information, and product attributes are all included.

A methodical guide for building an inventory simulation model to improve inventory management techniques is provided in Figure 7. It defines a series of sequential actions, such as order receipt, demand creation, inventory modifications, reorder choices, lead time calculation, and computation of pertinent variables. This thorough picture offers a clear blueprint for creating a powerful simulation model to enhance inventory procedures.

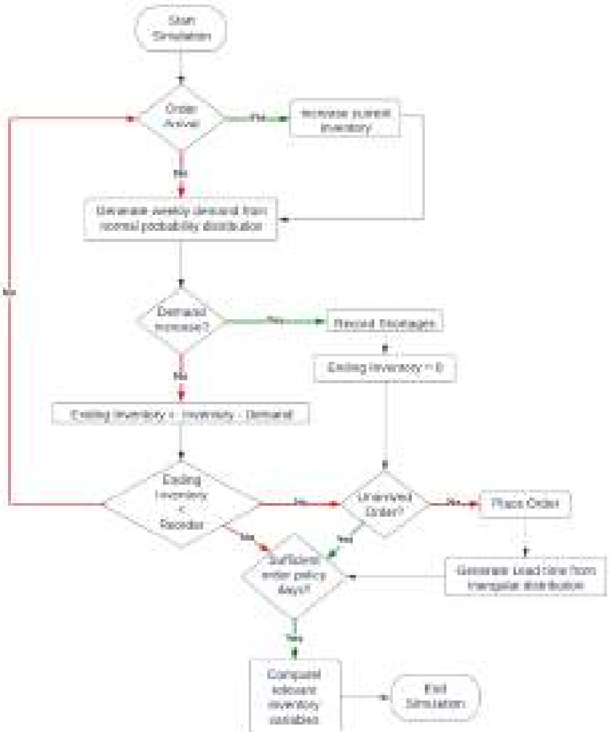

Figure 7: Flow Diagram of Inventory Management Simulation [40]

Development and verification of the simulation model for the investigated inventory management system should be based on the paper's literature study and data analysis. The inventory system's behaviour should be appropriately modelled in the model, incorporating the supply chain collaboration strategy and established inventory policies. Before implementation, it is necessary to evaluate the verification and validation phases.

It is essential to conduct simulations based on the validated model to gauge how well the inventory management system works. From these simulations, performance metrics should be measured. These metrics include stockout rates, service standards, inventory prices, and order fulfilment rates. To pinpoint potential areas for improvement, one can compare the simulation findings with the functionality of the present system.

Examining the effects of various policy settings on system performance inside the simulation environment can follow this. Gallego-García *at al*. [41] suggest that doing so will help determine the inventory policy settings leading to higher inventory levels, lower costs, and more effective operations.

6 CONCLUSION

This paper aimed to apply simulation-driven optimisation approaches to enhance an inventory management system. The study aimed to create a simulation model framework that can be tested, allowing for more precise inventory management decisions while considering supply chain performance. Simulation models were used in the research to address the complexity and dynamic nature of inventory management. These models offer a practical, risk-free way to evaluate various hypotheses and tactics.

The study's conclusions advance the field of inventory management by shedding light on the use of simulation-driven optimisation methods, particularly in the manufacturing industry. This research provides helpful advice for organisations looking to improve their inventory management practices by developing a thorough methodology that includes literature review, data analysis, simulation model development and verification, performance evaluation, and inventory policy optimisation.

Additionally, this research fills a gap in the current literature by offering a methodical approach to inventory management simulation models, especially in vertical supply chain collaboration. The study benefits the academic community by expanding our understanding of this topic and opening new avenues for investigation.

This research offers a thorough and trustworthy resource for firms looking to improve their inventory management systems. Organisations may improve their long-term profitability, increase competitive advantage, and make informed decisions by implementing simulation-driven optimisation strategies.

Prospective future research fields not only broaden the current study's scope but also present chances for the discipline to progress further through a focus on:

1. **Multi-Objective Optimisation:** Future research may explore the incorporation of multi-objective optimisation approaches whereas the current study largely concentrated on improving inventory management choices. This would make it possible to consider competing goals, such as cutting costs while boosting service levels, and would offer a more thorough method of decision-making. [42]
2. **Real-Time Implementation:** Its practicality might be improved by looking at the viability of applying the simulation-driven optimisation technique in real-time settings. Finding ways to combine real-time data streams with IoT (Internet of Things) technology might result in more responsive and adaptable inventory management systems [43].
3. **Dynamic Demand and Supply Patterns:** The usefulness of the model in situations with changing market circumstances may be improved by extending the simulation framework to incorporate dynamic fluctuations in demand and supply patterns. Time-series data and predictive analytics may help to produce inventory management methods that are more precise and flexible. [44]
4. **Machine Learning Integration:** Machine learning techniques might improve the simulation framework's ability to forecast outcomes. The algorithm might provide more educated suggestions for inventory rules in diverse scenarios by examining past data and spotting patterns.
5. **Multi-Echelon Supply Chains:** The complexity resulting from interactions between several levels of the supply network would be addressed by extending the study's scope to include multi-echelon supply chains. This expansion can result in inventory management systems that are more thorough and practical [45].

The suggested directions for future study present chances to improve and broaden the scope of the presented framework. Researchers and practitioners may continue to enhance the state of the art in inventory management optimisation by investigating these directions, which will ultimately result in more robust, effective, and informed decision-making processes.

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PREDICTING DATE YIELD USING MACHINE LEARNING

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ABSTRACT

Crop yield forecast is essential since the population's need for food security is growing steadily. This article reports on a study conducted to predict the yield of the date palm using machine learning. Reliable crop yield prediction models are limited for the date palm. We developed and present regression models to predict date yield using historical data, which was provided by a large date. Weather data, bunch measurements and actual yield values were included in the data sets. Significant features were extracted from the data, and prediction models were developed that were tested and compared to past yield records. The developed prediction models improved on the original prediction model used by the producer while eliminating laborious, physical data collection activities.

Keywords: yield prediction, date fruit, regression

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1 INTRODUCTION

Due to a growing population that is consuming resources, food security is currently a severe worldwide concern. More economically efficient food growth and production methods are constantly required due to the limited availability of natural and human resources. This need is gradually met by employing scientific techniques, such as yield estimation, to generate an adequate supply of high-demand goods while making a profit. Yield estimation also allows producers to better plan for adequate harvesting resources, personnel, and logistics.

The date palm served as the focus of this study, which is based on [1]. Uncertainty arises from the date palm's annual production changes, especially given that millions depend on the product. Forecasting yields offers financial security and can help with long-term food security. Due to population growth and climate change, agricultural yield estimation is becoming more and more crucial. Since the crop must be grown in hot, dry conditions, which demand much water, yield prediction of the date palm is particularly interesting considering the latter.

The date palm is a staple for the rural residents where this crop is grown, supporting their culture and the local economy. The date is generally relished as a fruit, but the palm tree also yields ancillary goods that offer social and financial stability [2]. UNESCO included the date palm as part of the Intangible Cultural Heritage of Humanity [3]. This crop is renowned for its functions in ceremonies, various items, and fruit, which is a staple diet in the Middle East [4].

The Middle East still dominates the Northern Hemisphere's date industry, centered there [5]. South Africa also grows the popular Medjool variety, which was the subject of the study. When most of the world's date producers in the Northern Hemisphere are out of season, South Africa and its competitors in the Southern Hemisphere supply dates. Due to its production being less than a century old, the Southern Hemisphere has an underdeveloped market. It is nevertheless a significant global industry, with date palms grown in more than 40 countries, producing roughly eight million tons of fruit annually [6, 7]. The photo in Figure 1 shows part of a palm tree and bunches of date fruit.

Figure 1: A date palm tree with fruit bunches [8]

A literature review and an industry analysis revealed the necessity for the development of date yield models that could forecast yield from specific factors. The study looked into whether it was possible to forecast yield based on factors affecting date production, especially in the setting of date cultivation in South Africa.

Crop yield estimation has a wealth of literature, and crop yield models have been widely developed, particularly for annual crops like apples [9], citrus [10], grapes [11], and rice [12]. However, only 57 papers that were particularly relevant to date yield were found, originating from a small number of countries. These countries' interest in and market share in date cultivation were corroborated by the fact that 52 of these articles originated in Egypt, Saudi Arabia, Iran, and the United Arab Emirates. We only considered papers that were published after 2002 and found only two studies focusing specifically on date yield prediction ([13], [14]), while [15] studied the growth curve. The majority of the date palm literature, for example, [16] and [17], focuses on the effects of cultivation management strategies like pollination. The lack of pertinent papers demonstrated the area's research potential. This study used weather, bunch count, and mass data over time to estimate yield and focused on perennials, particularly palm trees, as opposed to annuals, which have been studied extensively. This study concentrated on the factors affecting the date palm producer's production in South Africa. Data were obtained from the date producer, and different ways to learn from it were researched.

Since the study was conducted on a date farm with numerous date orchards in one specific location, all the orchards had the same weather conditions. The palms in the orchards are all the Medjool cultivar but differ in age and size. There are 36 orchards and 1 200 trees on the farm. The data producer routinely collected data required for other purposes, so the features of the study were determined by the data obtained and the literature review rather than by data explicitly collected for this study.

Knowing which data to record is the first step in collecting sufficient data to be useful. This knowledge can only be gained when enough data has been collected and utilized to determine the relevant factors required for the intended purpose.

Records kept over 11 years included data on palm bunches, harvest mass recorded each day of harvest from each orchard, and climatic measurements taken at the farm's weather station. These were considered pieces of a puzzle that hid a solution. The estimated mass and number of fruit bunches in each orchard were included in the data on the fruit. Fruit bunches from all the orchards were sampled, weighed, and averaged to determine the mass of the bunches. This is a labour-intensive process since workers must measure marked fruit and bunches every week over a period of 12 weeks, starting at the end of October until early January. Fifteen orchards are used, with a marked tree in each orchard. The length and diameter of a single fruit at the top, middle, and bottom of a bunch are measured and recorded. It is assumed that these fruits are representative of the other trees and excluded orchards. Furthermore, bunches on selected trees are counted and weighed.

The research objectives were (i) to identify the key factors influencing date production; (ii) to identify prediction models that were appropriate for the data type and structure; (iii) to determine whether or not it is possible to create a yield prediction model for a producer of dates in South Africa using historical information on agricultural practices, yield statistics, and other input features; and (iv) to improve the yield estimation accuracy for the farm under study, while considering critical factors.

The remainder of the paper is structured as follows: the methodology followed is presented and includes the methods chosen for implementation, the feature selection, and the selection of some measures and error estimators. Next, the results of the best models on both orchard and farm levels are presented and discussed. Lastly, concluding points are made and discussed.

2 METHODOLOGY

To forecast the date yield, various modelling strategies were examined. However, it became clear that low-complexity linear regression approaches were the most appropriate when considering the small yet highly dimensional datasets (yield data for 11 years were available). These methods were chosen primarily with one of the study's objectives in mind: to identify the key factors influencing yield. The methods needed to deal with challenges arising from regression (continuous data), particularly in small datasets where there were fewer observations than features. The following four methods were chosen for implementation:

1. A screening method employing the Pearson correlation coefficient, validated by means of SelectKBest from Scikit-learn [18].
2. Forward stepwise regression, a subset selection method.
3. Elastic net regression, a regularization method that combines
    a. lasso and
    b. ridge regression.
4. Partial least squares regression that has dimension reduction properties.

Although these four regression methods represent different regression method ideologies, they all share characteristics that make them suitable for prediction with available data while also having embedded feature selection capabilities. The processing of the data produced the meteorological features, which were applicable to the entire farm and comprised heat units, humidity, wind, rainfall, and the minimum, maximum, and mean temperatures for a month. It is assumed that the reader is acquainted with the features, but we briefly explain "heat units" here: crops need specific threshold (base) temperatures to start developing yield, and there are several methods to calculate heat units for a cultivar. The method used for dates is the daily average method, which considers the daily maximum and minimum temperatures minus the threshold temperature and is calculated as

$$\text{Heat units} = (\text{Max. daily temp.} - \text{Min. daily temp.})/2 - \text{Base temp. } [^\circ\text{C}] \qquad (1)$$

The base temperature of the date palm is taken as 18°C, and the palm requires 2000 heat units from flowering to fruit maturity.

The 14 features extracted from the data sets are as follows, where i is a month index (1, 2, …, 12) of the year:

1. Heat units for months $i - 1$ and i
2. Wind speed for months $i - 1$ and i
3. Humidity for months $i - 1$ and i
4. Rainfall for months $i - 1$ and i
5. Maximum temperature for months $i - 1$ and i
6. Mean temperature for months $i - 1$ and i
7. Minimum temperature for months $i - 1$ and i.

As a result, monthly features for the two years preceding a harvest were created using all the meteorological conditions that were taken into consideration. The mean bunch mass and mean bunch count of an orchard were the bunch characteristics used for each orchard. First, the meteorological features were considered and used to predict the harvest for the individual orchards and the farm. Then secondly, the bunch features were added to improve the yield predictions.

In a linear regression study, the statistical correlation between the predictors and response is expressed as a linear equation. Utilizing the residuals and analysing the analysis results, it is possible to confirm that an equation adequately fits the data. The results include the p-values and the predictor variable coefficients, among other things. The p-value evaluates the null hypothesis that each predictor (independent variable) has no effect on the target since its coefficient is zero. The variable is demonstrated to be statistically significant if $p < 0.05$. A higher p-value suggests that the predictor has no impact on the response.

Each developed model was evaluated and compared. To estimate the fit of the model, numerous measures were calculated to assess models and compare them with others [19]. Three measures for the models are subsequently discussed.

R-squared measure

The coefficient of determination, R-squared (R^2), is useful when evaluating the goodness of fit of a model and represents the proportion of variance explained by the model. The relative metric R^2 can be used to compare models that have been trained on the same dataset. It is a score that is positively orientated; therefore, a value closer to one is preferred. However, a value of one indicates an overfitted model.

R^2 is often adjusted to take the addition of predictors or features into account for improved evaluation accuracy. When the model's parsimony is emphasized, the adjusted R^2 score is useful. Regarding predictability, R^2 is preferred, while adjusted R^2 is utilized for simpler, more parsimonious models.

Mean errors

The mean absolute error (MAE) and root mean square error (RMSE) are two often used metrics to assess the accuracy of models that use continuous variables, which is the type of variables in the study. The MAE indicates the average magnitude of errors in a set of predictions and is the average of the absolute differences — individual differences are equally weighted — between predictions and observed observations. The MAE is a relatively simple measure of the average deviation of the model predictions for regression issues. MAE is calculated with

$$\text{MAE} = \frac{1}{n}\sum_{j=1}^{n}\left|y_j - \hat{y}_j\right|, \qquad (2)$$

where *n* is the number of observations, y_i the observation values and $\hat{y}_i$ the estimated values.

The average magnitude of the error is measured by the RMSE, a quadratic scoring rule and is the square root of the average of the squared deviations between predicted results and actual observations.

Both MAE and RMSE are negatively orientated scores that indicate the average prediction error of the model in units of the dependent variable. The large errors are weighted heavily since RMSE squares the errors prior to averaging. RMSE is always greater than or equal to MAE. RMSE is determined by

$$\text{RMSE} = \sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(y_j - \hat{y}_j\right)^2}. \qquad (3)$$

MAE is preferable for interpretation because it describes the average error, whereas RMSE is useful when large errors must be penalized.

The mean absolute percentage error (MAPE) is expressed as an error percentage with

$$\text{MAPE} = \frac{1}{n}\sum_{i=1}^{n}\left|\frac{y_i - \hat{y}_i}{y_i}\right| \times 100\%. \qquad (4)$$

It is a valuable measure when the data does not contain extreme outliers or zeros.

Cross-validation

A statistical technique called cross-validation (CV) is often used for model comparison and prediction model selection. It results in a less optimistic estimate of the model's capability. CV is a resampling technique that measures how well a predictive model performs when forecasting based on unseen data. To evaluate the expected overall performance of the model when used to predict using data that is not seen in the training set, CV uses a partial sample. The methods for determining statistical measures are presented here, with a focus on CV, because it is useful for small datasets.

The errors and R^2 estimates are calculated in the following three ways:

1. Re-substitution estimates: The model fitting and dependent variable estimations both make use of the same data set. This approach was not considered for the study because it is overly optimistic about the ability of the model to generalize future observations.
2. Cross-validation, specifically leave-one-out cross-validation (LOOCV). Both the fitting and evaluation of the model employed all the data, albeit not simultaneously. If a dataset is relatively large, LOOCV is not suitable. The advantages of LOOCV include reliability and high model performance estimation accuracy.
3. Train/test split: The technique is also known as holdout CV, and it splits the data into a training set and a test set. The training set is used for fitting the model while the test set consists of new data used for the estimation. Although dividing a dataset into train and test sets is more effective for larger datasets, the dataset in this research was too small to employ this technique.

The *k*-fold CV procedure is used to estimate the performance of a machine learning algorithm when it predicts using data that was not used for model training. The hyperparameter, k, controls the number of subsets into which the data is split, while each subset is used as a test set while the remaining subsets constitute the training set. Subsequently, *k*-fold CV is done by fitting and evaluating k models resulting in k estimates of the model performance on the data. This performance can be reported with summary statistics such as the mean and standard deviation.

LOOCV represents a configuration whereby a parameter *k* is chosen to equal the number of observations in the data set. Since a model is fitted and assessed for each observation in the data, it can be a computationally expensive version of *k*-fold cross-validation. It is therefore suitable for small datasets. LOOCV is advantageous in that it provides a robust estimate of the performance of the model because every data row is used for the testing of the fitted model. The final model score is calculated by averaging all *k* estimates.

3 RESULTS

The results of the various prediction approaches were compared with those of the producer's present method of prediction. The identified weather features were used as predictor variables to predict the yield of both individual orchards and of the entire farm. The chosen feature selection methods were implemented to identify the most significant features from the weather factors affecting the yield. The producer's method to predict yield on the farm determines the sum of the products of the bunch features, namely bunch count and bunch mass per orchard.

For demonstration, some of the regression equations are shown in Table 1, per orchard. The index '*r*' refers to the orchard number, $MaxT_i$ to the maximum temperature in month *i*, $MeanT_i$ to the mean temperature in month *i*, HU_i to the heat units in month *i*, $prevHum_i$ is the humidity of in month *i*, one year ago, *Bm(r)* is the bunch mass representing orchard *r* and *Bc(r)* the bunch count representing orchard *r*.

Table 1 Some regression model equations for individual orchards

Orchard no.	Weather features	Equation
17	May and August maximum temperature	$-6.294MaxT_5 + 1.525MaxT_8 - 2.015Bm(r) + 1.029Bc(r) + 255.084$
33	August heat units	$0.166HU_8 + 4.342Bm(r) - 1.034Bc(r) + 88.102$
56	Previous May humidity, previous June maximum temperature	$1.927prevHum_5 - 8.208prevMaxT_6 + 6.586Bm(r) + 1.199Bc(r) + 198.698$
57	May maximum temperature	$-13.847MaxT_5 + 10.495Bm(r) + 7.145Bc(r) + 374.834$
90	April mean temperature	$9.867MeanT_4 + 7.61Bm(r) - 1.846Bc(r) - 136.077$

When the predicted yield values were compared to the actual yield values, and the date producer's current predictions, the errors (RMSE, MAE, and MAPE) were lower for either using orchard predictions and summing them to compute a total or using mean values to predict the total farm yield. It was observed that using the weather features only improved on the producer's method; however, adding the bunch mass along with the weather features enhanced prediction accuracy.

When the sum of the orchard predictions was used, a MAPE of 2.89% was produced, with the best prediction for the yield of each orchard achieved with a unique subset of weather and bunch attributes. A MAPE of 3.15% was obtained when using weather features and bunch mass instead of bunch count. This improved the value of the MAPE of the date producer’s method, which was 7.74%.

Table 1 shows the MAE of the models predicting the yield on the orchard level. The developed models outperformed the current estimation model while using different feature combinations. The MAPE is 4.04% when predicting the total farm yield with a single set of weather features and the bunch mass and bunch count and 4.24% without using the bunch count, compared to the date producer’s error of 7.12%.

Table 2 Comparison of mean absolute errors of models predicting orchard total yield (tons)

Feature combinations	Model	Current
Both bunch features	34 719	38 264
Weather features	33 811	N/A[1]
Weather and bunch mass	16 581	N/A
Weather and bunch features	14 531	N/A

[1] The farm did not have data on these features.

Table 2 shows the MAE of the yield prediction models of total yield, thus on the farm level. The developed linear models, using the weather, bunch features or both the weather and bunch features in any combination as predictors, outperform the current estimation model. Although the prediction errors are slightly higher, it is advised that the bunch mass and weather features be employed because they have proven to be the most critical.

Table 3 Comparison of the mean absolute errors of models predicting farm total yield (tons)

Features	Model	Current
Both bunch features	34 719	38 264
Weather features	33 811	N/A
Weather and bunch mass	16 581	N/A
Weather and bunch features	14 531	N/A

4 CONCLUSION

Crop yield prediction is important in global food production because it supports agricultural producers, importers, and exporters in making financial and management decisions that increase food security. Accurate crop yield prediction is a complex task that involves numerous challenges. Many factors add to this complexity, including the genotype information of the crop and its interaction with the environment as well as farm management practices.

Crop yield prediction is well-developed for annual crops; however, it is not as well-established for perennials. This study researched an approach to yield prediction of the date palm with the use of collected data and selected mathematical methods. The data available for the study comprised records of fruit bunch count and mass, meteorological measurements as well as the harvested mass values of the orchards on the farm under study.

In the study, four regression approaches were considered, namely 1) a correlation-based method, 2) forward stepwise regression, 3) elastic net regression and 4) partial least squares regression. The results support the proposed regression models using meteorological data and bunch mass. Using the features identified as significant led to decreased prediction errors. The approach developed in this study is applicable to individual orchards, with unique feature sets selected for each orchard or the entire farm. The yield prediction for the next year is done with four features as predictors, namely the mean temperature for September and the previous October, the mean bunch mass, and the mean bunch count.

The current method employed by the farm, which calculates yield by multiplying manually measured bunch mass and bunch count, was compared with the results of the developed models. The current prediction method simply multiplies the estimated number of bunches with the estimated bunch mass. The counting of the fruit bunches is proven not to be required for greater yield prediction accuracy; therefore, the labour-intensive effort and inevitable costs resulting from bunch counting can be reduced or even eliminated. Some significant practices on the farm were not included in the study due to data unavailability, including thinning, the time of pollination, and the irrigation and fertilization regimes. The prediction accuracy could be improved when adding more meaningful features to the regression models with data on these practices.

The date palm is not extensively cultivated in the southern parts of Africa and research on the topic, specifically on yield prediction of the date palm, is limited. For this reason, this research study is relevant to agricultural practitioners and date consumers. The study also contributes to research on handling high-dimensional and small sample-size problems as it applied techniques on a very small-sized yet high-dimensional dataset. Furthermore, from a system and industrial engineering perspective, a large manual labour effort can be eliminated should the prediction methods be used.

The procedure to predict the yield was implemented in MS-Excel with Python coded procedures as backbone. The user needs to provide the two average temperature values of the previous October and current September, and the measured bunch mass and bunch count, and the tool will then determine the predicted yield. In future, the regression coefficients should be updated as more yield data is collected. The study was limited to orchards in one geographical area and further studies in other regions are needed to assess the general applicability of the results.

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COMPARING SHAPE-BASED AND FEATURE-BASED CLUSTERING TECHNIQUES FOR GROUPING STOCK KEEPING UNITS IN A RETAIL ENVIRONMENT

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ABSTRACT

In the retail sector, it is often required to group *stock keeping units* (SKU) together which exhibit similar sales attributes. Time series clustering has often been performed in this respect in areas such as inventory management, demand forecasting, and marketing. Two commonly adopted approaches towards time series clustering are shape-based clustering and feature-based clustering. The former involves partitioning time series data according to the similarities of their shapes, with similarity being measured in terms of an appropriate distance measure, while the latter involves clustering time series according to statistical measures such as their means, variances, and degrees of autocorrelation. Both the demand patterns and time series features are, however, important in time series representing retail sales. This paper is a comparative study of shape-based clustering and feature-based clustering of SKUs in a retail context. The effectiveness of both clustering approaches is examined in terms of their relative accuracies and their associated computational complexities.

Keywords: Inventory management, Demand planning, Time series clustering, Machine learning

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1 INTRODUCTION

Retail organisations continually seek ways in which to increase their competitive advantage while being challenged with increasing customer expectations, demand volatility, and large-scale supply-chain inefficiencies. Although retail organisations typically cannot mitigate all these challenges, there is much they can do to increase their competitive advantage. In particular, the rise of e-commerce has allowed retail organisations to *collect* and *analyse* large amounts of data which, in turn, increases their ability to manage inventory efficiently. Efficient inventory management in a retail organisation often requires clustering together of groups of *stock keeping units* (SKUs) which are similar in some sense, but which may differ in terms of demand frequency, demand quantity, demand regularity, and demand variation [1].

Inventory management in large supply chain networks involves managing thousands of SKUs spread across different locations and exhibiting complex interrelationships. Figure 1, for example, contains an illustration of the typical hierarchical structure of data generated in the retail sector. The example in the figure starts at product level and contains 30 490 time series which may be aggregated to the levels of departments, product categories and stores located in three American states, namely in California (CA), Texas (TX), and Wisconsin (WI). It is computationally expensive to manage inventory effectively when considering each SKU individually during inventory replenishment decisions. By grouping together clusters of SKUs exhibiting similar demand patterns, for instance, a retail organisation can develop methods for better managing, characterising, controlling and forecasting demand for inventory, which may lead to reductions in the cost of holding inventory [2]. Clusters of SKUs which exhibit similar demand patters may also furnish a retail organisation with enhanced knowledge about consumer behaviour. The validity of information extracted from clusters of time series, however, depends strongly on the quality of the clusters formed. A retail organisation should, therefore, ideally consider different approaches towards clustering SKUs [3].

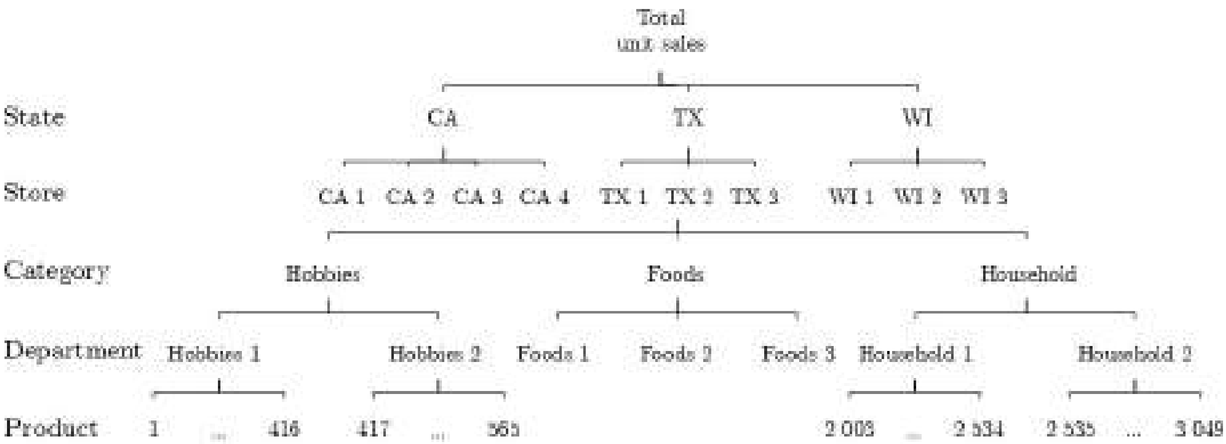


Figure 1: An example of hierarchical structure in a data set of Walmart [4].

Time series clustering is typically employed to identify underlying structures in large temporal data sets [5]. In the case of clustering SKUs based on time series of unit sales, there are two well-known approaches, namely *shape-based clustering* methods and *feature-based clustering*, each utilising as input a different representation of the time series. Consider, for example, the two time series representations in Table 1 and **Error! Reference source not found.**. The former representation involves three time series in their univariate format, while the latter is a transformed feature representation of the same three time series. These two time series representations may be clustered by applying shape-based clustering methods and feature-based clustering methods, respectively.

Table 1: A fictitious set of time series represented as a set of monthly observations.

	May	Jun	Jul	Aug	Sep	Oct	Nov
t_1	88	67	79	73	89	82	72
t_2	67	68	89	83	79	62	74
t_3	78	65	91	83	86	73	68

Table 2: A feature representation of the fictitious set of time series in Table 1.

	Mean	Min	Max	Peaks	Throughs
t_1	68.75	67	89	2	2
t_2	74.57	62	89	1	1
t_3	77.71	65	91	2	2

In this paper, we study shape-based clustering methods and feature-based clustering methods in the context of clustering time series representing the unit sales of SKUs in the retail sector. More specifically, we present an empirical comparative study in which the different advantages and disadvantages of shape-based clustering and feature-based clustering are highlighted.

The remainder of the paper is organised as follows. Section 2 contains a review of the literature pertaining to the different clustering approaches, with a particular focus on shape-based clustering methods and feature-based clustering methods. Thereafter, a description follows in Section 3 of the data sets, clustering methods, and evaluation metrics adopted in our comparative study. The numerical results obtained upon implementing the different clustering methods are presented in Section 4. Finally, conclusions are drawn and future research directions are proposed in Section **Error! Reference source not found.**.

2 LITERATURE REVIEW

This section is devoted to a brief review of the literature on time series clustering. First, a review is provided in Section **Error! Reference source not found.** of different time series representations, after which the focus shifts in Section **Error! Reference source not found.** to a review of different similarity or distance measures typically employed in time series clustering. This is followed in Section 2.3 by overviews of three popular classes of time series clustering algorithms, namely *hierarchical clustering*, *optimisation clustering*, and *self-organising maps*. Finally, Section 2.4 contains a review of various validity criteria often used to evaluate the results returned by clustering methods.

2.1 Time series representation

A commonly adopted approach towards time series clustering involves considering different representations of a time series, each with reduced dimensionality [6]. Dimensionality reduction techniques are typically aimed at representing a raw time series in another space of lower dimensionality. A popular example of a dimensionality reduction technique is feature extraction, which involves representing a time series in a smaller feature space. Dimensionality reduction is an important prerequisite to time series clustering as it is capable of reducing the memory requirements for large clustering applications significantly. Furthermore, calculating similarities and distances between raw time series data is typically computationally expensive, and so dimensionality reduction may also increase the computational efficiency of clustering time series [7]. In some cases, clustering raw time series data may, however, return highly unintuitive results as some distance measures are highly sensitive to distortions in time series data [8], therefore generating clusters of time series which are similar in noise rather than in shape. Reduction techniques are typically employed to reduce noise and promote the performance of clustering algorithms when clustering time series which are characterised as high dimensional [9]. Ultimately, the choice of an appropriate dimensionality reduction technique is a trade-off between speed and quality [5].

Consider a time series $T_i = \{t_1, \dots, t_\Omega\}$ in its original raw representation. Then, $T_i' = \{t_1', \dots, t_x'\}$ is a time series with a reduced dimensionality where $x < \Omega$. In the case of a good transformation from the former to the latter representation, two time series which are similar in the original space should remain similar in the transformation space. According to Ratanamahatana *et al.* [10], the selection of an appropriate time series representation may be considered a key component of time series clustering since it affects both the accuracy and efficiency of a clustering solution. Generally, a time series may be represented in one of four formats, namely a *data adaptive* representation [6], a *non-data adaptive* representation [10], a *model-based* representation [11], or a *data dictated* representation [12].

2.2 Similarity or distance measures

Agrawal [13] proposed the theoretical notion of time series similarity/dissimilarity search. Time series clustering is highly reliant on the underlying distance measure employed. There is a large selection of measures available in the literature for measuring distances between time series, some of which are specific to certain time series representations. Two of the most commonly employed distance measures are *Euclidean distance* and *Dynamic Time Warping* (DTW), where the former is preferred for clustering feature-based time series representations and the latter for shape-based time series representations [5].

The primary difference between the Euclidean distance and DTW lies in the fact that distance is accumulated according to the latter measure over pairs of time series entries which are not necessarily observed at the same time and the connections are not required to be one-to-one, whereas these pairs necessarily have the same time values in the former measure. This difference is best explained graphically. Figure 2 contains an illustrative example of the way in which the two distance measures establish multiple pairwise connections between observations of two different time series [14]. The dotted lines indicate connections made by employing DTW as distance measure whereas solid lines indicate those achieved when employing Euclidean distance.

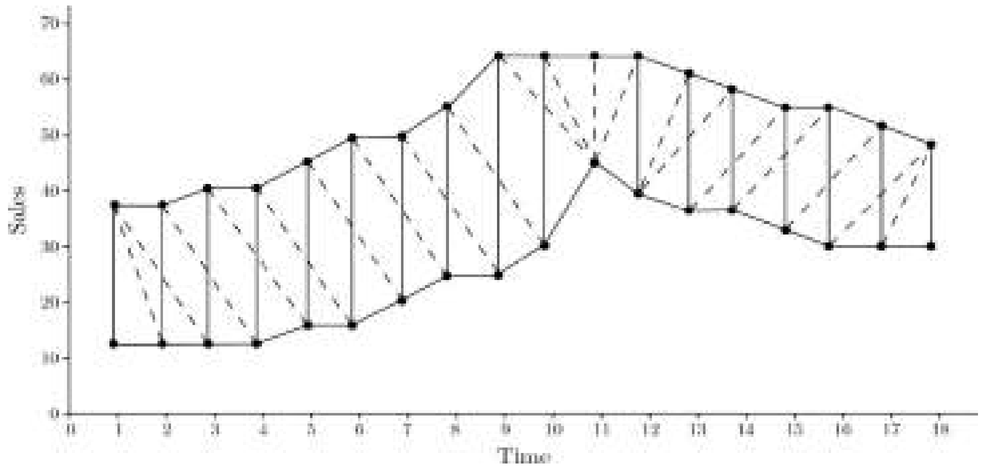
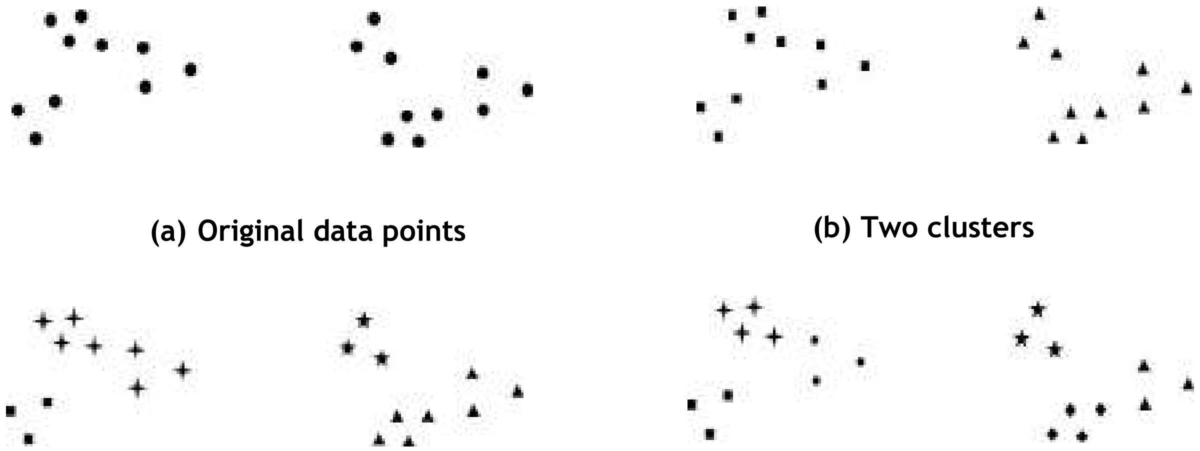


Figure 2: A comparison between Euclidean distance and DTW as distance measures when clustering a hypothetical time series.

2.3 Time series clustering algorithms

In an attempt to understand a new phenomenon, it is natural to investigate features that best describe it, and to compare the values of these features with those of known phenomena, based on their similarity or dissimilarity. This intuition may be employed within the realm of data analysis, where observations are often unique and unidentified. Clustering is the unsupervised task of grouping unlabelled data into meaningful and/or useful partitions [15]. The goal during clustering is to assign each of a number of objects to clusters based on information that best describes the object and its relationship with other objects. More specifically, the aim in clustering is to group data into a specific number of sets, where objects in the same set are as similar as possible, but dissimilar from objects in other sets [16]. The difficulty of defining what best constitutes a cluster is illustrated in Figure . The remainder of this section is devoted to brief discussions on three classes of clustering algorithms, namely *hierarchical clustering*, *optimisation clustering*, and *self-organising maps*.



(a) Original data points **(b) Two clusters**

(c) Four clusters **(d) Six clusters**

Figure 3: Clustering of a set of data points in two dimensions, where Euclidean distance is adopted as dissimilarity measure (adopted from [17]).

2.3.1 Hierarchical clustering

Ward [17] argued that the largest amount of object-related information is available in an initial state of n ungrouped objects. Clustering these objects into groups may, however, be particularly useful for classification purposes. He therefore proposed iteratively grouping the n objects by merging together those groupings that least affect the amount of information available during each iteration, starting with the situation in which each object resides in its own group. The result of this systemic reduction in the number of groups of objects is a collection of mutually exclusive groups that may be represented in a hierarchical structure. Most commonly, this hierarchical structure is represented graphically in what is known as a *dendrogram* [18].

Hierarchical clustering involves iteratively amalgamating pairs of clusters based on their similarity or the distance between them. There many methods in the literature for measuring the similarity between two clusters [19], [20]. Three well-known methods for measuring similarity between clusters are the *single linkage* method, the *complete linkage* method, and the *group average* method [15]. Generally, the degree of dissimilarity between clusters is represented in the form of a *distance matrix*, also known as *proximity matrix* [18].

2.3.2 Optimisation clustering

As the name suggests, optimisation clustering involves partitioning a set of data points into K clusters by optimising some clustering criterion, where K is an exogenously specified parameter [18]. This optimisation process is typically accomplished by minimising an objective function that represents the variability of data points within the clusters [21]. The K-means clustering algorithm partitions a population of objects into K clusters by minimising the sum of the squared errors during an iterative optimisation process [22]. The most elementary version of the K-means clustering algorithm may be summarised as follows:

1. Initialise K data points as cluster centroids.
2. Calculate the distances between all data points and cluster centroids by utilising an appropriate distance measure.
3. Form K clusters by assigning each data point to its closest cluster centroid.
4. Update the cluster centroids based on the new partitioning.
5. Repeat the previous three steps until no change is observed for any cluster.

Variations on the above K-means algorithm differ in their method of selecting initial centroids as well as in the distance measure adopted [15].

2.3.3 Self-organising maps

Self-organising maps (SOMs) is a non-linear projection method often utilised in clustering and dimensionality reduction applications. In both these applications, SOMs map high-dimensional spaces to low-dimensional spaces, thus reducing complexity and increasing the interpretability of multidimensional data [23]. More specifically, a SOM maps the manifold in which vector samples are located into a two-dimensional grid. Figure contains a graphical illustration of the architecture of a SOM with two clusters and M input features, represented as neurons --- a structure rather reminiscent of that of a neural network.

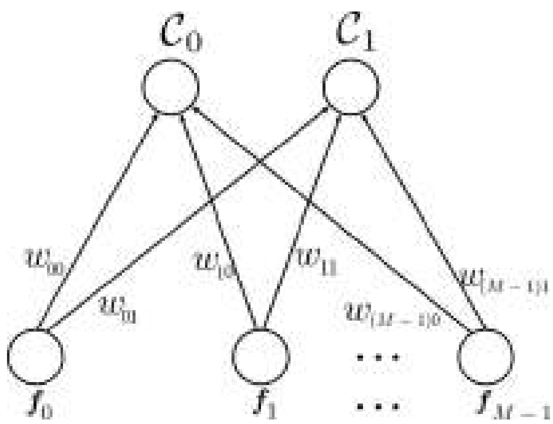


Figure 4: The architecture of a SOM with two clusters, $\mathcal{C}_0$ and $\mathcal{C}_1$, and M input features, $f_0, f_1, \ldots, f_{M-1}$. The quantity w_{ij} is the weight associated with feature f_i and cluster $\mathcal{C}_j$.

2.4 Cluster validity criteria

Clustering validation measures reside in one of two main categories, namely *external clustering validation* measures and *internal clustering validation* measures [24]. External clustering validation involves considering external information for validation purposes — entropy may, for example, be employed to evaluate the purity of clusters with respect to given class labels [25]. As the name suggests, internal clustering validation, on the other hand, involves relying on information embedded within the data and evaluating the quality of clustering structures without any external information [15]. Unlike external validation measures, which are employed only to choose the most appropriate clustering algorithm, internal validation measures may be employed to select the best clustering algorithm as well as a suitable number of clusters [24].

In practice, internal clustering validation is employed more often than external clustering validation because of the general lack of external information in many application scenarios. Various internal clustering validation measures have been proposed in the literature, the three most common being the *silhouette coefficient*, the *Calinski-Harabasz index*, and the *Davies-Bouldin index* [18].

2.4.1 Silhouette coefficient

Proposed by Rousseeuw [26], the *silhouette coefficient* (SIL) is a measure of clustering separation. Let $\mathcal{O} = \{t_1, \ldots, t_N\}$ be the set of time series objects being clustered and let $\mathcal{C} = \{C_1, \ldots, C_N\}$ be the set of clusters into which these objects are grouped. If object $t_i \in \mathcal{O}$ is in cluster $C_j \in \mathcal{C}$, then the average distance between object t_i and its neighbouring objects in cluster C_j is denoted by a_{ij}. Moreover, let d_{iq} be the average distance between object $t_i \in \mathcal{O}$ and the objects of another cluster $C_q \in \mathcal{C}$, with $q \neq j$. Also, b_{iq} is computed as the minimum average distance d_{iq} for all clusters $C_q \in \mathcal{C}$ with $q \neq j$. Finally, the silhouette of a single object t_i is expressed mathematically as

$$SIL_i = \frac{b_{ij} - a_{ij}}{max\{a_{ij}, b_{ij}\}}, \tag{1}$$

where the denominator represents a normalisation term. It is clear that $SIL_i \in [-1, 1]$, where a value of SIL_i close to unity indicates a good assignment of object $t_i \in \mathcal{O}$ to its respective cluster $C_j \in \mathcal{C}$, and that a value of SIL_i close to negative unity indicates an incorrect assignment of object $t_i \in \mathcal{O}$ to the cluster $C_j \in \mathcal{C}$ [26].

The silhouette coefficient is defined as the average silhouette score SIL_i of all objects $t_i \in \mathcal{O}$ and is expressed mathematically as

$$SIL = \frac{1}{N} \sum_{i=1}^{N} SIL_i, \tag{2}$$

where N denotes the total number of objects. SIL is maximised if the intra-cluster distance (based on a_{ij}-values) is minimised and the inter-cluster distance (based on b_{ij}-values) is maximised for each object $t_i \in \mathcal{O}$, with the maximum SIL-value indicating a best possible partition [18].

2.4.2 Calinski-Harabasz index

Proposed by Calinksi and Harabasz [27], the *Calinski-Harabasz* (CH) index, also known as the *variance ratio criterion*, measures the validity of a cluster by comparing the average sum of between-cluster dispersion and within-cluster dispersion. Here, *dispersion* is defined as the sum of squared distances between data points [28]. The CH index may be employed to evaluate clustering models without external knowledge about the true labels of the data (*i.e.* internal clustering validation) [27].

For N time series and K clusters, the CH index may be expressed mathematically as

$$s = \frac{tr(\boldsymbol{B_K})}{tr(\boldsymbol{W_K})} \times \frac{N-K}{K-1}, \tag{3}$$

where $\boldsymbol{B_K}$ and $\boldsymbol{W_K}$ denote the between-cluster dispersion and within-cluster dispersion matrices, respectively. The trace of the between-cluster dispersion matrix is

$$tr(\boldsymbol{B_K}) = \sum_{j=1}^{K} n_j \left|\left|\boldsymbol{\bar{c}_j} - \boldsymbol{c}\right|\right|^2, \tag{4}$$

where n_j is the number of objects in cluster $C_j \in \mathcal{C}$, $\bar{\boldsymbol{c}}_j$ is the centroid of this cluster, and $\boldsymbol{c}$ is the centroid of all objects $t_j \in \mathcal{O}$ [29]. Similarly, the trace of the within-cluster dispersion matrix may be expressed as

$$tr(\boldsymbol{W_K}) = \sum_{j=1}^{K} \sum_{x \in C_j} \left|\left|\boldsymbol{x} - \bar{\boldsymbol{c}}_j\right|\right|^2. \quad \textbf{(5)}$$

Clusters of high quality will yield a large CH index value since the between-clusters dispersion will be larger than the within-cluster dispersion. Because of the efficiency of computing the CH index, it is often utilised as a criterion for determining the 'natural' number of clusters for a set of objects [28].

2.4.3 Davies-Bouldin index

The *Davies-Bouldin* (DB) index [30] is aimed at measuring the average similarity between clusters. The similarity between cluster $C_j \in \mathcal{C}$ and one of its neighbouring clusters C_q, with $q \neq j$ is defined as

$$R_{jq} = \frac{s_j + s_q}{d_{jq}}, \quad \textbf{(6)}$$

where s_j denotes the average distance between the objects in cluster C_j and its centroid $\bar{\boldsymbol{c}}_j$, also known as the cluster diameter, whereas d_{iq} denotes the distance between the cluster centroids $\bar{\boldsymbol{c}}_j$ and $\bar{c}_q$ [29]. The DB index is expressed mathematically as

$$DB = \frac{1}{K} \sum_{j=1}^{K} \widetilde{R}_J, \quad \textbf{(7)}$$

where

$$\widetilde{R}_J = \max_{i \in C, i \neq q} \{R_{iq}\}. \quad \textbf{(8)}$$

Naturally, the smaller the similarities between clusters, the better the partitioning of the objects [24]. As such, a DB index with a value closer to zero indicates a better partition [28].

3 METHODOLOGY

Based on the review of clustering methods presented in Section 2 it should be clear that there is no single best approach for clustering time series representing the unit sales of SKUs in the retail sector. Furthermore, we could find no empirical comparison study focused on highlighting the effects of adopting different algorithms for clustering retail sales time series at different levels of aggregation. The primary objective of this study is, therefore, to compare the difference in cluster quality obtainable by adopting the three popular clustering approaches reviewed in Section 2. Moreover, our aim in this study is to highlight the effects on the quality of clusters obtained when employing different similarity or distance measures. Figure 5 contains a schematic illustration of the methodology adopted in this paper to compare the relative efficacy of different approaches towards time series clustering.

The first step of the methodology presented in Figure 5, the data collection step, involves selecting a data set which is sufficiently representative of time series data generated in the retail sector. These data are then processed during the pre-processing and the time series aggregation steps to ensure that the data are of respectively a suitable quality and structure for achieving the objectives of this study (*i.e.* comparing clustering methods at different levels of time series aggregation). During the shape-based representation step, the shapes of time series are matched as best possible, by applying a non-linear lengthening or shorting of the time axes. In this case, modified dissimilarity measures, such as DTW, are considered appropriate to compute the distance matrix during time series clustering. Unlike in the shape-based representation step, where a clustering algorithm is initialised with clusters which represent time series based on their raw, observed values, the feature-based representation step involves partitioning the time series data according to a selected feature set. Clustering techniques based on this feature representation typically invoke conventional approaches towards generating cluster-extracted feature vectors which best describe the underlying characteristics or attributes of the input time series. After having selected a time series representation, it is important to select an appropriate dissimilarity measure during the dissimilarity step which matches the time series representation adopted. Some clustering algorithms, such as the K-means clustering algorithm, require an *a priori* identification of the natural number of clusters in the data set. An appropriate number of clusters is therefore identified during the determine number of clusters step. Following the selection of a time series representation, a dissimilarity measure, and an appropriate number of clusters, the three clustering algorithms reviewed in Section 2.3 are employed during the clustering algorithm step. Thereafter, the evaluation step involves evaluating the quality of the different clusters returned by the various clustering algorithms. This step returns as output a table of clustering validation criteria, such as those reviewed in Section 2.4, which allow for an objective comparison of cluster qualities achieved by the different clustering approaches.

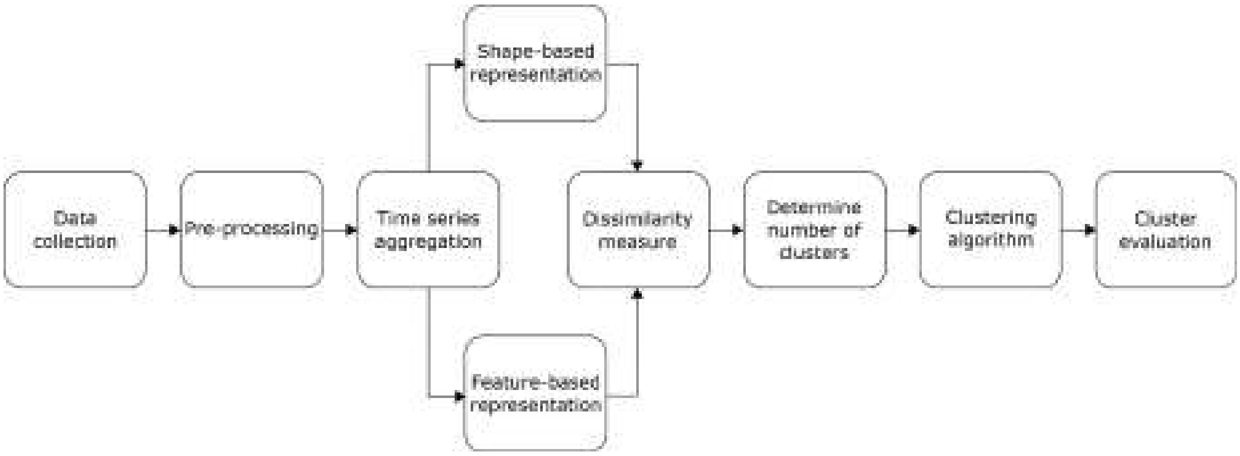


Figure 5: A summary of the methodology adopted in this paper.

4 RESULTS

When employing the methodology proposed in Section 3, the data set identified during the data collection step was the well-known M5 times series forecasting competition data set [4]. Following the pre-processing step of the proposed methodology, the M5 data set was aggregated at a weekly level (which is representative of data sets typically generated in a retail context [31]). The pre-processed M5 data set contains retail sales time series spanning a period of 278 weeks, ranging from January 2011 to June 2016.

A balanced sample of $14\,000$ time series was considered for the exploration of clustering performances at different levels of aggregation. As may be seen in Table 3, the time series data were transformed to a format in which each row represents a specific product, *e.g.* HOBBIES 1 001 CA 1, indicating the product category, type, state, and store. Furthermore, to avoid the clustering biases associated with the magnitude of time series entries and the length of sequences of leading zeros present in a time series, each time series was trimmed of leading zeros and its remaining values were normalised to between zero and one during the pre-processing step of the methodology of Section 3.

In order to evaluate the effects of time series dimensionality on clustering performance, different levels of aggregation were considered in the time series aggregation step of the methodology presented in Figure 5 (these aggregations may reduce the degree of intermittency and sparsity present in a time series). The lowest time series aggregation levels (*i.e.* the most disaggregated levels) typically exhibit a larger number of zeros than do their corresponding aggregated derivatives. For example, a sample of $10\,000$ time series of the products per store level were found to contain, on average, 68% zero values per time series, whereas a sample of $1\,000$ time series aggregated by product contained only 29% zero values per time series, on average.

Table 3: Data entries (rows) representing the weekly sales of SKUs over a period of 278 weeks spanning the period January 2011 to June 2016.

	id	w_1	w_2	w_3	…	w_{276}	w_{277}	w_{278}
1	HOBBIES 1 001 CA 1	0	0	0	…	5	11	7
2	HOBBIES 1 002 CA 1	0	0	0	…	1	3	2
…	…	…	…	…	…	…	…	…
30489	FOODS 3 824 WI 3	0	0	0	…	9	7	13
30490	FOODS 3 827 WI 3	0	0	0	…	10	4	19

In an attempt to understand the effects of clustering time series of unit sales at different levels of aggregation, three different levels of time series aggregation were selected, namely the p*roducts per store* level, the *products per state* level, and the *total products* level. The clustering performances obtained for these aggregation levels were evaluated in respect of their different representations (*i.e.* shape-based *vs.* feature-based). Clustering methods that require shape-based representation include the conventional clustering methods reviewed in Section 2.3. There are, however, differences between the distance/dissimilarity measures employed in these methods. For the purposes of this case study, only DTW and Euclidean distance were utilised as dissimilarity measure when clustering shape-based and feature-based representations at the three levels of aggregation, respectively.

Determining an appropriate number of clusters is a fundamental problem in unsupervised clustering [32]. It is important to identify the "natural" number of clusters embedded in an aggregated data set. Various methods for determining a suitable number of clusters are available in the literature. By analysing the performance of a clustering algorithm in respect of the three performance measures reviewed in Section 2.4, it became clear that four clusters would seem to be an appropriate number (by a majority vote). The elbow in Figure 6 is considered an indicator of an appropriate number of clusters which, in this case, corresponds to four. This number of clusters was, therefore, adopted going forward.

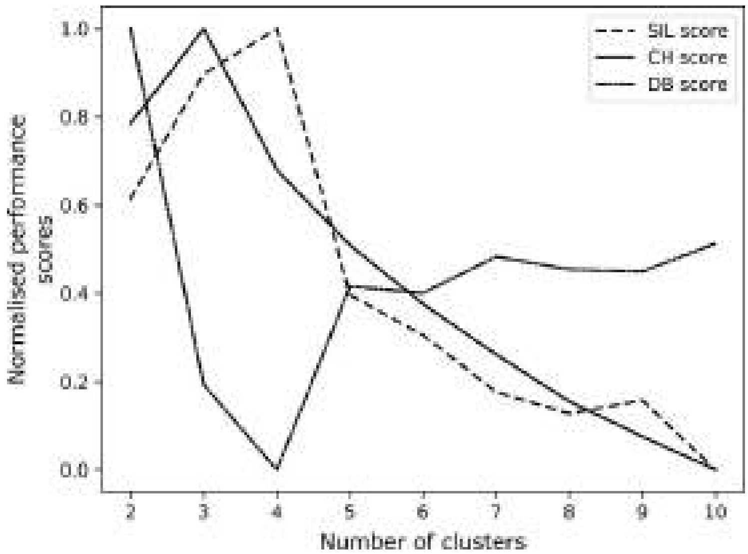


Figure 6: An illustration of the performance scores obtained when considering different numbers of clusters.

4.1 Shape-based clustering

After having determined an appropriate number of clusters, an evaluation of the clustering performances of the shape-based time series representations could commence. A distance matrix for the shape-based representation of the aggregated time series data set was calculated in terms of DTW. This distance matrix was provided as input to the clustering algorithms considered in this comparative study. The resulting clustering performances are quantified in Table 4 for representative samples of the data set in terms of the silhouette scores achieved by the three clustering algorithms (in combination with shape-based time series representations at three levels of aggregation).

Table 4: The silhouette scores obtained by three clustering algorithms, with DTW as dissimilarity measure, when applied to a shape-based representation of representative samples of the M5 data set.

Algorithm	SKU/store (10 000)	SKU/state (3 000)	SKU (1 000)	Combined (14 000)
K-Means	0.062	0.062	0.094	0.073
Agglomerative	0.002	0.026	0.073	0.007
SOM	0.038	0.034	0.062	0.031
	0.034	0.041	0.076	0.037

Based on the silhouette scores reported in Table 4, the K-means clustering algorithm was found to return the best clustering results. The algorithm achieved a silhouette score of 0.094 when clustering the time series at SKU level. This improved clustering performance was expected at the highest level of aggregation of the original time series because clustering algorithms are typically sensitive to noise.

The clusters returned by the K-means clustering algorithm, equipped with DTW as distance measure, were also evaluated subjectively. Five time series were randomly selected from each time series cluster so as to allow for a visual inspection of the time series clusters. Figure 7 contains time plots of each of the five randomly selected time series, along with the barycentres of their associated clusters. These barycentres, more commonly referred to as cluster centroids, were computed in terms of DTW. All time series in the figure are scaled according to their mean values.

The time series in Cluster 1, depicted in the first time plot of Figure 7, exhibit long periods of zero sales followed by a strong increasing trend. This phenomenon may be due to social trends which rapidly influence the unit sales of products, or it may be attributable to newly introduced products which gain increasing acceptance amongst consumers.

The time series in Cluster 2, depicted in the second time plot in Figure 7, increase at a steady pace and show signs of seasonality as unit sales fluctuate annually (*i.e.* every 52 weeks). The large range of these time series is not indicative of everyday consumables. Instead, the time series in Cluster 2 may be associated with the unit sales of non-consumable high-value products, such as home appliances. These products are typically sold sporadically, either on promotion or at the end of the financial year when consumers tend to have money in hand.

As in the case of time series in Cluster 2, the time series in Cluster 3 depicted in the third time plot of Figure 7, exhibit unit sales of established products which are sold at a steady rate. The time series in Cluster 3 do, however, slightly increase over time. Furthermore, these time series fluctuate over a large range, suggesting that the unit sales of these products are sensitive to external factors. Generally, the unit sales of low-value consumable products, such as drinks and snacks, exhibit such behaviour as these products are sold at a steady rate while being sensitive to calendar days. Moreover, Cluster 3 exhibits signs of annual seasonality.

As in the case of time series of Cluster 1, the time series in Cluster 4 depicted in the last time plot of Figure 7, exhibit many leading zeros which represent a period of sporadic/intermittent sales. Thereafter, the time series assigned to Cluster 4 undergo a rapid increase which stabilises after approximately 100 weeks (*i.e.* two years). Generally, electronic products or products related to emerging technologies exhibit such behaviour.

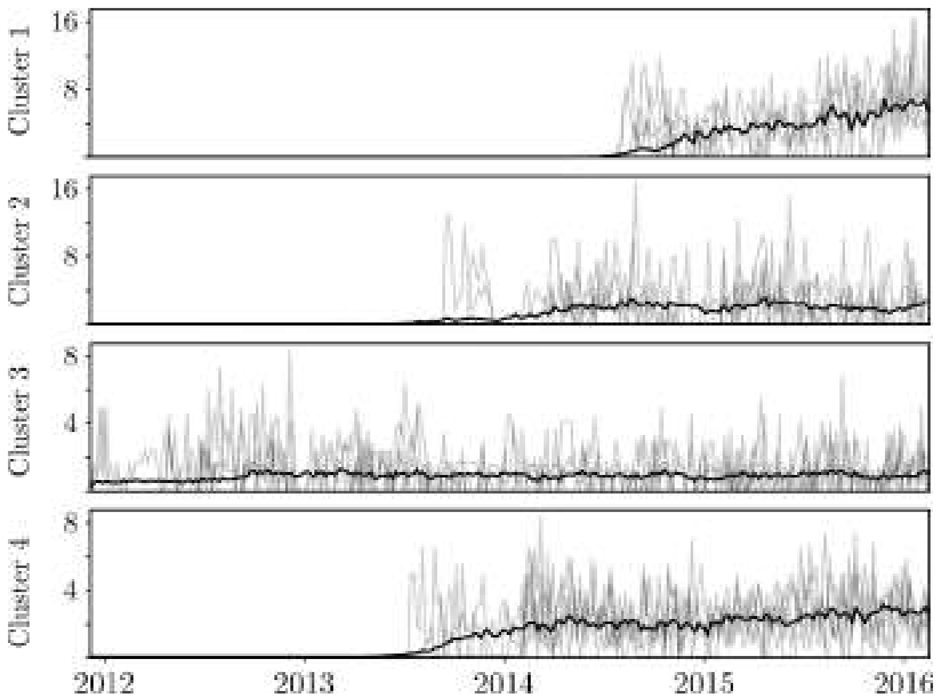


Figure 7: Time plots of the time series of the four best clusters returned by the K-means clustering algorithm equipped with DTW as distance measure.

4.2 Feature-based clustering

In order to initialise feature-based clustering methods, an appropriate feature representation of the time series had to be selected. Wang *et al.* [33] proposed the use of classical and sophisticated statistical features to describe the global characteristics of a time series. Table 5 contains a list of the features proposed for this purpose in the literature. In addition to the features proposed by Wang *et al.* [33], Makridakis *et al.* [34] also identified a number of statistical features relevant to time series data sets, such as intermittency, the squared coefficient of variation and the average inter-demand interval, which are well-known features for describing time series [35].

Table 5: Features used to evaluate feature-based clustering. Those denoted by asterisks are applicable to both the stationary adjusted and original versions of a time series.

Trend	Seasonality	Self-similarity
Intermittency	Average demand interval	Coefficient of variation
Chaos	Entropy	Non-linearity*
Kurtosis*	Skewness*	Serial correlation*

The features in Table 5 were calculated for each time series. In this manner, each time series could be expressed as a generalised set of features instead of its raw observations. This data-adaptive representation reduced the dimensionality of each time series in an attempt to improve upon clustering performance. Furthermore, the feature representations of the time series were also normalised to between zero and one in order to avoid any bias associated with the scale of a feature. Utilising the set of normalised features, representing the intrinsic characteristics of the time series, a distance matrix associated with the feature-based representations of the aggregated time series data set was calculated in terms of the Euclidean distance measure. This distance matrix was provided as input to the clustering algorithms considered above. The performances of the three clustering algorithms were subsequently evaluated in terms of the cluster validity criteria reviewed in Section 2.42.4.

Based on the results reported in Table 6, the K-means clustering algorithm would again seem to have returned the best clustering results (with respect to all three validity criteria). More specifically, the K-means clustering algorithm achieved a silhouette score of 0.256 when clustering a combination of all three levels of aggregation. Furthermore, Table 6 shows no clear relationship between the cluster quality and the number of time series provided as input to a clustering algorithm. This phenomenon suggests that clustering algorithms which employ a feature-based time series representation are less sensitive to noise than those which employ a shape-based time series representation.

Table 6: The clustering performances achieved by three clustering algorithms, with Euclidean distance as dissimilarity measure, when applied to a feature-based representation of a sample of the M5 data set.

Algorithm	Validity criteria	SKU/store (10 000)	SKU/state (3 000)	SKU (1 000)	Combined (14 000)
K-Means	SIL	0.191	0.215	0.227	0.256
	CH	2581	1052	383	4144
	DB	1.571	1.41	1.334	1.231

Agglomerative	SIL	0.141	0.168	0.193	0.168
	CH	2348	859	316	3030
	DB	1.756	1.578	1.471	1.498
SOM	SIL	0.176	0.136	0.179	0.184
	CH	2640	684	272	3687
	DB	1.651	1.743	1.715	1.644

As a final evaluation of the clusters returned by the K-means clustering algorithm on a feature-based time series representation, a *principal component analysis* (PCA) was performed in a bid to visualise the structure of the clusters graphically. More specifically, the PCA reduced the 16 features of Table 5 to two principal components. These components were used to represent the feature space as a two-dimensional scatter plot, shown in Figure 8. This PCA plot allows for the evaluation of the goodness of cluster structures by subjectively inspecting the clusters visually. In particular, reducing the dimensionality of the feature-based time series representation to two dimensions allows for the generation of a scatter plot diagram of the clusters in which within-cluster similarities and between-cluster separation can be analysed subjectively.

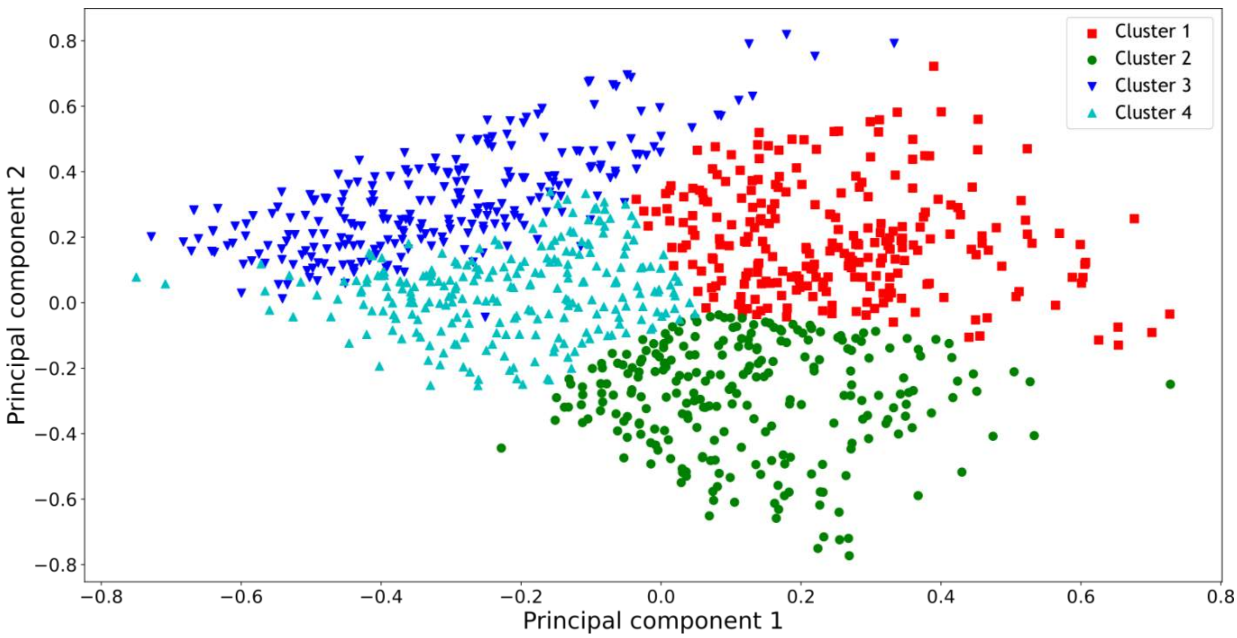


Figure 8: A scatter plot of the two-dimensional PCA feature representation of 250 time series from each cluster, illustrating the intrinsic structure of the clusters.

The clustering results obtained for both the shape-based clustering and the feature-based clustering approaches are comparable with those reported in previous empirical papers on the clustering of the time series in the M5 competition data set [36].

5 DISCUSSION AND CONCLUSION

When clustering time series of the unit sales of SKUs in the retail sector, shape-based clustering approaches are memory intensive and require a large storage space. Also, distance calculations are computationally expensive and distance measures are typically highly sensitive to distortions in the data. This sensitivity of shape-based clustering approaches may lead to the identification of clusters of time series which exhibit similar noise patterns rather than clusters which exhibit similar shapes.

Feature-based clustering approaches, on the other hand, are less sensitive to noise, because time series may be represented in a lower-dimensional feature space. Nevertheless, the clustering performance of a feature-based time series data representation is limited to the quality of the features selected for representing the characteristics of the time series in the input data set.

The hyperparameters of clustering algorithms should be selected meticulously so as to ensure the success of any clustering procedure, as clustering algorithms such as SOM are highly sensitive to the selection of hyperparameter values. Moreover, the selection of an appropriate distance measure for the computation of the distance matrix underlying a clustering algorithm is considered integral to the success of the algorithm.

Cluster validation, which involves the evaluation of algorithmic clustering results, is recognised as essential for the success of any clustering application [37]. The comparative analysis carried out in this paper between shape-based and feature-based clustering approaches involved the use of general validity criteria capable of quantifying clustering quality and identifying the best approach towards clustering time series of the unit sales of SKUs in the retail sector. Cluster validation was conducted in this paper by adopting two different approaches — *subjective cluster analysis* and *objective cluster analysis*. The parallel execution of subjective and objective cluster analyses allows for a comprehensive evaluation of clustering performance on unit sales of SKUs in the retail sector. More specifically, the objective cluster analysis sub-module in the methodology proposed in Section 3 supplements cluster analysis with a quantitative evaluation of cluster quality.

In order to avoid the potential of obtaining spurious clusters, it is important to follow a sound selection methodology carefully, facilitating the selection of an appropriate clustering approach for any particular input data set. This comparative study may aid a retail organisation in the selection of appropriate time series clustering approaches for grouping their SKUs together so that an efficient inventory managing strategy can be applied to each cluster.

As mentioned, the problem of selecting a single approach towards managing SKU inventories is common in real-world applications, where businesses have limited knowledge pertaining to expected demand. Such a lack of knowledge may influence their control over production and replenishment decisions. This may, in turn, affect the capital tied up in on-hand inventory and the cost incurred to maintain service levels [38]. The comparative study in this paper may fulfil a supplementary decision support role in addition to a retailer's greater inventory management solution approach. The usual range of application of such a comparative study may be extended by adopting a generic methodology towards selecting an appropriate SKU clustering approach.

Finally, the methodology proposed in this paper is applicable to a wide range of retail practitioners. The methodology proposed may, for instance, be applied to both *small and medium enterprises* (SMEs), on the one hand, and also to multinational retail corporations on the other.

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SIMULATION-BASED ASSEMBLY LINE BALANCING TO IMPROVE PRODUCTION EFFICIENCIES IN A RAILCAR MANUFACTURING COMPANY

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ABSTRACT

Line balancing is a useful strategy for increasing assembly line throughput while decreasing the bottleneck, improve smoothness index and the cycle time. In assembly line balancing the problem is to assign tasks to workstation along the production line optimally. This research work investigates alternative layout configurations with the aim of improving the production throughput, overall productivity and the utilization of resources. Firstly, the current production line is studied with the objective of identifying problem areas as well as areas of improvement. Data is then collected from a real case industry to be used in Discrete Event Simulation to evaluate the performance of the proposed layout configuration using Anylogic simulation. The Largest Candidate Rule and the Ranked Positional Weight methods are used to calculate the line balancing metrices. The results of the simulation model are used to make recommendations for the case industry.

Keywords: Assembly line balancing, Line Efficiency, Largest Candidate Rule, Cycle Time

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1 INTRODUCTION

The increase in demand for railcars in a South African tier 1 organization led to efforts to improve their production performance during production ramp-up phase. n any company, the production ramp-up phase is highly difficult to manage, especially when the operations are labor-intensive with frequent design modifications [1]. The setting of this research is the rail manufacturing organization, which has to adopt the localization strategy in their value chain, where local suppliers and tier 1 railcar company operators had to learn new skills. One of the challenges of production ramp-up is maintaining a new complex production system that operates as efficiently as possible while working through start-up-related issues [2].

Several innovative solution methodologies have been used to solve the line balancing problems. However, the feasibility of obtaining the similar or precise solution in a reasonable time from the traditional optimization techniques is limited to small sized problems. The computation time for obtaining a precise solution using conventional approach would possibly increase with an increase in problem size [3]. Assembly line balancing methods have been widely used in manufacturing industries to improve the utilization of resources and to improve throughput, however the use of these techniques has been rarely used in industries where there are high design cycle times (DCT) as well as high level of allocation constraints. The process of railcar manufacturing is characterized with high DCT and resource allocation constraints.

Assembly line balancing techniques has been found to be one of the most effective FLP drivers [4]. Assembly line balancing has a considerable impact on whether production objectives are successfully met [5]. The problem of not reaching the production target by the railcar manufacturing organization is categorized as the FLP as it was correctly identified during problem identification. This paper presents a logical way of eliminating bottlenecks by applying line balancing algorithms in an environment where there are fractional tasks.

Common problems with assembly lines are the balancing as well as sequencing of operations or tasks [6]. In this paper, the issue is to balance the underframe production line which involves the planning of the configuration of assembly line so that the required production target is met.

2 PROBLEM IDENTIFICATION

The first phase in the proposed methodology is problem identification. Problem identification is a very important step in any problem-solving initiative. It is crucial to critically evaluate the problem so that the real problem is dealt with and not just the symptoms. This process begins by gathering preliminary information from the broadly identified area of concern followed by a specific data collection process.

The focus of this study is the underframe line with the main aim of improve the line so that it can ultimately achieve the targeted production plan. The current layout of the underframe is divided into four main sections as it is illustrated in figure 1 which is the layout of the underframe production line. CBS1080 consist of four jigs which are labelled jig 1, 2, 3 and 4 as per figure 1. CBS1070 has two jigs which are CBS1070A and CBS1070B followed by CBS1140 and CBS1150 respectively. CBS1140 and CBS1150 has technological constraints zoning constraints due to the number and type of welds done as well as the amount of the space these jigs occupy.

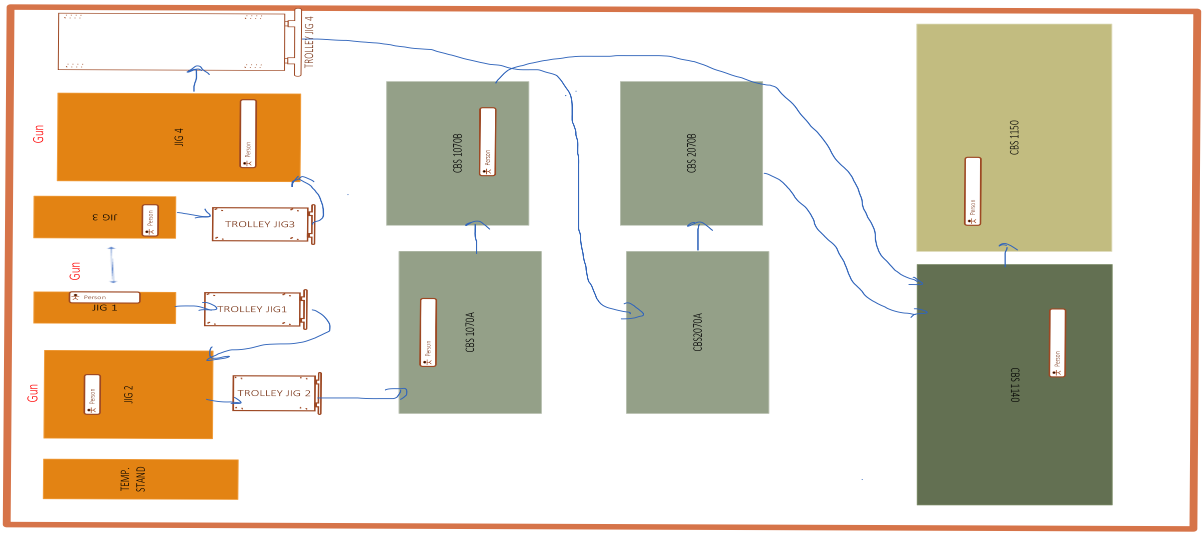

Figure 1: Exploded view of the underframe line

Figure 2 offers a clear presentation of method times in hours required to produce the main components of a railcar in the Car Body Shell section. It is evident that the underframe line is a constraint in the section as it accounts for more than 40% of the total time to manufacture the complete unit.

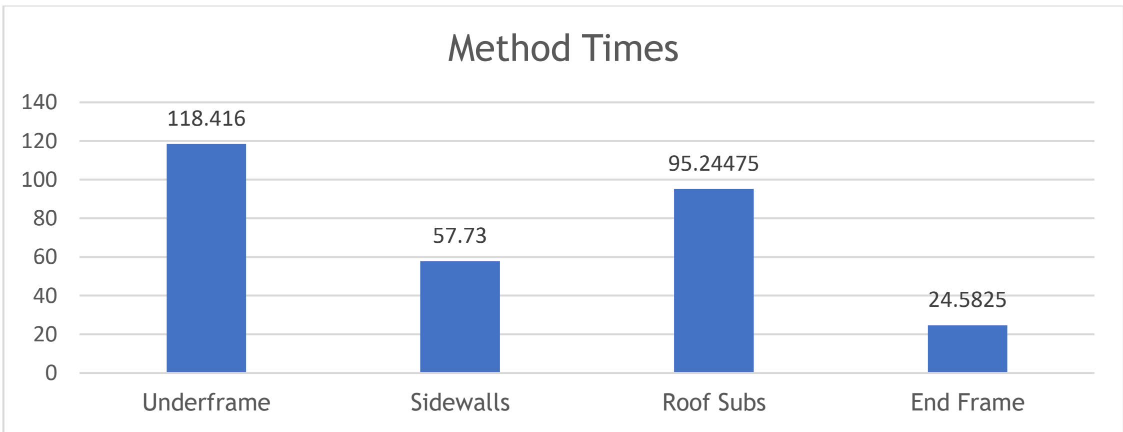

Figure 2: Car Body Shell method times

Figure 2 clearly indicates that the workload in the underframe line is a serious constraint in the production process of the car body shell. Therefore, there is a need to find a solution to this problem as this could directly affect the productivity of this line. The workload is not evenly balanced. To achieve this target, the company resorted to double shifts and overtime for the operations with excessive workloads, which ultimately increase the operational costs and reduce the profit margin. This bottleneck causes a slew of issues for the railcar manufacturer since it skews production targets, thus resulting in customer penalties.

Based on the assessment of the challenges faced in the underframe production line, it could be suggested that the improvement that is required could be solved by improving the layout configurations in the underframe line.

To address the performance challenges faced by the manufacturer, various drivers of productivity are identified and applied. The investigations and analysis of production data show that the main problem in this line is the low efficiency and poor utilisation of resources. Therefore, productivity improvement techniques such as line balancing, simulation and layout design optimisation were deemed to be suitable for improving productivity and to improve the production throughput.

The cycle time, number of workstations and task precedence relations are the main constraints for an assembly line balancing problem (ALBP) [7]. However, a number of other restrictions may be present in actual production systems as a result of organizational and technological constraints. Table 1 depicts the activity and the design cycle times involved in producing a complete underframe.

Table 1: Underframe line work allocation

Workstations	Assembler	Code	Method Time(hrs)	Number per car	Total time per part (hrs)
CBS1080 Jig1	A1040	A	0,9	4	3,52
CBS1080 Jig1	A1018	B	0,9	2	1,76
CBS1080 Jig1	A1020	C	0,9	4	3,52
CBS1080 Jig1	A1024	D	0,9	2	1,76
CBS1080 Jig3	A1146	E	0,66	2	1,32
CBS1080 Jig3	A1010	F	0,634	12	7,62
CBS1080 Jig3	A9375	G	0,66	2	1,32
CBS1080 Jig2	A1014	H	1,53	2	3,08
CBS1080 Jig2	A2078	I	1,28	2	2,56
CBS1080 Jig4	A4105	J	1,68	1	1,68
CBS1080 Jig4	A1006	K	1,68	1	1,68
CBS1070A	A6353	L	27,45	2	27,45
CBS1070B	A6353	M	27,45	2	27,45
CBS1140	DT7201	N	15	1	15
CBS1150	DT72012	O	19,75	1	19,75

3 LITERATURE REVIEW

Line balancing is an effective tool to improve the throughput of an assembly line while reducing bottleneck and cycle time [8]. Assembly line balancing is the process of allocating tasks to workstations in such a way that the overall time spent at each workstation is approximately the same [9]. Assembly line balancing is the problem of assigning tasks to workstations along the production line with the main objective of minimizing the number of workstations and maximizing production output [10]. Assembly lines are common in today's manufacturing and production systems and have been around for a while [11]. In an assembly process, parts and subassemblies are combined to create the finished product [12]. Assembly is one of the most economical methods for producing a wide range of products, such as in railcar production and automobile production. Assembly lines were originally intended for cost-effective mass production sectors of standardized products [13]. An assembly line is a manufacturing process where components are added to (or operations are performed on) in succession as they pass by workstations in accordance with a predetermined sequence [14].

There are basically three type of assembly lines. Single-model assembly line (SMAL) also named A simple assembly line (SAL), which is a production system that consist of several workstations producing one model [6,15].

Multi-model assembly line is used in advanced lean organizations because of their flexibility and most of the extant literature on how to staff assembly lines focusses on either single-model or mixed-model lines [14]. In a mixed model assembly line (MAL) various models of the same product are produced in the same production line [6]. A mixed-model assembly line is a cost-efficient and flexible production system employed to obtain efficient production flow [16]. According to [17] in manual assembly line balancing problems good results are achieved by the LCR, KWM and the RPW methods because: 1) methods are heuristic, meaning that they are based on common sense and experimentation rather than mathematical optimization; 2) the total work required to assemble a product can be divided into small elements; it is technological impossible or economically infeasible to automate the assembly operations.

The Kilbridge and Westercolumn method (KWC) and the Largest Candidate Rule method (LCR), are used to improve the efficiency of the line by reducing the number of workstations and, consequently, the balance delay [18]. To increase efficiency and reduce bottlenecks, organizations use the Largest Candidate Rule (LCR), the Kilbridge and Western Method (KWM) and the Ranked Positional Weight (RWP) methods [19]. According to [20] the RPW is a technique used to find out how to synchronize the sorting of workstations at a time of limited data availability and it presents precise results than other methods.

The balancing efficiency (Eb) or line efficiency (LE) is two other important measure that deals with the fact that it is virtually impossible to get a perfectly balanced line. Balancing efficiency is an indicator that measures the quality of the allocation of work elements to workstations, which has an impact on increasing production levels [21]:

$$\boldsymbol{E_b = \frac{T_{wc}}{wT_s}} \quad (1)$$

The higher the balancing efficiency the better. The complement of the balance efficiency is balance delay, which indicates the amount lost due to imperfect line balancing as a ratio to the total available time; that is:

$$\boldsymbol{d = \frac{(wT_s - T_{wc})}{wT_s}} \quad (2)$$

Another important measure in assembly line balancing is the smoothness index (SI) which is used to measure the distribution of working time between the working hours in the assembly line. The smaller the smoothness index number, the smaller the working time fluctuation between the working stations of the assembly line, the better the balance effect [22]. This index indicates the relative smoothness of a given assembly line balance. A smoothness index of zero indicates that the production line is perfectly balanced [23]. The formulae used to calculate SI is:

$$\text{SI}= \sqrt{\sum_{i=1}^{k}(ST_{max} - ST_i)^2} \quad (3)$$

Where, ST_{max} is the maximum station time (in most cases it is the cycle time),

ST_i is the workstation time. The smaller the SI for the line the better. Table 2 indicates the summary of literature conducted on key line balancing techniques.

Table 2: Summary literature on assembly line balancing techniques

Authors and date	Title	Algorithms used	Industry	Findings
[10]	Line Balancing Techniques for Productivity Improvement	RPW and LCR	Garment industry	Line efficiency improved from 70% to 77%. The study found that the RPW method was better than the LCR. The results show the effectiveness of the two methods in improving line efficiencies.
[14]	Balancing Workload and Workforce Capacity in Lean Management: Application to Multi-Model Assembly Lines	Integer Linear Programming	Cell phone manufacturing	A novel approach to compute the necessary workforce in manual assembly systems is developed and applied to multi model assembly line following the principles of lean management.
[24]	Assembly line balancing with fractional task allocation	Mixed integer programming model	Not mentioned	Fractional task allocation can often allow better resource utilization with relatively low costs
[25]	Assembly line balancing using genetic algorithm method to minimize the number of workstations: A case study in car manufacturing	Priority rule-based methods (PRBMs) and Genetic Algorithm	Automotive	Line efficiency improved from 85% to 92%. Balance delay decreased from 15% to 8%.
[21]	Mixed-model assembly line balancing in the process of assembling trimming area to minimize workstation using RPW-MVM method	Rank Positional Weight-with moving target (RPW-MVM)	Automotive	Allocation constraint added due to machine restrictions that cannot be moved. There was a reduction from 15 to 14 workstations as well as an increase of line efficiency from 70% to 88% in line efficiency.
[26]	Use of ranked position weighted method for assembly line balancing	RPW	Cashew nut shelling machine production	The results show a decrease in the balancing delay and the smoothing index.

Table 2 (continued): Summary literature on assembly line balancing techniques

Authors and date	Title	Algorithms used	Industry	Findings
[17]	Application of line balancing heuristics for achieving an effective layout: a case study	LCR KWM RPW	Garment industry	RWP improved productivity significantly. Line balancing efficiency increased from 38% to 84%. Manpower reduced from 62 to 54.
[18]	Efficiency improvement in the assembly line with the application of assembly line balancing method	RPW KWM	Excavator manufacturing	Line efficiency improved from 71% to 77%. This study is very relevant to this study due to the size of the product in question.
[27]	Improvement of garment assembly line efficiency using line balancing technique	RPW	Garment industry	RPW produces a well-balanced assembly line with higher line efficiency when there is no consideration of resource constraint in a workstation.
[28]	Line balancing analysis by using Ranked Positional Weight	RPW	Not Mentioned	Balancing delay reduced from 68% to 62.7%.
[29]	Implementation of Ranked Positional Weight method for a double-sided assembly line balancing problem	RPW	Automotive	Line efficiency increased from 86% to 92% and workstations decreased from 17 to 16.
[30]	Assembly line balancing with method ranking positional weight: Case Study XYZ Company	RPW	Not indicated	The results show a decrease in the balancing delay and the smoothing index.
[26]	Use of ranked position weighted method for assembly line balancing	RPW	Cashew nut shelling machine production	Line efficiency improved from 70% to 77%.
[31]	A comparative study of largest candidate rule and ranked positional weights algorithms for line balancing problem	LCR RPW	Electronic and Food industry	Balancing delay reduced from 68% to 62.7%.
[32]	Branch, bound and remember algorithm for two-sided assembly line problem.	BBR	Not mentioned	Smoothing index reduced from 8.22 to 5.19. line efficiency improved from 58.9% to 85%.
[33]	Design of mixed-model assembly lines integrating new energy vehicles	Mixed integer programming	Automotive	Line efficiency increased from 86% to 92% and workstations decreased from 17 to 16.

Figure 3 presents the summary of ALB algorithms used in the literature from 2013 to 2021. The results show that RPW is the most popular method followed by the LCR.

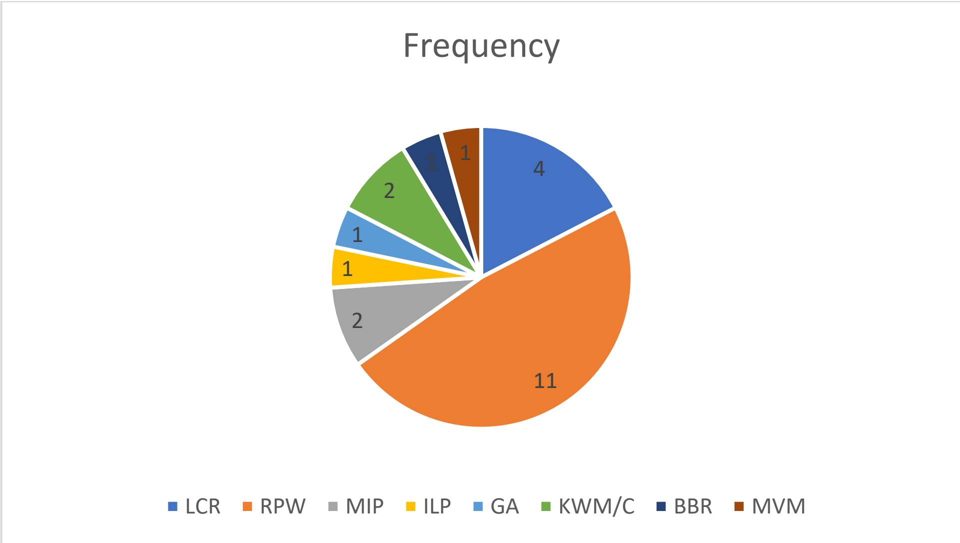

Figure 3: Summary of line balancing algorithms used in literature

Out of the 16 articles presented in the table indicated that line balancing efficiency, balancing delay and smoothing index could be improved substantially. The articles present the use of a single technique or two techniques as in the case of [10] where RPW and LCR are used in the same study. The results demonstrate that the use of RPW and LCR provides the basis for some improvements on the production line hence they are the preferred methods for line balancing activities.

4 METHODOLOGY

To achieve the objectives of the study, problem analysis is conducted in order to eliminate waste in the underframe production process. The study was quantitative in nature. Production data which was in the form of historical data from the production records of the company such as the manufacturing information system and standard operation procedures was collected. The production process was observed for several days to establish the facts and the reasons why the underframe line was not achieving its desired output or production set targets. Thereafter, the RPW and the LCR was used with the aim of increasing the line efficiency, productivity, reduce idle time, increase the utilization of resources, minimize bottlenecks and ultimately achieve the production target.

4.1 Simulation of the current production line

Once the problem and the collection of the data for the current production system, a simulation model was built which represent the un-balanced production line. The DES model was built as a representation of the actual underframe line. It was identified as the ideal method for the modelling and optimisation of the underframe layout. Anylogic software was used to develop the models. Figure 4 represents the model of the current underframe production line.

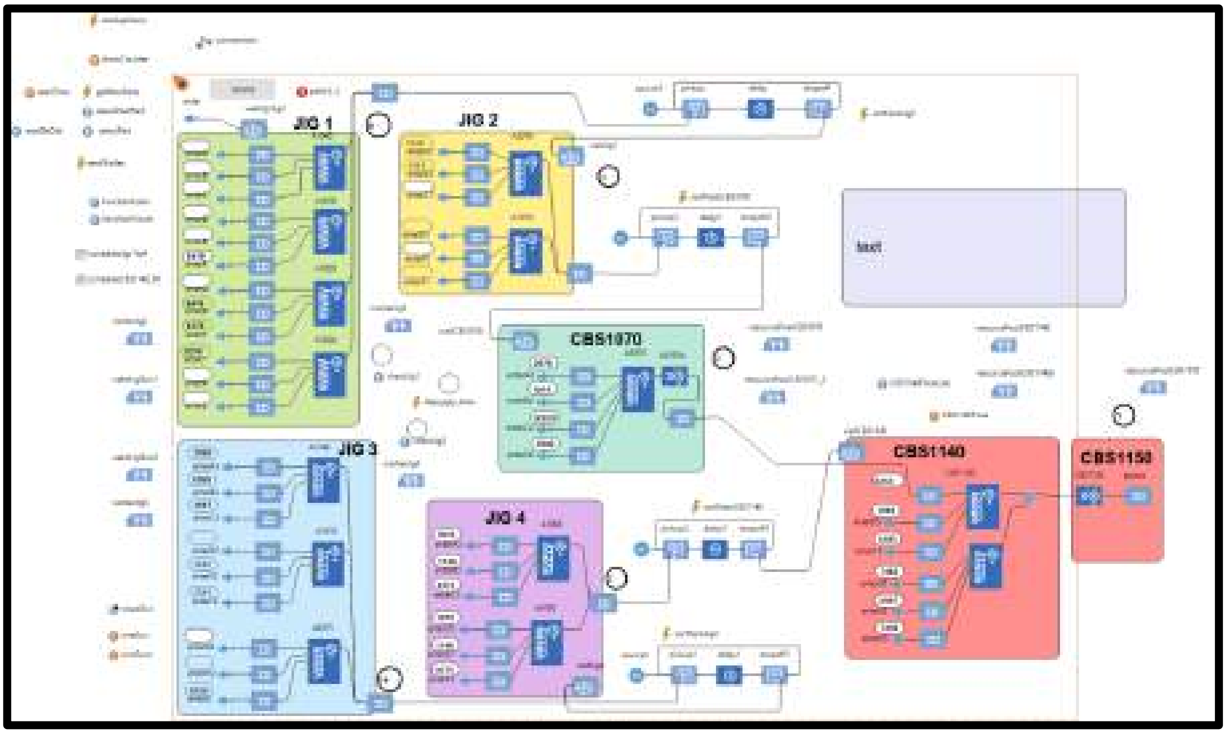

Figure 4: Simulation model for the current production system

4.2 Line balancing algorithms

The main aim of this research is to balance the underframe production line by using RPW and LCR. In most studies the minimization of the number of workstations is the most common goal in line balancing. However, for this research other means such as the doubling or increase of workstations where bottlenecks are experienced and the use of common jigs were resources are underutilized was considered to be the most effective way to improve the efficiency and the balance delay. Figure 5 show the technological precedence diagram for the assembly of an underframe. The nodes represent the tasks or products to be assembled as well as the method time required as shown in table 1.

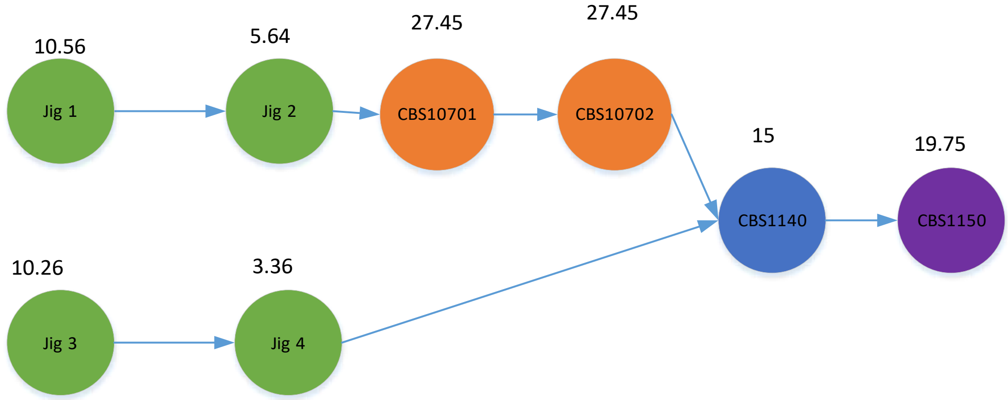

Figure 5: Precedence diagram for the operations

The following are some work processes or operations that have allocation constraints includes:

1) Products A, B, C and D must be processed in jig 1
2) Products E, F and G must be processed in jig 3
3) Product L and M must be processed in jig CBS1070

4) Jig CBS1140 and CBS1150 cannot be moved due to the excessive relocation costs that could be incurred

Operations A, B, C, D are processed in jig 1, whilst operations E, F, G are processed in jig 3. These two jigs share a welding gun which means that the problem we are dealing with has got an element of fractional task allocation or work sharing. The current process is scheduled in a manner that jig 1 with assemble the first crossbeam then pass the welding gun to jig 3 to assemble the first crossbeam. The jigs will alternate as such until all work is completed. This arrangement is limited in that it creates a lot of idle time between the two jigs. Summarized drawbacks of the AS IS process

1) Sharing of resources which results in excessive idle time.
2) Low level of productivity leading to missing production targets delivery dates.
3) Underutilization of resources due to unevenly distribution of work.

Table 4 provides the results of the assignment of the tasks to workstations by using the Largest Candidate Rule method for the current underframe line. The line balancing of the current layout is based on the following calculations:

Total sum of the work content= 118.41hours

Highest Cycle time($\boldsymbol{T_s}$)= 27.45 hours

Number of workstations = 8

Balance delay =$\boldsymbol{d} = \frac{(\boldsymbol{wT_s - T_{wc}})}{\boldsymbol{wT_s}}$
= (8*27.45)-118.41/8*27.45
d=0.46079

Line efficiency (Eb) = 118.41/8*27.45 or 1- 0.46079=53.92%

Possible reasons for high balance delay:

1) The line has a wide range times for the work elements. This is the case for the underframe line as workstation times range from the maximum of 27.45 hours to just below 10 hours. 2) There is also a large amount of inflexible line mechanisation and automation. In the underframe line, all the activities are performed manually by welders without any automation. This has to do with the strategic goals of the organisation which have their main objective as the creation of employment. The automation of activities in this line might mean that fewer workers would be required for this line. If a welding robot was an alternative in some of the welding stations, then the cycle time could be drastically reduced and ultimately reducing the balancing delay 3) Indiscriminate choice of cycle time. The cycle time is basically the expected output from the system or production line. The cycle time for a production line is based on the demand of the specific product. Therefore, in this case, the cycle time will depend on production demand determined by the client.

Table 4: Initial line balancing results with LCR

WORKSTATIONS	JIGS	Task	Preceded by	Work Content	Available time
CBS1080	Jig1	A	none	3,52	23,93
		C	none	3,52	20,41
		B	none	1,76	18,65
		D	none	1,76	16,89
	Jig3	F	none	3,66	23,79
		E	none	1,32	22,47

		G	none	1,32	21,15
	Jig2	H	A, B, C	5,94	21,51
		I	A, D	2,56	18,95
	Jig4	J	E, F, G	1,68	17,27
		K	E, F, G	1,68	15,59
CBS10701	Jig A	L	H, I	27,45	0
	Jig B	M	L	27,45	0
CBS1140	Jig A	N	M	15	12,45
CBS1150	Jig B	O	N	19,75	7,7

Table 5 provides the results of the calculated Positional weight for each task and its relative ranking.

Table 5: Rank Positional Weights

Sections	Workstation/Jigs	Code	Method Time(hr)	RPW	Ranking
CBS1080	Jig 1	A	3,6	95,81	3
		B	1,8	97,09	2
		C	3,6	98,89	1
		D	1,8	94,01	5
	Jig 3	E	1,32	37,75	10
		F	7,62	44,05	9
		G	1,32	37,75	11
	Jig 2	H	5,64	95,29	4
		I	2,56	92,21	6
	Jig 4	J	1,68	36,43	12
		K	1,68	36,43	13
CBS1070	Jig A	L	27,45	89,65	7
	Jig B	M	27,45	62,2	8
CBS1140	Jig A	N	15	34,75	14
CBS1150	Jig B	O	19,75	19,75	15

Table 6 is the task loading for workstations when the ranked positional weight method is used for the current assembly line.

Table 6: Task Loading for Workstations

Sections	Workstation/Jigs	Task	Time
CBS1080	1	C; A; B; D	10,56
	3	F; E; G	10,26
	2	H; I	5,64
	4	J; K	3,36
CBS1070	A	L	27,45
CBS1070	B	M	27,45
CBS1140	A	N	15
CBS1150	B	O	19,75

The balancing delay, line efficiencies and the smoothing index for the LCR and RPW are:

Balance delay=0.46079

Line Efficiency = 1-0.46079=53.92%

The SI of the current line is 43.024, which is much more than the desired index of ≤ 10. This is an indication that the line is not perfectly balanced as confirmed by the line efficiency of 53.92%.

5 PROPOSED LAYOUT

The Systematic Layout Planning (SLP) methodology by Richard Muther was used to generate layout alternatives with the aim to find a layout design that could improve productivity. The methodology allows for the design of alternative layout configuration that are then evaluated with the main objective of selecting the best layout. The proposed layout for this production line is depicted in figure 6. This layout is based on the concept will improve line balancing metrics of balancing efficiency as well as reducing the cycle time for workstation CBS1070. The suggestion to have a dedicated gun in jig 1 and jig 2 will ensure that the utilization of the resources in these two jigs is improved. This concept represents a scenario that seeks to duplicate CBS1070, then introduce a new jig that will replace jigs two and jig four. This layout configuration will create more space that will increase the efficient flow of products and increase the overall utilisation of the resources in workstation CBS1070 and merge jig 2 with jig 4 in CBS1080 with the allocation of additional space requirements. This option will also mean that one welder will be assigned to the newly suggested merged jig, saving one welder and the welding gun.

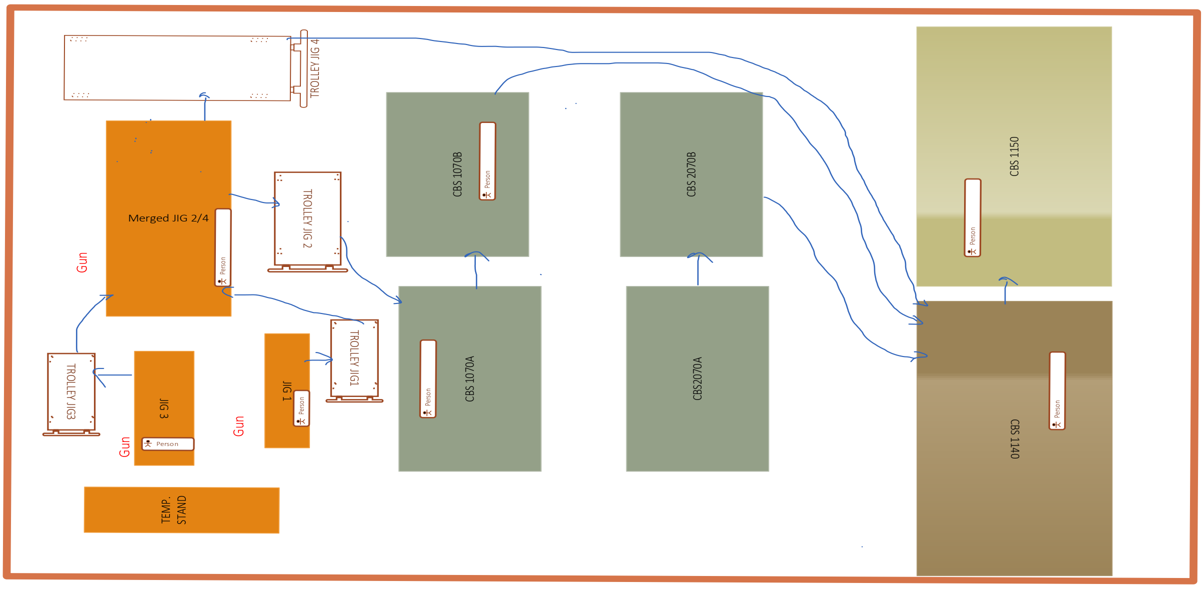

Figure 6: Proposed Layout

The adding of the welding gun was just the first step in improving the balancing efficiency of the line. Figure 7 presented the distribution of the workload for the underframe line, which clearly indicated that the workstation CBS1070 was a bottleneck station.

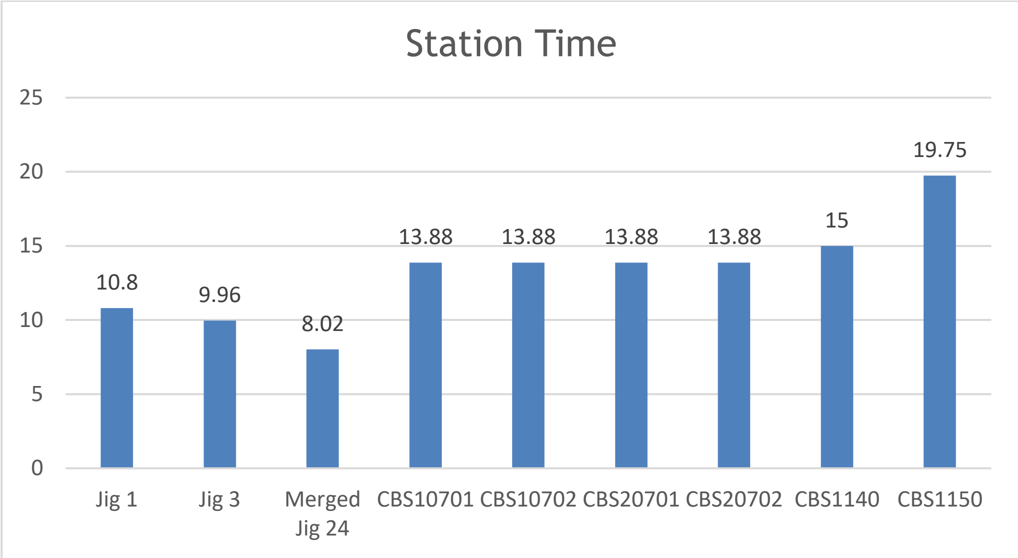

Figure 7: Distribution of work after more changes

To achieve a much more balanced workload amongst the workstations, the capacity of the identified bottleneck was doubled so that the workflow could be improved. Considering the initial work distribution, jig 2 and jig 4 were found to have been under loaded when compared with jig 1 and jig 3. Therefore, the proposal was to merge these two jigs so that the workload could be evenly balanced as indicated in figure 8.

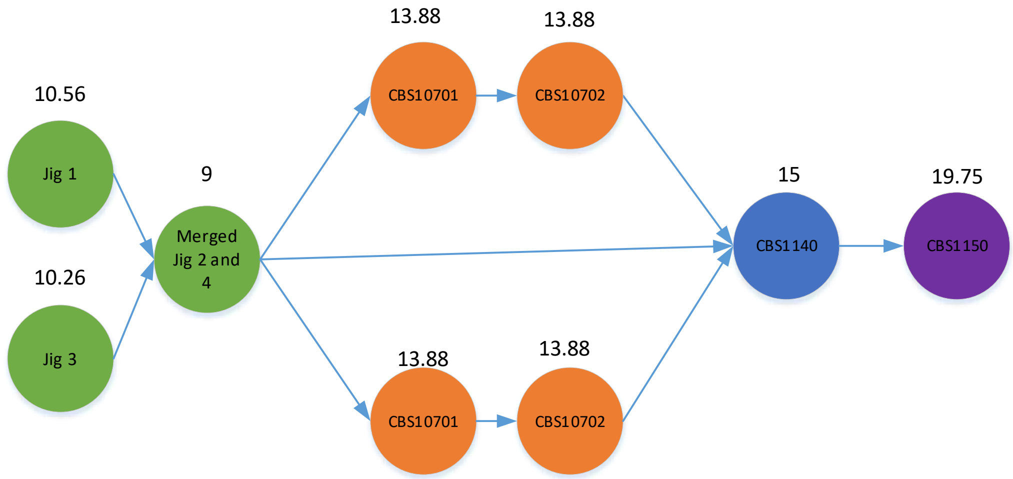

Figure 8: Precedence diagram after improvement

Table 7 shows the line balancing results after improvements based on the LCR method.

Table 7: Line balancing after improvements

WORKSTATIONS/JIGS	Task	Preceded by	Work Content	Available time
CBS1080 Jig1	A	none	3,52	16,23
	C	none	3,52	12,71
	B	none	1,76	10,95
	D	none	1,76	9,19
CBS1080 Jig3	F	none	3,66	16,09
	E	none	1,32	14,77

	G	none	1,32	13,45
CBS1080 Jig2/4	H	A, B, C	5,94	13,81
	I	A, D	2,56	11,25
	J	E, F, G	1,68	9,57
	K	E, F, G	1,68	12,13
CBS1070A	L	H, I	13,88	5,87
CBS1070B	M	L	13,88	5,87
CBS2070A	L	H, I	13,88	5,87
CBS2070B	M	L	13,88	5,87
CBS1140	N	M	15	4,75
CBS1150	O	N	19,75	0

Table 8 shows the SI computed after the suggested improvements.

Table 8: Smoothing index after improvements

Jig	ST_i	$(ST_{max} - ST_i)^2$
1	10.56	84.46
2/4	5.64	115.56
3	10.26	90.06
CBS1070A	13.88	34.46
CBS1070B	13.88	34.46
CBS2070A	13.88	34.46
CBS2070B	13.88	34.46
CBS1140	19.75	0
CBS1150	15	22.56
SUM	119.47	450.47
SI		21.39

After some improvements were introduced into the line, the SI improved from 43.024 to 21.39, an improvement of 50.28%. This improvement is attributed to changes in the cycle time. The number of workstations increased from eight to nine.

Table 9: Comparison of before and after improvements

Parameter	Before Improvement	After Improvement
Number of workstations	8	9
Line efficiency	53.92%	66.6%
Smoothness index	43.024	21.39
Balance delay	0.46079	0.38376

6 SIMULATION MODEL AFTER IMPROVEMENTS

The final phase in this study was to develop a simulation model that represent the production line after improvements, which is the simulation of the balanced production line. The improvements suggested in the production line included having a dedicated welding gun to jig 1 and 3 as well as merging jig 2 and 4 to ensure that the workload is evenly balanced. The simulation model shows great improvements from the current system with reduced bottlenecks. The improvements include increased production output and utilization of resources.

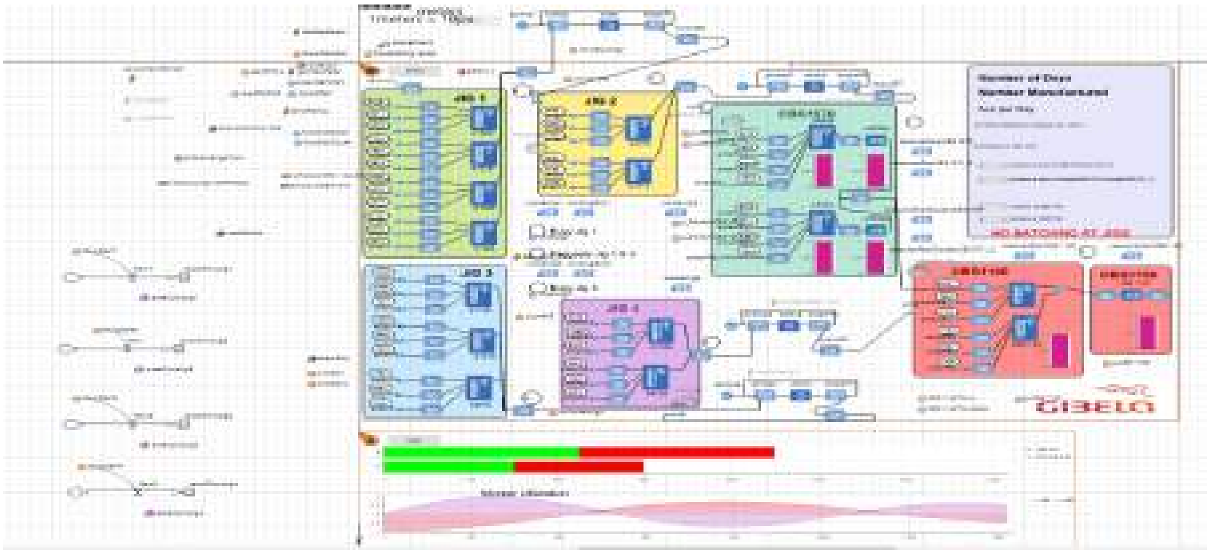

Figure 9: Simulation model after line balancing

The simulation results based on the before and after improvement is depicted in table 10.

Table 10: Simulation results for the non-batching model

Alternatives	Before	After
Operators	12	20
Production output	288	567
Productivity	24	28.35
Utilization	57.75	69.44
Production Rate	0,79	1,55

7 CONCLUSION

Based on the analysis of the results it evident that the proposed layout resulted in improved productivity. The RPW and the LCR were then used to evaluate key performance measures such as line efficiency and balancing delay. The line balancing results from the two heuristics methods resulted in a more efficient assignment of tasks and an improvement of line efficiency from 61% to 66.6%. The balancing delay was also reduced from 46% to 38% with as well as a reduction from 43 to 21 in smoothness index. This study also gives credence to the fact that line balancing is also possible even when the product in question comprises of high method times with significance constraints and restrictions in the allocation of tasks due to higher costs involved in making changes to the AS IS layout configurations. The improvement suggested lead to improvements in other metrics such as productivity, utilization of resources as well as line balancing metrics. The proposed changes show an improvement from 288 to 567 in production output as well as an increase from 57.75 to 69.44 in utilization.

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THE EFFECT OF MULTIPLE TEAM MEMBERSHIP VARIETY OF TASKS ON COORDINATION OF WORK: A CASE WITHIN THE TRAINING AND DEVELOPMENT SECTOR IN SOUTH AFRICA

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ABSTRACT

Multiple team memberships (MTM) can affect the coordination of variety of tasks as the amount of work increases. The study aimed at identifying the relationship between MTM task variety and coordination of work. Trust, job autonomy and centralised systems were proposed as moderators that would have positively improve the relationship between MTM variety of tasks and coordination of work. The study was conducted within the training and development industry where 102 respondents participated the online survey. The result showed a positive effect of job autonomy on implicit coordination however job autonomy negatively moderated the relationship between task complexity and implicit coordination and explicit coordination. The use of centralised systems was partially proven as Integrated System Enablement and Initiated Interdependence show a positive interaction effect to explicit coordination. It is recommended that further attention is given to centralisation of data and management thereof together with the increased use of technology.

Keywords: Multiple Team Membership, Task variety, Task complexity, Interdependence, Coordination of work.

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1 INTRODUCTION

Van De Brake, et al. [1] describe the Multiple Team Membership (MTM) as the number of active and simultaneous memberships that one individual holds. This is further determined by the working time allocated within a certain period for each team membership that the individual holds. Being part of more than one team at a time has its own complexities. Involvement of team members in multiple teams results in their tasks becoming reasonably varied which in turn allows them to learn from each other's practices and experiences [2]. Organisations are no longer utilising individual members for one specific role, changing individual memberships, and adapting their function to new organisational demands. Members need to become very dynamic and have the ability to self-configure and adapt to new organisational requirements. This is known as a multi teaming phenomenon meant to support the organisations to cut resources slack and improve work efficiencies or resource utilisation [3]. Multiple project team membership are composed by individuals that are simultaneously involved in more than one project team [5]. Project teams have taken a different shape with their nature changing over time which are now being seen as dynamic systems with penetrable boundaries [4]. This phenomenon is more and more prevalent in organisations and has become significant across many disciplines [6].

When the membership in multiple teams increases the role strain for that individual also increases, which in return can impact the individual well-being [10]. Therefore, careful allocation of tasks in line with specific members' expertise will be required while keeping and maintaining clear team focus. The allocation of a range of different activities to perform the job at hand characterised by the degree to which they need to be performed is defined as task variety [9]. This involves the usage of diverse skills and aptitudes of a specific individual. On the other hand, an individual requires to demonstrate ability to constantly shift between tasks and prioritise. Coordination of independent tasks within a different and dynamic team environment could present a challenge for that specific member since the attention may be only partially allocated to the task [3].

MTM takes place at multiple levels and therefore there are many factors that could have a positive or a negative effect on member belonging to a multiteam environment. Increased involvement in multiple teams can contribute to learning [5], task mastery as well as network opportunities. Van De Brake, et al. [1] argue that MTM can be perceived by some individuals as a positive challenge while others may appraise it as a hindrance not being sure of how to do the work. This individual perception and evaluation, be that positive or negative could impact the job performance and absenteeism. This could further impact on the coordination of work of the other members' that hold the same team membership. Coordination can be thus defined as the accomplishment of organised effort by the group while attained in unity of action for the same common purpose [11].

Within a multiple team environment coordination needs between different teams are created by two forces, one related to task interdependencies and a second related to changes that can occur during development process. Teams' inputs depend on other teams' outputs to enable completion of their own specific tasks. Timing and synchronisation of activities are therefore critical to effectiveness of coordination of work. The second force relates to changes which characterise innovation. In innovative work, coordination is affected by potential changes that arise from fine tuning or collaboration with other teams requiring adjusting of the initial planning [12]. Many individuals are more and more involved across different teams making the need for coordination of tasks even more relevant to sustain an efficient delivery of the job at hand. Lack of coordination of work between teams results in a non-fit for purpose result and potential rework. This in turn results into work pressure, mistakes, and crises.

There is however limited research conducted regarding potential implication at individual levels and their ability to coordinate work as their multiple team membership variety of tasks increases. Matthews, et al. [3] indicated that multiple team which appears complex for the individuals were successfully managed through productive collaborations which could compensate for the added demands. It was further suggested that future research could look into the types of relationships that can occur between different collaborations and potential productive combinations. Teams with increasing task variety also have higher demands on coordination of activities.

The relevance of this research was driven by the desire to find a good balance between MTM variety of task and coordination of work. It was further sought to identify specific factors that could contribute to a more effective coordination of work while variety of tasks increases. The research objectives were to firstly investigate the relationship between execution of different tasks and coordination of work and secondly to identify the moderating factors that could improve the relationship. These objectives led to the following research questions:

1. Q1: What is the impact of MTM variety of tasks on coordination of work?
2. Q2: What are the enabling factors that will support / improve the relationship between MTM variety of tasks and coordination of work?

2 LITERATURE REVIEW

2.1 Understanding Variety of Tasks within MTM Context

2.1.1 Task Variety

Variety within the MTM context can be measured across a number of variables such as team tasks, locations, technologies, relationships, roles, backgrounds and so forth [7]. A common element prevailing in MTM structures is task variety. When a job environment requires an employee to perform a wide range of tasks it is known as task variety [13]. From an interaction and individual effort perspective three types of tasks can be identified. Individual, or personal tasks which are performed by a specific individual but not contributing to a group effort; activity tasks which contribute to teamwork but are performed by a specific individual within his or her individual time and don't require interaction with any other team members and group tasks which require to be performed in a coordinated manner by a group of individuals. These collective efforts will contribute to the delivery of the group work and requires high level of coordination between different members [14]. According to Zoethout, et al. [15] a task is comprised of multiple actions which requires skills to enable its performance. Task variety is seen as a job characteristic that enhances knowledge in the workplace [16] which is positively related to performance as well as job satisfaction [17]. Variety of tasks in a work situation provides the individuals with opportunities of engaging in creative thinking and explore different methods of work [18]. Research conducted by Morf, et al. [19] suggests that a low variety of tasks performed by an individual is negatively related to the counterproductive work behaviour which could contribute to dysfunctional behaviours for organisations. The opposite is true. This is supported by the findings of the study and emphasises that employees are more likely to be stimulated in a work environment where they are exposed to a higher variety of tasks. A higher range of task variety can contribute to employees using a different set of skills and job content and it can decrease repetitiveness of work, therefore higher variety positively affects learning [7].

2.1.2 Task Complexity

Task performance may vary from a difficulty level in such that an individual can be involved with complex tasks or simple tasks. It is argued that the higher the difficulty or complexity of a task the higher skills level of an individual is required, simply because the task will be mentally more challenging and demanding to perform [16]. Research conducted by Basoglu, et al. [20] suggested that the higher the task complexity the higher the anxiety to perform when the individual was not exposed to similar complexities before. Performing a task for the first time normally requires more effort. The difficulty level in performing a task is determined by the following different dimensions: (1) tasks with dynamic features – where information changes continually and requires the individual to continuously engage in understanding it; (2) tasks with static features; (3) simultaneous tasks; (4) sequential tasks; (5) level of task novelty. All these dimensions could impact the difficulty in performing a task and therefore its complexity level [21]. A positive correlation between the order of task complexity and cognitive load was found by Basoglu, et al. [20] suggesting that an individual will perform better due to experience gained from pervious task accomplishment hereby reducing anxiety when moving to a more difficult level.

2.1.3 Task Interdependency

Task dependencies arise as different tasks are performed by different members of the team and the input from one becomes the output for another for work to progress or vice versa. It is also possible that individuals are responsible for different portion of a particular task, and they require to interact to achieve the final output. Task interdependency is therefore defined as the degree of interaction between different team members to achieve completion of specific activity task through coordinative action [22]. It therefore reflects the level of "connectedness" of one activity to another. Two different forms of interdependence can be observed: (1) initiated and (2) received. The former relates to the workflow from one activity to another, where the later relates to level of impact of an activity on another [16]. Tasks that overlap can impact on members' ability to synchronously coordinate activities [2]. Interdependence of activities require regular interactions between members clear division of labour, defined roles and work objectives [23]. MTMs are characterised by inter-team connectivity and interdependency of tasks required to be performed based on process input and output. Therefore the interdependency of activities are based on the degree of input required to produce a desired output or on high degree of process required for an outcome [24]. Dealing with multiple projects and activities at the same time becomes more complex when individuals need to coordinate their tasks with members in different teams. This complexity comes from the waiting time required to receive a response from a different individuals to enable continuation of the work and enable decisions on how to proceed with the task [14].

2.2 Coordination of Work and Process

2.2.1 Understanding Coordination

According to Rousseau and Aubé [25] a set of four standard and sequential functions can determine successful task completion. This involves (1) planning, (2) actioning, (3) review and (4) make necessary changes to improve it as and where required. Coordination of work forms part of the actioning of the plan as it requires timeous integration of members' activities to achieve the completion of the task. Coordination is the effect of performing a series of interdependent tasks in a synchronic manner, through collecting input and contributions which could rely on someone else's outputs [22]. The minute these tasks are no longer flowing from one person to another the coordination is not in complete sync causing a delay effect on the expected output [26]. Managing activities dependencies and integrate them to achieve the collective desired tasks is what defines coordination. This process requires different level of effort depending on the team engagement requirements and the complexities and interdependencies of the tasks at hand. Individuals require to collaborate much more frequent and coordinate especially when teamwork requires them to do constant adjustments to their plans due to unpredictable events [27]. Furthermore failure of coordination between members could impact on the successful completion of their interdependent planned activities thus causing inefficiencies and duplication of work [25]. Coordination of work is shaped by a number of factors, time allocation for work to be performed at defined periods for specific teams [28], prompt and accurate integration of tasks [25], routines and work cultures [27]. This involves management of three work areas such as teams, activities and resources [23]. Coordination of work requires more effort to manage as dependencies related to team, task and increase in variety. Teams therefore need to develop defined processes to effectively manage all these dependencies [29]. Coordination processes can be reviewed at two levels: explicitly (coordination activities such as plans, meetings, schedules, tools etc.) [30] and implicitly (predictability and dynamic adjustment [31]) however task dependencies could be managed by different teams using both coordination mechanisms as they are complementary [29].

2.2.2 Implicit Coordination

Individuals that belong to more than one team are required to coordinate work within the teams as well as outside the teams. When team members are able to predict specific actions and coordination requirements of specific individuals, which allows for necessary adjustments without the need to directly communicate with one another, is known as implicit coordination [32]. Being able to anticipate what other team members would do, allows a member to adjust and complete a task without explicit need for engagements or planning with the others [31]. Implicit coordination relies on shared mental models and team cognition based on team members' shared knowledge [29]. Therefore, anticipation and dynamic adjustment become two major components of implicit coordination [31]. Teams that are able to develop mental models are more likely organise their actions and coordinate their work more efficiently as they share a more compatible and similar conceptualisation of the tasks at hand [24]. Understanding the needs and performance requirements of the team members enables a member of the team to adjust his/her own behaviour, adapt to the situation at hand, and meet the requirements and work demands without explicit engagements on how this needs to be performed. When this is not in place a member cannot rely on implicit coordination as this could lead to errors and inaccuracies in coordination efforts. The ability of team members to accurately predict the coordination needs and adapt accordingly avails more time for the delivery of other tasks [31]. However this requires members to build a mental model that allows them to share a common understanding of the tasks as well as what needs to be performed to achieve the common goal [30]. In the event of increased workload teams could maintain their performance levels without specific articulation of plans or direct communication hence coordinating implicitly. This coordination pattern highlights the ability of team members to provide feedback without a need for a previous request or being proactive in assisting another team member through anticipating the expected need. It is a behavioural process that takes place in the absence of specific and direct communication [31].

2.2.3 Explicit coordination

Coordination methods between team members can be both personal and impersonal. A personal mode of coordinating would typically involve face-to-face and personal engagements where an impersonal mode would involve tools such as plans, manuals, schedules etc. [29] guided by standard procedure and specific rules [27]. Explicit coordination is defined as a process to manage multiple interdependencies through planning (known as programming or task organisation) and communication [31] which are explicitly and intentionally used by the team to coordinate work. This coordination mechanism requires more time and support as members need to explicitly engage to achieve the required performance [30]. Individuals in MTM structures require skills and techniques to collectively coordinate efforts with multiple interdependent teams as MTM creates unique challenges. Having the entire team dedicated to a specialised area becomes beneficial since the reliance is no longer on single individual [24]. Transactive memory system (TMS) has at its basis individuals or groups of individuals that have a long-tenured within the team and therefore share the tendency of reliance on one another with respect to communication of specific information and process, which is also known as cognitive interdependence [34]. This reliance allows individuals to develop greater expertise in their specialisation areas and facilitate access to coordinated activities and knowledge. It could therefore be an essential tool for shared cognition as TMS would increase the knowledge of team members of whom is assigned to what, and support them to access this knowledge to improve coordination [33]. Accessing the transactive memory from one individual to another is dependent on communication between individuals as well as the interpersonal relations [34].

3 CONCEPTUAL MODEL

3.1 Relationship between MTM variety of tasks and Coordination of Work

There are a number of factors that can cause coordination to be challenging. The level of coordination of work depends on the complexity of the project and variety of tasks at hand. Heavy workloads in current organisations and environments results in multiple demands on time from team members and creates overburdened individuals which in return information and communication loss can occur [27]. Research has shown that increased workload has a negative consequence on team members [14] when MTM is grated than optimal. Coordination of work is thus impacted by level of task interdependency between teams and individual allocation of work across teams [14]. Exposure to a wider variety of tasks requiring team member to input more effort to perform them and adequately switch between them can pose challenges on coordination of work [7]. Individuals that belong to a MTM structure normally experience high level of coordination requirements as MTM variety of different tasks increases. This is further dependant on the complexity and interdependencies of associated tasks with the project and variety of tasks at hand. At high level of interdependence and when the number of MTM increases the performance of tasks would normally require more integration of tasks between individuals and increased communication which in turn requires a higher level of coordination of work. Increased workloads result in more time allocation from team members which in turn could create stress and difficulty in coordinating activities at hand. It is therefore hypothesised:

H1: *MTM variety of tasks negatively impacts the coordination of work. The higher the MTM variety of tasks the lower the coordination of work.*

3.2 Job autonomy as a moderator

In research conducted by Morgeson and Humphrey [16] job autonomy is classified as a characteristic of work which is defined as the extent to which an individual has the discretion and freedom to make an independent decision in scheduling work and perform specific tasks. Thus, the authority of making decisions as well as scheduling work are both aspects of job autonomy. Autonomous control is suggested by Barros, et al. [23] to be fundamental to work coordination especially when it is related to basic parts of tasks. This is even more so prevalent when teams are geographically distributed or that rely on self-organisation. In the theoretical model for “purposeful work behaviour” proposed by Barrick, et al. [18] autonomy was strongly related to an individual’s openness to experience (meaning an individual that is adaptable as well as intellectual and imaginative) in such that when individuals’ openness to experience is very high they have an strong desire for autonomy.

According to Barrick, et al. [18] autonomy relates to the degree of freedom that a job allows for as well as the extent to which an individual can use his or her discretion in making decisions with regard to methods and scheduling thus providing the required control over what, when and how to perform a specific task. An individual that is assigned to multiple teams with higher discretion and freedom in scheduling the work could have a positive impact on coordination of work. A strong desire for autonomy could be related to an individual adaptability and creativity in addressing critical work schedule aspects and aligning to the new demands. Having control over schedules and ability to focus attention from one team to another may be a critical moderating factor in better coordination of work [2]. Coordination of interdependent tasks generally require a greater level of autonomy. A benefit of MTM related to coordination of tasks and autonomy associated with it is that an individual can attend to other tasks from a different team while awaiting a response from another team. MTM can therefore be seen as a structure that provides individuals the opportunity to adopt more effective practices while utilising their time appropriately and recognising that this is limited [35]. It is therefore hypothesised that:

H2: *Job autonomy positively moderates the relationship between MTM Variety of tasks and coordination of work. The higher the autonomy the lower the negative impact of MTM variety of tasks on coordination of work.*

3.3 Trust as a moderator

One critical characteristic of team attributes is trust. Teams that display trust are more likely to engage and actively participate in coordinative activities and openly exchange information. Therefore trust is seen as critical to team members' interaction especially when engagements take place to correct errors or discuss concerns related to specific tasks. Since trust facilitates the exchange of information which in turn facilitates learning and knowledge sharing it becomes critical to team functioning and engagement. Teams that do not display a high level of trust inhibit interactions among team members and withheld information that may be critical to effective functioning and similar mental models [31]. Teams with high level MTM variety may require assistance from other colleagues to complete specific tasks and for such they rely on this help [36]. Trust becomes a critical element in organisations that rely on more collaborative approaches. When individuals are involved in high interdependent tasks they tend to trust the input coming from another team mate and not check the work.

The input received is processed to form an output to a different task. It is argued that team longevity (defined by the period of time the members engaged and worked with one another) contributes to the strength of the social relationships and better understanding of how each member operates. This contributes to the development of a better mental model and level of trust that outline implicit coordination of work [31]. Lack of trust in this event could impact the coordination process and the project could experience further delays [37]. Teams operating with high interdependent tasks could benefit more from a trustworthy relationship. In addition to the level of trustworthiness a further element that could improve the coordination is the level of trust the team members have in relation to their knowledge and input expertise. This will reduce the risk of double-checking information received that could otherwise contribute to increased coordination costs. Having the element of trust as team attribute could facilitate a more implicit coordination of actions based on openness and common understanding. This can further contribute to information exchange and integration of perspectives. It is therefore hypothesised that:

H3: *High level of trust positively moderates the relationship between MTM variety of tasks and coordination of work. The higher the level of trust the lower the impact of MTM variety of tasks on coordination of work.*

3.4 Centralised systems as a moderator

It is hypothesised that coordination of a variety of interdependent activities and tasks could be improved by a centralised system as this will have the ability to support automation of specific tasks, guide the project workflows and issue notifications at critical timeframes allowing the team members to focus on additional tasks and coordination goals. With team members leaving the organisation or being reassigned to other jobs it is highly likely that the coordination suffers especially when members do not use a central repository of data to make access to information easier to the newcomer. This could also be valid for those working together on multiple tasks and requiring input to coordinate specific activities. A central point could improve access to data and facilitate a more effective coordination between team members. This could positively moderate the relationship between performing a higher variety of tasks and their subsequent coordination. Coordination of work can be affected both positively and negatively by team members departures or arrival into the team. When members shift to a different team or leaving the organisation the absence can create a vacuum in terms of coordination and disturb the effective team functioning [4]. At this point the knowledge flow and communication are affected negatively since the its transfer is more difficult to achieve due to lack of mutual knowledge between the members which is essential for coordination [38]. Malhotra and Majchrzak [39] investigated the use of virtual workplace tools and how this affects coordination of knowledge in virtual teams. Designing workplace tools with specific functionality allows team members to engage and facilitate the knowledge required to accomplish the task (this premise was tested in virtual teams). Information systems could serve as a platform to knowledge transfer and support in closing the gap left by departing member [40]. Use of technology could support data management and enhance decision making processes, providing access to critical information and data required for coordination [20] as well as address the problem related to shared cognition [33]. These systems can be used as centralised repository of documents and knowledge that is available across the organisation. Gupta and Woolley [33] suggests that information dashboard can be a moderator of the negative effect of MTM as this type of information technology allows team members to have open access to each members expertise and maintain their transactive knowledge. Furthermore, this may support coordination through allowing them to focus on other work and allocate their time accordingly in the absence of input from other team members busy with other tasks. It is therefore hypothesised that:

H4: *Centralised system positively moderates the relationship between MTM variety of tasks and coordination of work. The higher the centralisation and access to information the lower the impact of MTM variety of tasks on coordination of work.*

Figure 1 represents the proposed model in the study and summarises the presumed relationship between the variables and moderators.

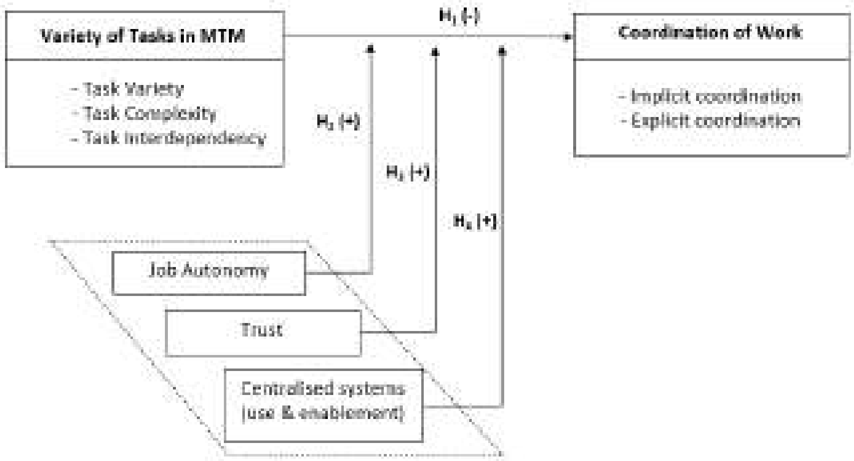

Figure 1: Conceptual Model

4 RESEARCH METHOD

4.1 Research Design

This study is conducted as empirical research through use of primary data collected by means of a survey questionnaire. The quantitative research approach was used as this method supports the analysis of numerical data and statistical interpretation techniques. This further supports the review of different relationships between defined variables [41]. Since this research is based on proving/disproving hypotheses the adoption of quantitative technique was considered to be the most appropriate method. The distribution method chosen was web-based to increase the reach to many respondents and faster collection of data. This method made it logistically easier for the research to collect the required data and allowed the respondents to come back to the questionnaire if they had to deal with an interruption while taking the survey.

4.1.1 Sample and Instrument

The research focused on collecting data primarily from the training and development sector with specific focus on occupationally directed programmes governed by the Sector Education Training Authorities (SETA) policies in South Africa. The total population is however not easily determinable since the data of all these companies is stored by each individual SETA and there is no integrated database of all training providers, within occupationally directed programmes scope where data can be drawn up from. In some cases, these databases are incomplete or lack up-to-date information creating difficulty in identifying respondents that meet the criteria for sample selection. The researcher therefore employed the non-probability sampling technique as the respondents were not chosen at random [41]. This method could therefore have an impact on the generalisation of the results on the total population [42]. The Volunteering sampling through snowballing method was utilised for this study, whereby individuals meeting the criteria were approached and thereafter requested to recommend those that they know which meet the criteria [41]. The unit of measure selected were individuals working within the training and development industry. The questionnaire was shared with 241 professionals that work in a MTM project environment with particular focus on training industry. From this number only 113 completed the questionnaire, either partially or entirely. This provides a response rate of 47%. 11 responses were excluded as no data was recorded against any variables. The remaining 102 responses were considered for analysis however 18 were partial completions of which a total of 10 respondents answered only the questions related to control variables.

4.2 Measurement of variables

This study used measures adopted from previous research and used 5-point Likert scale (strongly disagree to strongly agree).

4.2.1 Variety of tasks in MTM

Three constructs (Task Variety, Task Complexity and Task Interdependence) were measured using Work Design Questionnaire developed by Morgeson and Humphrey [16]. Task Variety and Task Complexity were measured using 4 items; Task Interdependence was measured using two subscales (Initiated Interdependence and Received Interdependence) with 3 items each. Some examples of questions used are as follows: “The job requires the performance of a wide range of tasks”; “The job comprises relatively uncomplicated tasks (reverse scored)”; “Unless my job gets done, other jobs cannot be completed”; “The job depends on the work of many different people for its completion”.

4.2.2 Coordination of Work

Coordination of Work was measured using two different scales: (1) Implicit coordination using the 17 item coordination scale developed by Rico, et al. [31] used to measure the implicit coordination construct. An example of questions used: “When I am under time pressure, other team members proactively help me”; (2) Explicit coordination – the 5 items coordination scale developed by Lewis [34] used to measure the explicit coordination construct. An example of questions used: “Team members had very few misunderstandings about what to do”.

4.2.3 Moderators

Job autonomy was measured using the scale developed by Morgeson and Humphrey [16] containing 3 items; Trust was measured using 5 items Credibility scale developed by Lewis [34] and Centralised Systems (Non-Integrated Systems and Integrated Systems) – this construct was measured with 1 item scale for systems use from Bertolotti, et al. [43] but adopted to the current research as well as 4 item scale from Malhotra and Majchrzak [39] to measure the coordination through centralised system enablement.

4.2.4 Control Variables

Years in the Organisation (YO), Number of MTM (No. MTM), Highest Education (HE), Job Category (JC) and Age were used as control variables for this study.

5 RESULTS

5.1 Analysis of variables reliability

Data collected through the survey was downloaded in excel and analysed through statistical methods. Descriptive statistics, such as nominal variables, standard deviation and mean, were used together with hypothesis testing that included correlation and regression analysis. Some data required cleaning due to abbreviations and/or misspelling. Data that was not entered in a recognisable value was coded as missing data. A defined numerical code was given to the categorical data. Reliability test was conducted for all variables to determine the internal consistency for each scale, through combining all items in the scale.

Table 1: Internal Consistency

Variable	Cronbach Alpha
Task Variety (TV)	0.881
Task Complexity (TC)	0.799
Task Interdependence	
- Initiated Interdependence (II)	0.769
- Received Interdependence (RI)	0.797
Implicit Coordination (IC)	0.882
Explicit Coordination (EC)	0.723
Job Autonomy (JA)	0.884
Trust	0.637
Non-Integrated Systems Enablement (NIS Enable)	0.851
Integrated Systems Enablement (IS Enable)	0.899

In Table 1, except for the moderator Trust the Cronbach Alpha was higher than 0.7 for each of the variables (0.7 being a widely acceptable reliability level according to Easterby-Smith, et al. [42]). However, a minimum value of 0.6 could be considered as acceptable [44]. Therefore, the items of each scale were combined into the average for each measured variable. Trust (which consists of five items) had a Cronbach Alpha of 0.513. As this was below the minimum acceptable reliability score, one item (Item 4 - ”When other members gave information, I wanted to double-check it for myself.”) was excluded and recalculated. The new Cronbach Alpha was calculated at 0.585 which was still below 0.6. Item 5 – “I did not have much faith in other members’ “expertise.”” was excluded and the internal consistency was recalculated. The Cronbach Alpha resulted in 0.637 without Items 4 and 5.

5.2 Correlation

The researcher used the two-tailed significance tests for the variables event though the hypothesis were directional. It was observed that some of the independent variables tested indicate correlations between them which could lead to collinearity issues. Table 2 indicates the following:

5.2.1 Correlation between independent and dependent variables

Weak and negative correlation (-0.292, $p < 0.01$) between the independent variable Initiated Interdependence (II) and dependant variable Explicit Coordination (EC) was noted, however it does not show any significant correlation with Implicit Coordination (IC). It is further noted that the other three independent variable, i.e. Task Variety (TV), Task Complexity (TC) and Receive Interdependence (RI), have a weak negative correlation with Explicit Coordination (EC) but it is not significant.

5.2.2 Correlation between moderators and dependent variables

It further shows positive weak correlations between the moderators Job Autonomy (JA) (0.259, $p < 0.05$) and Trust (0.375, $p < 0.01$) as well as Integrated Systems Use (0.247, $p < 0.05$) and the dependent variable/s.

5.2.3 Correlation between control variables and dependent variables

The control variable Years in Organisation (YO) has a significant positive correlation with Explicit Coordination (EC) (0.244, $P < 0.05$). However, the Highest Education (HE) and Number of MTM (No. MTM) are negatively and significantly correlated with Explicit Coordination (EC) (-0.265, $p < 0.05$ and -0.222, $p < 0.05$ respectively). No correlation was observed between the control variables and implicit coordination (IC).

Table 2: Correlation

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
1. YO	--																
2. HE	.061	--															
3. No. MTM	.137	.098	--														
4. JC	**.196***	**.388****	.161	--													
5. Age	**.312****	.151	.153	**.372****	--												
6. TV	-.077	.205	.022	.001	-.025	--											
7. TC	-.003	.045	.018	.074	.052	**.212***	--										
8. II	.008	.174	.158	-.032	**-.276****	**.216***	-.161	--									
9. RI	.088	.080	.129	.103	.017	**.375****	.036	**.481****	--								
10. IC	.080	-.089	-.029	-.029	.054	-.141	-.102	-.034	-.042	--							
11. EC	**.224***	**-.265***	**-.222***	-.037	.076	-.122	-.032	**-.292****	-.114	**.497****	--						
12. JA	.117	-.078	-.103	.051	-.043	.091	-.033	-.089	-.003	**.259***	**.237***	--					
13. Trust	.031	-.110	.002	-.153	-.026	.033	-.182	.168	.111	**.375****	**.251***	.187	--				

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
14. NIS† Use	-.081	**.236***	.092	-.071	-.077	.177	-.040	**.212***	.071	-.148	-.198	-.036	-.003	--			
15. NIS Enable	-.009	-.181	-.127	-.144	-.071	-.082	**-.384****	-.013	-.134	.198	.077	-.049	.180	-.055	--		
16. IS‡ Use	.117	.101	-.019	-.061	-.042	.107	-.098	.170	.090	**.247***	.199	.034	**.298****	-.081	.150	--	
17. IS Enable	-.028	-.053	.046	-.030	-.114	.070	.017	-.091	.063	.181	-.002	.093	**.302****	-.168	**.438****	**.275***	-

**Correlation is significant at the 0.05 level (2-tailed); **Correlation is significant at the 0.01 level*

5.3 Regression Analysis

A linear regression analysis was performed in order to analyse the relationship between a dependent variable and one or more independent variables [41]. Four different models were analysed for each dependent variable as follows: **Model 1** measured the direct relationship the control variables have on the dependent variable. The control variables used for the analysis were Years in the Organisation, Highest Education and Number of MTM; **Model 2** measured the direct relationship between the independent variable and dependent variable; **Model 3** measured the direct effect of the moderator on the dependent variable; **Model 4** measured the moderating effect of the moderator on the relationship between the independent variable and dependent variable. Coordination of Work was analysed for both Implicit (DV_1) and Explicit Coordination (DV_2) constructs separately as the two dependent variables (DV). The regression results are presented using the following formulas:

Model 1: $DV_n = \beta_0 + \beta_1 CV_1 + \beta_2 CV_2$

Model 2: Model 1 $+ \beta_4 IV_1 + \beta_5 IV_2 + \beta_6 IV_3 + \beta_6 IV_4$

Model 3: Model 2 $+ \beta_7 M_1 + \beta_8 M_2 + \beta_9 M_3 + \beta_{10} M_4 + \beta_{11} M_5 + \beta_{12} M_6$

Model 4: Model 3 $+ \beta_{13} (IV_1 M_6) + \ldots + \beta_{38} (IV_4 M_6)$ *(1)*

5.3.1 Regression Analysis for Implicit Coordination

In the analysis of Implicit Coordination, the variable Number of MTM was used by the researcher to allow case selection to include only the respondents that were members of more or equal to two teams. Only Years in the Organisation and Highest Education were used as control variables in this model.

Table 3: Overall Regression Analysis Results for Implicit Coordination as DV_1

IV_m & M_m	Model 1	Model 2	Model 3	Model 4
Direct effect of CV_n on DV_1	3.649***	4.252***	3.598***	3.556***
CV_1 - Years in the Organisation	0.094	0.084	0.044	0.047
CV_2 - Highest Education	-0.069	-0.050	-0.034	-0.022
Direct effect of IV_1 on DV_1				
IV_1 - Task Variety		-0.097	-0.125	-0.116
IV_2 - Task Complexity		-0.028	-0.027	-0.111
IV_3 - Initiated Interdependence		-0.090	-0.100	-0.099

† Non-Integrated Systems

‡ Integrated Systems

IV_m & M_m	Model 1	Model 2	Model 3	Model 4
IV_4 – Received Interdependence		0.053	0.064	0.042
Direct effect of M_1 on DV_1				
M_1 – Job Autonomy			0.263**	0.051**
M_2 – Trust			0.320***	0.343***
M_3 - Non-Integrated System (NIS) Use			-0.201	-0.205
M_4 - NIS Enablement			0.166	0.372**
M_5 - Integrated System (IS) Use			0.237*	0.275**
M_6 - IS Enablement			0.176	0.246*
Moderating effect *(only showing significant ones)*				
IV_2 x M_1				-0.335***
IV_4 x M_4				-0.346***
IV_4 x M_6				-0.223*

*: p<0.1; **: p<0.05; ***: p<0.01

The control variables Years in the Organisation it is observed that **Model 1** is not significant across the analysis of each individual variable ($\beta = 0.094$, $p > 0.1$). This indicates that there is no impact of control variable over the dependent variable. Similar finding is observed for control variable Highest Education, where no significant impact was noted ($\beta = -0.069$, $p > 0.1$). This indicates that there is no impact of control variable over the dependent variable. There is no significant relationship between independent and dependent variables depict by the proposed model however Job Autonomy, Trust and Integrated Systems Use have a direct effect on Implicit Coordination. It is further noted that Job Autonomy (M_1) and Task Complexity (IV_2) have negative interaction effect whereas Non-Integrated (M_4) and Integrated System Enablement (M_6) have negative interaction effect with Received Interdependence (IV_4).

5.3.2 *Regression Analysis for Explicit Coordination*

In the analysis of Explicit Coordination, three control variables were used as follows: Years in the Organisation, Highest Education and Number of MTM.

Table 4: Overall Regression Analysis Results for Explicit Coordination as DV_2

IV_m & M_m	Model 1	Model 2	Model 3	Model 4
Direct effect of CV_n on DV_2	3.832***	4.246***	3.800***	3.818***
CV_1 – Years in the Organisation	0.319***	0.331***	0.299**	0.303**
CV_2 – Highest Education	-0.230**	-0.219*	-0.208*	-0.213*
CV_3 – Number of MTM	-0.225*	-0.230*	-0.227*	-0.218*
Direct effect of IV_1 on DV_2				
IV_1 – Task Variety		-0.060	-0.079	-0.082
IV_2 – Task Complexity		-0.023	-0.023	-0.030
IV_3 – Initiated Interdependence		-0.139	-0.139	-0.137
IV_4 – Received Interdependence		-0.001	-0.011	-0.020
Direct effect of M_1 on DV_2				
M_1 – Job Autonomy			0.156	0.161
M_2 – Trust			0.223*	0.224*
M_3 - Non-Integrated System (NIS) Use			-0.145	-0.174
M_4 - NIS Enablement			-0.019	0.098

IV_m & M_m	Model 1	Model 2	Model 3	Model 4
M_5 – Integrated System (IS) Use			0.241**	0.245*
M_6 – IS Enablement			-0.037	-0.021
Moderating effect *(only showing significant ones)*				
IV_1 x M_4				-0.323***
IV_2 x M_1				-0.210*
IV_2 x M_3				0.192*
IV_3 x M_5				0.287***

*: p<0.1; **: p<0.05; ***: p<0.01

From the analysis in Table 4 it is noted that all three control variables Years in the Organisation, Highest Education and Number of MTM have a positive and highly significant impact on the dependent variable Explicit Coordination. There is no significant relationship between independent and dependent variables depict by the proposed model however Trust and Integrated Systems Use have a direct positive effect on Explicit Coordination. It is further noted that Job Autonomy (M1) and Task Complexity (IV_2) have a weak and negative interaction effect (β = -0.210; p<0.1). Non-Integrated System Enablement (M4) and Task Variety (IV_1) have negative and significant interaction effect (β=-0.323; p<0.01). There are two positive and significant interaction effects found: (1) Task Complexity (IV_2) and Non-integrated Systems Use (M_3) (β= 0.192; p<0.1) and (2) Integrated System Enablement (M_5) and Initiated Interdependence (IV_3) (β=0.287; p<0.01).

6 CONCLUSION

The research objective was to investigate the existence of a relationship between the independent variable Task Variety, Task Complexity, and Initiated and Received Interdependence and coordination of work (examined from an Implicit and Explicit point of view). This was also responding to the first research question. The second objective was to investigate moderating factors that could improve the relationship and support a more efficient coordination of work when the MTM variety is increasing. The study observed partial significant negative correlation between independent and the dependent variables as well as a negative effect between them however these were not statistically significant.

A negative correlation was found specifically between Initiated Interdependence (independent variable) and Explicit Coordination of work. As a recommendation, managers could consider better balance of roles between individuals assigned to active multiteam structures to avoid decreased coordination both from an intra and inter team level perspective.

H1: *MTM variety of tasks negatively impacts the coordination of work. The higher the MTM variety of tasks the lower the coordination of work*

It was hypothesised that the MTM variety of tasks negatively impacts the coordination of work, meaning that the higher the variety, complexity and interdependence of task the lower the coordination of work. From the analysis of data it can be observed that the three independent variables Task Variety, Complexity and Initiated Interdependence have a small negative effect on coordination of work however this is not significant. Even though a significant negative correlation was found between Explicit Coordination and Initiated Interdependence (r = -0.292, p< 0.05) the regression analysis did not prove the causal effect. It is therefore concluded that hypothesis 1 was not supported meaning that coordination of work was not be negatively affected by MTM variety of tasks but potentially other factors.

H2: *Job autonomy positively moderates the relationship between MTM variety of tasks and coordination of work. The higher the autonomy the lower the negative impact of MTM variety of tasks on coordination of work.*

In this study Job Autonomy seems to have a direct positive and significant effect on Implicit Coordination ($\beta = 0.250$, $p < 0.05$) when evaluating the Task Variety and Implicit Coordination of work. The same has been observed to be the case when evaluating the relationship between Initiated Interdependence and Implicit Coordination of work ($\beta = 0.254$, $p < 0.05$) as well as Received Interdependence and Implicit Coordination of work ($\beta = 0.249$, $p < 0.05$). This is consistent with research related to the need of autonomy and control that team members should have in coordinating activities [23]. However, Job Autonomy was found to negatively impact the relationship between Task Complexity and Implicit Coordination ($\beta = -0.335$, $p < 0.01$) as well as Explicit Coordination ($\beta = -0.210$, $p < 0.1$). When team members use unintentional coordination mechanisms such as anticipation of actions or coordination needs without being explicitly asked job autonomy will play an inverse role in the relationship between task complexity and implicit coordination. This means that the higher the job autonomy the higher the negative impact the task complexity will have on implicit and explicit coordination.

H3: *High level of trust positively moderates the relationship between Variety of tasks in MTM and coordination of work. The higher the level of trust the lower the impact of MTM variety of tasks on coordination of work.*

Trust has a direct effect on implicit coordination when evaluating the following variables:

- When analysing the interaction of Trust with Task variety this was found to have a direct positive significant effect over implicit coordination ($\beta = 0.320$, $p < 0.01$).
- When analysing the interaction of Trust with Task complexity this was found to have a direct positive significant effect over implicit coordination ($\beta = 0.327$, $p < 0.01$).
- Similarly the interaction between Trust and Initiated interdependence was found to have a direct positive significant effect over implicit coordination ($\beta = 0.329$, $p < 0.05$) This was also the case when analysing the explicit coordination variable ($\beta = 0.22$, $p < 0.1$).
- The interaction between Trust and Received interdependence was found to have a direct positive highly significant effect over implicit coordination ($\beta = 0.321$, $p < 0.01$).

The findings are consistent with current research where trust is considered as a critical element to be displayed by the team members when engaging in coordination of work [37], hence a direct component of coordination of work.

H4: *Centralised system positively moderates the relationship between MTM variety of tasks and coordination of work. The higher the centralisation and access to information the lower the impact of MTM variety of tasks on coordination of work.*

Centralised systems were reviewed from a use and enablement perspective for both integrated (learner management systems) and non-integrated systems (excel spreadsheets etc.). The study found that: When **non-integrated systems use** interacts with task complexity, this has a positive and slightly significant effect on explicit coordination ($\beta = 0.192$, $p < 0.1$). Further to this, **Integrated systems use** has a positive significant direct effect on explicit coordination (when evaluating all four independent variables individually, with $0.219 < \beta < 0.241$, $p < 0.05$). It was also observed that when integrated systems use interacts with initiated interdependence, this has a positive impact on explicit coordination ($\beta = 0.287$, $p < 0.05$). Furthermore, when Integrated Systems Use interacts with task variety, a direct positive and slightly significant impact implicit coordination was observed ($\beta = 0.237$, $p < 0.1$).

The study found that the moderators have a positive and significant direct effect on coordination of work: Managers can consider improving trust among team members as this could increase their level of engagement and support, and it could improve developing the inter-team mental models. Further to improving trust, increased autonomy could add value to members in better adapting to new and increased work demands. However, caution must be exercised when the task complexity is high as the interaction between high autonomy and high complexity could negatively impact coordination. System centralization can benefit improved coordination however managers should ensure that the tools availed to the members are not impeding the coordination process as the data shows that system enablement when tasks vary or are being received by an individual could have a negative impact on coordination.

Research focuses on only one aspect of MTM variety in relation to tasks, i.e. task variety, complexity and interdependence, and its impact on coordination. This study included an unique combination of variables within MTM context that could impact the coordination of work. The results could provide support to management in aligning and correctly allocating the tasks within MTM to support a higher level of coordination of activities within different teams. It is further recommended that a longitudinal study within the training and development industry is used to determine the moderating effect of centralised systems have within an organisation. This could be measured prior the organisation deployed a centralised system and after a period of time the members of the teams experienced the system. It could further investigate the role that leadership has in instituting the change process from a non-centralised to centralised system environment. In recent years many companies have been using remote work and virtual workspaces where team members rarely meet face-to-face [39].

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THE EFFECT OF MULTIPLE TEAM MEMBERSHIP VARIETY ON INDIVIDUAL LEARNING AND INDIVIDUAL PERFORMANCE IN THE ENGINEERING TEAMS

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ABSTRACT

Simultaneous membership on more than one team aims to manage time, attention, and information. This research focuses on the impact of variety of multi team membership (MTM) on individual learning and performance in Engineering teams. MTM variety is proposed to be negatively related to individual performance and has an inverted U-shaped relationship with individual learning. 58 respondents participated in the online survey. Positive relationships between aspects of MTM variety and innovative performance were obtained while negative relationships with job performance. An inverted U shape relationship was determined between individual learning and some aspects of MTM variety. Emotional skills and social skills negatively moderate the relationship between job performance and aspects of MTM variety. Cognitive skills positively moderated the relationship between MTM variety aspect and job performance hence it is recommended for managers to employ people with cognitive skills in MTM set ups.

Keywords: Multiple Team Membership, Variety of multi team membership, Individual learning, Individual performance, Innovative performance, Job performance

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1 INTRODUCTION

Multi team membership is defined as interdependence of membership across teams [1]. Multi team membership involves changes in tasks, roles, technology, routines, and locations. Components of multi team membership are team, membership, and time. Teams can be defined as sets of individuals that work interdependently to achieve a set goal. Individuals are members of a team who share reward and responsibility for the task they also recognise each other. Members of a team recognise each other [2]. A group is a representation of people who interact with each other, aware of existence of other group members and recognise each other. Work group is a representation of two or more people who interact while sharing some tasks which are related to a common goal. A team consists of people who have complementary skills which are used for carrying out a common task with joint responsibility. Work team is a group with personal commitment, spirit of unity, human relations, cohesion, member's adherence to group with which they identify, the convergence of efforts for performing tasks which will constitute a joint work [3].

Multi team membership dimensions are number of teams and variety of teams. Number of teams are the number of unique, non-overlapping other teams the focal team's members are involved with. Variety of teams covers diversity in tasks, roles, routines, and locations that are characterizing the teams. This present study focuses on the variety of the multi team membership because of its theoretical impact on individual performance and learning. Also, another factor in the choice of focusing on multi team membership variety impact on individual performance and learning is because many studies have been done on the number of teams an individual is a member of and very little has been covered on the variety of multi team membership [4].

The dimensions of work performance are task performance, contextual performance, adaptive performance, and counterproductive work behaviour. Task performance is the proficiency of an individual to perform job tasks. Contextual performance is individual behaviour that support social, organizational, and psychological environment where the central job tasks are done. Adaptive performance covers ability to adapt to changing environments and work roles. Counterproductive work behaviour carters for behaviours that are harmful to the organisation [5].

Learning is any process which leads to permanent capacity changes, and which is not only because of biological aging. The two major views of learning and process are acquisition and participation. Learning as acquisition refers to the process were the person teaching deposits knowledge into the person who is learning. Learning as participation involves the social aspect which involves individual elements which comes through experiencing and participating in routine life processes [6]. Learning can be defined as an indicator for change in routines, knowledge, and behaviour. The process involves having to store, retrieve, encode, and attend to information which is existing in the environment of the learner. At a team level learning can be activities which individuals partake in to share, acquire, and combine knowledge through experience and interacting together. At an organisational level learning can be the process whereby knowledge is shared, created, and mobilised to ensure the organisation adapts to the changing environment. Learning at an organisational level includes exploratory and exploitation which convers integration, search, and transfer processes [2].

Preliminary investigation suggests that multi team membership variety is characterised with benefits and challenges that are learning, and performance related. Multi team membership variety fosters a wide range of unique simultaneous experience hence more knowledge is gained. Individual learning because of multi team membership variety has a point of saturation after which increase in multi team membership variety yield negative effects [2]. The performance of an individual is negatively related to multi team membership variety because it is detrimental to employees' well-being as it creates role strain through conflicting experiences and overload of demands [4]. Thus, an investigation into multi team membership variety is important to gain certainty of the relationship with individual learning and performance.

Research objectives are to investigate the effects of multi team membership variety on individual performance, learning in Engineering teams and investigate the moderators of the relationships. With these objectives the research questions are what are the different constructs of multi team membership variety, what is the impact of multi team membership variety on individual's performance and individual's learning as well as what are the moderators that affect the relationships?

2 LITERATURE REVIEW

2.1 Constructs of variety in Multi Team Membership

Multiple team membership variety constructs are diversity of tasks, procedures and interpersonal expectations that characterise teams. These constructs of multi team membership variety are based on the role theory. According to the role theory human beings behave in ways that vary and are predictable depending on the situation. Based on the role theory roles in organisations are assumed to be associated with social positions and each role has expected behaviours and beliefs. Also, in the role theory a person is a member of a social position, and they hold expectations for the behaviour of other people and their own. This implies that an individual in multi team membership simultaneously holds different roles. Expected beliefs and behaviours for an individual in multi team membership of others could be different for each role they hold. Therefore, studying multi team membership variety from the role theory perspective is important in explaining employee's behaviour in different settings. It is suggested that employees who participate in different roles in multi team membership behave differently in each team, thus potentially affecting performance [4].

Diversity in tasks are the skills required by an individual to perform their job. These skills are learned by training or experience. Diversity in procedures is associated with the expected products and services of the job, however it can also carters for how employees are working. This covers team alignment to tasks, joint decision making and problem resolution [7]. Diversity in interpersonal expectations covers expectations of the leader from the team in terms of how employees perform the job and when employees have deadlines as well as the characteristics of the client or principle. Characteristics of client or principle covers their expectations of the team and how team members behave to customers. Team members can have expectations for their fellow team members. These expectations cover dress code, shared organizational routines and shared language [4].

Multi team membership variety can be viewed as diversity in roles, tasks, locations, technologies, and routines. It is important to note that each team has a meaningful symbolic domain which has its own social definitions and meanings [2]. Constructs of multi team membership variety can be viewed as the extent to which teams are different. Differences in teams in terms of knowledge and skills used in the team to perform the required tasks. The work process that is involved in performing of tasks or work methodologies in the specific team. Another construct of multi team membership variety is differences in the outcome of teams in terms of product or service. Differences in task complexity is a construct of multi team membership variety. Differences in extent of task interdependence are a construct of multi team membership variety which is the extent to which group members depend on each other to complete a task [8].

2.2 Impact of Constructs of variety in Multi Team Membership on individual performance

High levels of multi team membership variety have a negative relationship with individual performance due to the need to manage a greater amount of diverse information due to increased information load. This induces need to put more time and effort in adjusting to varying contexts, people, tasks, and roles. As work complexity increases the more switches between teams disrupts routines and negatively affect productivity [4].

Time pressure is the scarcity of time to complete a task. As multi team membership variety rises individuals are likely going to experience time pressure. Excessive workload has a probability of creating time pressure. The time individuals dedicate to a particular team reduces as they engage in multi team membership variety while juggling different tasks and roles in varying teams. Individuals involved in multi team membership variety experience competing demands which induces time pressure. Division of time across different teams where there is need to perform tasks which vary from one team to the other induces intense time pressure. As individuals distribute time across varying teams the available time reduces which leads to individuals experiencing time pressure [9].

2.3 Impact of Constructs of variety in Multi Team Membership on individual learning

Multi team membership variety creates access to more diverse inputs thus more opportunities of learning. As a result of multi team membership variety individuals gain access to information on simultaneous variations of teams and helps individuals to integrate and apply new knowledge. Superior ideas and approaches can be discovered at higher rates due to more diverse ideas and information. Individual learning is enhanced due to more variety within teams due to increased experiences. When individuals are involved in multiple project teams at the same time, they encounter more diverse ideas thus enhancing learning. Low levels of multi team membership variety implies that less exposure to diverse ideas and information thus less chances of learning. This has a consequence of higher chances of tunnel vision and reduced chances of exposure to better ideas and approaches. Thus, reducing the individual learning in the process. Therefore, multi team membership variety has a positive relationship with individual learning [4].

Multi team membership variety has a largely positive, albeit curvilinear, relationship with individual learning. Multi team membership variety helps with unique concurrent experiences, hence fostering learning. It is important to note that heightened differences between teams have the potential to limit learning and possibility of knowledge transferring across dissimilar experiences. Thus, individual learning due to multi team membership variety has a saturation point where further increase in variety results in the relationship being negative [2].

3 HYPOTHESES DEVELOPMENT

Multi team membership variety has a tendency of increasing amount of diverse information due to increase in load thus creating need to manage the situation. With this situation at hand there is need for more time and effort to adjust to the varying team context, people, tasks, and roles [4]. Multi team membership variety induces an increase in cognitive demand for individuals due to need to shift attention across several teams with diversity in technologies, tasks, and location. Task switching and multi-tasking are sources of cognitive demand. Another source of increase in demand for cognitive resources is workload accruing due to tasks in multi team membership variety. When there is increase in demand for attention there is possibility of time famine, with a lot of work to do thus inducing cognitive demand and therefore not enough time to do work. Cumulative demand generates competing goals thus causing time pressure and cognitive demand to solve this problem of increasing job demand [9]. Individuals usually view hindrance stressors as out of control, and it is anticipated that stressors are negatively related with effort input and goal actualization due to the belief that their out of control. Typical hindrance stressors are red tape, role ambiguity, organizational constraints, and interpersonal conflict these are viewed as uncontrollable factors that disturb personal goals. Role conflict and role ambiguity are associated with threatening personal growth and individual goal attainment. Role strain perspective argues that involvement in multiple roles may lead to role strain because of conflicting expectations which negatively affect employee wellbeing. Individuals who have multiple roles at the same time may experience role conflict as the pressures and demands of one role might be incompatible with the pressures of other roles. Incompatible role demand on individuals is caused by occupying multiple roles. Working in several groups is a cause of role conflict because of the conflicting information about their role. Role conflict is a hindrance stressor because individuals feel they cannot simultaneously implement demands of multiple roles regardless of the effort and resource allocation. Increases in multi team membership variety is likely to generate incompatible roles. The intersection between multiple roles on some tasks and social responsibilities can generate role conflict. Increase in diversity of teams, leads to role conflict. Individuals who are involved in multi team membership variety would have multiple leaders with multiple requests which might not be compatible thus leading to confusion on the individual. Individuals in multi team membership variety will span boundaries of their focal team and boundary spanning activities are positively related to role conflict. Role ambiguity results from complications associated with increase in demands. Complications might be due to frequent change in technology, organisational size, and changes in environment of organisation [9].

Multi team membership variety enhances opportunities of learning by providing diverse inputs. There is access to different information simultaneously due to multi team membership variety which helps to integrate and apply new knowledge. New better ideas and approaches can be developed at higher rates due to more diverse ideas and information. Multi team membership variety increases the experience of individuals. At low levels of multi team membership variety there is less exposure to diverse ideas, information, and approaches [4]. Multi team membership variety has a largely positive, albeit curvilinear, relationship with individual learning. Multi team membership variety aides unique concurrent experiences, hence fostering learning. Heightened differences between teams have capability to limit learning and possibility of knowledge transferring across dissimilar experiences. Thus, individual learning due to multi team membership variety has a saturation point beyond which further increase in variety results in the relationship being negative [2]. Moderators proposed to the relationship between multi team membership variety and individual performance are familiarity, context switching, external advice, instant messaging, emotional skills, and social skills, while for the relationship between multi team membership variety and individual learning are cognitive skills and context switching. The schematic diagram for the conceptual model is shown in Figure 1.

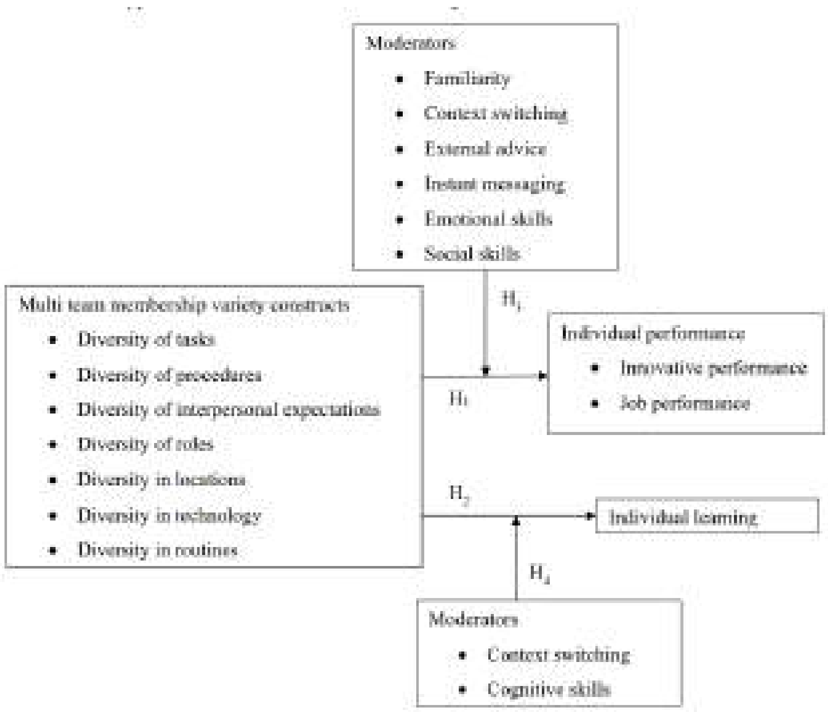

Figure 1: Schematic diagram of conceptual model

The hypothesises are:

H1: Multi team membership variety is negatively related to individual performance.

H2: Multi team membership variety has an inverted U-shaped relationship to individual learning.

Hypothesises 3 and 4 are based on the moderation effect of each moderator on hypothesis 1 and 2 respectively.

4 RESEARCH METHOD

4.1 Research Approach and Design

A literature survey to understand the different constructs of multi team membership variety was conducted. Causal design was used to investigate the impact of multi team membership variety on individual's performance and learning as well as the moderation on the relationships. Causal design is used because its relevant for investigating relationships. Quantitative method was selected because they are utilised to examine relationships [10]. Questionnaire was used in this research targeting engineering teams. Emails with link to the questionnaire were sent to potential respondents because the targeted people to respond are technologically competent.

4.2 Sample and Setting

Study was conducted within Engineering teams from varying Engineering sectors to investigate relationships which need to be tested across a diversified field not limited to a sector. The study population is all individuals working in multi team membership variety in Engineering for companies that questionnaires were distributed. Snowball sampling was utilized and completed questions were 58 respondents.

4.3 Measures

Various questions from various sources were used to measure the independent variable, dependent variables, moderators, and control variables.

4.3.1 Measurement of Independent variable

Multi team membership variety was measured using questions from [4], [9] these had Cronbach's alpha of 0.87 and 0.74 respectfully. Since the Cronbach's alpha was greater than 0.6 it is reliable to use the questions. Refer to Appendix 1 for all the measures of independent variable.

4.3.2 Measurement of Dependent variables

Job performance was measured using questions with Cronbach's alpha of 0.97 [11]. Innovative performance was measured using questions with Cronbach's alpha of 0.79 [4]. Individual learning was measured using questions from [12] which were used by [13] they had a Cronbach's alpha of 0.81. Since all Cronbach's alpha values are greater than 0.6 it is reliable to use the questions. Refer to Appendix 1 for all the measures of dependent variable.

4.3.3 Measurement of Moderators

Description of each moderator is found in appendix 2. Familiarity was measured using a question from [4] external advice and instant messaging were measured using questions from [14] and emotional skills were measured using questions from [15] which were used by [16] they had a Cronbach's alpha of 0.670. Social skills were measured using questions from [17] which had a Cronbach's alpha of 0.851 when used by [16]. Cognitive skills were measured using questions from [16] with Cronbach's alpha of 0.614 when used by [16]. Refer to Appendix 1 for all the measures of moderators.

4.3.4 Measurement of Control variables

Previous studies have shown that performance of an individual is affected by number of concurrent multi team membership, gender, age and organizational tenure [4]. Thus, these factors have been included in the study as control variables. Gender, age and education have been previously proved to influence individual learning [13]. It is suggested by previous studies that the number of teams an individual has been a member of in the past month has an impact on multi team membership results [9].

5 RESULTS

5.1 Reliability Analysis

The reliability of measurement is determined using the Cronbach's alpha which determines the internal consistency of the questions used. It is widely acceptable that the threshold for Cronbach's alpha should be 0.7, a cut-off value of 0.6 can be conditionally accepted [19], [20]. The Cronbach's alpha which was obtained are Variety .822, Job performance .893, Innovative performance .878, Individual learning .887, External advice .846, Emotional skills .620, Social skills .844 and Cognitive skills .609. All values were greater than 0.6 which implies the questions were reliable.

5.2 Factor Analysis

The factor analysis for Multi Team Membership Variety by subjecting to principal components matrix (PCA) using the Varimax rotation method to establish any underlying dimensions. Before utilising factor analysis data appropriateness for factor analysis and sampling adequacy must be performed [21]. KMO is used to determine the sampling adequacy while the Bartlett's test is used to determine data appropriateness. KMO values greater than 0.9 are best with KMO values lower than 0.5 being unacceptable [21]. For Bartlett's test of sphericity to be significant p-value must be less than 0.05 [20]. In this test KMO was .734 with Bartlett's test of sphericity significant p-value .000. Results demonstrate the sampling is adequate and appropriate. Table 1 contains factor analysis results for Multi team membership variety. Multi team membership variety can be split into competency (component 1) and collaboration (component 2). The highest factor loading (presented in bold in Table 1) of the variable indicates which component it falls under. Variety 12 fits in both components as its factor loadings are similar in magnitude.

Table 1: Multi team membership variety factor analysis results.

Variable	Description	Component	
		1	2
Variety_1	Skills individuals, learned by training or experience, to do their job	**0.742**	0.195
Variety_2	Working methods individuals use to perform their job	**0.683**	0.312
Variety_3	Expected results of the job the individual performs	0.257	**0.690**
Variety_4	Level of collaboration the individual has within teams	0.120	**0.692**
Variety_5	Expectations of the team leader of the individual team members	0.298	**0.403**
Variety_6	Characteristics of principal or client that are part of the team	**0.422**	0.101
Variety_7	To what extent are the tasks in work teams different	**0.666**	0.311
Variety_8	To what extent are your roles different	**0.632**	0.202
Variety_9	To what extent are the technologies used different in the teams	**0.729**	-0.052
Variety_10	To what extent are the knowledge, skills, and abilities necessary to work effectively different	**0.866**	-0.018
Variety_11	To what extent are the geographical locations of the teams	-0.138	**0.852**
Variety_12	To what extent are the people that you work with different	0.378	0.363

5.3 Hypothesis Testing

5.3.1 Correlation Analysis Results

Table 2 contains significant correlation analysis results for dependent variables and independent variables. It is important to note that the average for Multi Team Membership Variety items is being used as independent variables.

Table 2: Significant correlation analysis results

	1	2	3	4	5	6	7
1. JobPerformance_ave		0.313*	0.544**				
2. InnovativePerformance_ave			0.276*			0.395**	
3. IndividualLearning_ave							
4. Age							0.303*
5. Variety_ave						0.786**	0.515**
6. Variety_Competency							
7. Variety_Collaboration							

*. Correlation is significant at the 0.05 level (2-tailed)
**. Correlation is significant at the 0.01 level (2-tailed)

5.3.2 Regression Analysis Results

Regression Analysis for testing hypothesis 1 and 2

Table 3 shows the significant regression analysis results for testing hypothesis 1 and 2.

Table 3: Regression analysis for testing hypothesis 1 and 2 results

Variable	H1: DV =Innovative Performance	H1: DV = Job Performance	H2: DV = Individual Learning
Variety_ave	0.309*		
Variety_Competency	0.480***		
JobTenure		-0.399*	
Variety_3			0.611**
Variety_4		-0.460**	
Variety_10		-0.663*	
Variety_Competency_sq			-0.393*

*p < 0.10; ** p < 0.05; *** p < 0.01

Regression Analysis for testing hypothesis 3

Due to the previous analysis were there was a significant relationship between Variety 4 and Job performance. Table 4 shows the results of significant moderating effect on the relationship between Variety 4 and Job Performance. The moderating effect is tested by entering the multiplication term between Variety 4 and the MV (Variety_4 x MV), which both were first mean centred before multiplication to avoid multicollinearity issue.

Table 4: Significant regression analysis results on moderation of variety 4

Variable	H3: DV = Job Performance	H3: DV = Job Performance
Variety_4xMV	-0.546***	-0.594***

*p < 0.10; ** p < 0.05; *** p < 0.01

Due to previous analysis were there was a significant relationship between Variety 10 and Job performance. Table 5 shows the results of significant moderating effect of the relationship between Variety 10 and Job Performance. The moderating effect is tested in the same way done for variety 4. It is important to note that this moderation effect is not covered in the conceptual model of the study, but moderation of the relationship does occur.

Table 5:Significant regression analysis results on moderation of variety 10

Variable	H3: DV = Job Performance IV = Variety 10 MV = Emotional skills	H3: DV = Job Performance IV = Variety 10 MV = Social skills	DV = Job performance IV= Variety 10 MV= Cognitive Skills
Variety_10xMV	-.492***	-.419**	.321**

*p < 0.10; ** p < 0.05; *** p < 0.01

6 DISCUSSION

Proposed relationship is multi team membership variety is negatively related to individual performance with moderators being familiarity, context switching, external advice, instant messaging, emotional skills, and social skills. Multi team membership variety is proposed to be positively related to individual learning up to a saturation point with further increase beyond saturation point making the relationship negative moderators are cognitive skills and context switching.

Job tenure was found to have an impact on job performance based on the regression analysis. This is consistent with previous studies which suggested that job tenure does in fact affect job performance [4]. Job tenure had a negative relationship (β= -0.399; p<0.1) with job performance.

Individual performance in this study was split into job performance and innovative performance. Hypothesis 1 states the relationship between multi team membership variety with individual performance is negative. In the present study a positive relationship (β= 0.309; p<0.1) between variety average and innovative performance was obtained. Also, a positive relationship (β= 0.480; p<0.01) between variety competency and innovative performance was obtained. Variety 1 which is skills individuals learned by training or experience to do their job in a team has a moderate positive relationship with innovative performance the coefficient is 0.488 with p < 0.01. Variety 10 which is to what extent are the knowledge, skills, and abilities necessary to work effectively different also has a moderate positive relationship with innovative performance the coefficient is 0.393 with p < 0.01. Variety 1 and variety 10 are both competency variety hence it is justified that they yield the same results pertaining to their relationship with innovative performance as variety competency. This similarity in the results using correlation analysis and regression analysis is evidence of consistency in the study. The results pertaining to innovative performance are contrary to the hypothesis. This can be explained by the fact that as an individual is involved in diverse work activities measured by variety average, they are bound to be innovative to achieve their results this enhances the innovative performance. Variety in competency has a tendency of requiring innovativeness to be implemented as the competencies differ with the tasks which will be done. Job performance had a negative relationship (β= -0.460; p<0.05) with variety 4. Variety 4 is level of collaboration the individual has within teams. Job performance has a negative relationship (β= -0.663; p<0.1) between variety 10. Variety 10 is to what extent are the knowledge, skills, and abilities necessary to work effectively different. Job performance results are in line with the hypotheses. It is expected that as the level of collaboration the individual has within teams differ the job performance decreases due to the need to adapt to the different people to be collaborated with. When the knowledge, skills, and abilities necessary to work effectively are different job performance is bound to decrease because of the need to utilise varying cognitive demands.

A positive relationship (β= 0.611; p<0.05) between variety 3 (expected results of the job) and individual learning. This finding supports hypothesis 2 which says multi team membership variety is positively related to individual learning up to a saturation point such that further increase in multi team membership variety beyond the saturation point makes the relationship negative. This finding supports the positive relationship up to a certain point because variety in expected results of job helps with unique concurrent experiences, hence fostering learning. For learning an individual needs to access new information and integrate thus varying expected results of job helps in learning [2]. Variety 3 allows individuals gain access to information on simultaneous variations of expected results of the job within teams thus helps individuals to integrate and apply new knowledge hence fostering learning [4]. Variety 3 creates access varying knowledge sources which provides an individual the opportunity to acquire more diverse knowledge hence improving learning [13]. Variety competency squared has a negative relationship (β=-0.393; p<0.1) with individual learning. Which is in line with the part of hypothesis 2 which suggests that further increase in multi team membership variety makes the relationship negative. This is due to increased information variety and decreased integration time which makes individual learning deteriorate [4].

Emotional skills negatively moderated the relationship between Variety_4 (expected results of the job the individual performs) and job performance (ß=-0.546; p<0.01) also relationship between Variety_10 (to what extent are the knowledge, skills, and abilities necessary to work effectively different) with job performance (ß=-0. 492; p<0.01). Emotional intelligence is very important to individuals as it helps with exploratory methodology of processing information by utilising cognition. This ensures that information is processed in a faster method due to this reasoning. It is important to note that positive emotions are useful in creative tasks therefore emotional skills are positively related to innovative performance [16]. Emotional intelligence ensures that individuals nurture positive relationships at work, build social capital and work effectively in teams [22].Job performance mainly focuses on delivery of job requirements not conditions which results are obtained. Emotional intelligence is very critical in improving innovative performance, nurture positive relationships at work, build social capital and work effectively in teams but not necessarily job performance (which is mainly results oriented). Therefore, emotional intelligence is not able to moderate the relationship between variety 4 and variety 10 with job performance. With emotional intelligence the work environment and atmosphere improve but at the expense of moderating the negative effects of variety on job performance.

Cognitive skills positively moderate relationship between variety 10 (of differing knowledge, skills, and abilities necessary to work effectively) and job performance positively (ß= 0. 321; p<0.05) which is expected. Since cognitive skills are necessary for individuals to gain knowledge, procedures, and rules necessary to perform the job they engage [16]. Availability of cognitive skills helps in coping with differing knowledge, skills and ability needed to perform thus they can moderate the relationship positively. Also, cognitive skills have the capability to enhance the ability to develop strategies and techniques in individuals [16]. An individual with cognitive ability therefore can develop strategies and techniques that are necessary to cope with variety 10, hence moderating the relationship. Cognitive skills are vital in solving complex problems thus people with them can address all the differing knowledge, skills, and abilities [16].Other factors associated with cognitive skills that help in moderation of the relationship is that they offer skills of mental functioning which include spatial and causal reasoning, memorizing, focusing attention, rate of processing information, remembering, and inhibiting which are vital in performing [23].Individuals with high need for cognition have a natural tendency to acquire, seek, think, and reflect on information at their exposal. Ability to contain more information and being very strongly cognitively motivated to engage in a lot of reasoning and reflection [13].

Social skills moderate negatively relationship (ß=-0.419; p<0.05) between job performance and Variety 10 (variety in terms of extent of knowledge, skills, and abilities necessary to work effectively) also relationship (ß=-0.594; p<0.01) between job performance and variety 4 (expected results of the job the individual performs). This is justified because social skill mainly impacts social capital, which is linked to individual being well connected with others which enhances innovative performance [16]. Aspects which are covered by social capital do not directly cover job performance which is determined by the competency of an individual to deliver the job requirements while in Variety 10 and Variety 4. Another aspect of social capital is concerned with creating networks and relationships which enhances high trust, a working environment associated with effective connections and cooperation of managers and employees [24]. With the above social skill of an individual is mainly concerned with aspects which are not directly involved in improving job performance.

7 CONCLUSION AND RECOMMENDATION

7.1 Research Conclusions

Individual performance had two aspects innovative performance and job performance. Variety average and variety competency have positive relationship with innovative performance. Job tenure, variety 10 (what extent are the knowledge, skills, and abilities necessary to work effectively different) and variety 4 (level of collaboration the individual has within teams) have a negative relationship with job performance. An inverted U shape relationship was determined between individual learning and some aspects of multi team membership variety. There is a positive relationship between variety 3 (expected results of the job the individual performs) and individual learning. Variety competency squared has a negative relationship with individual learning. Emotional skills and social skills negatively moderated the relationships between job performance and aspects of multi team membership variety. Cognitive skills positively moderated the relationship between multi team membership variety aspect and job performance. No moderators for negative relationship of individual learning with high multi team membership variety were found.

7.2 Theoretical Contribution

The study established two components of multi team membership variety which are variety competency and variety collaboration. Variety competency contains aspects such as skills individuals, learned by training or experience, to do their job in a team, working methods individuals use to perform their job, characteristics of principal or client that are part of the team, to what extent are the tasks in work teams different, to what extent are your roles different, to what extent are the technologies used different in the teams and To what extent are the knowledge, skills, and abilities necessary to work effectively different. Variety collaboration covers expected results of the job individual performs, level of collaboration individual has within teams, expectations of team leader of team members and to what extent are the geographical locations different.

7.3 Managerial Recommendation

Managers who employ individuals for working in multi team membership variety in the engineering field should prioritise candidates with high cognitive skills. This will help reduce the negative impacts of multi team membership variety on job performance as cognitive skills positively moderate the relationship between job performance and aspects of variety.

7.4 Future Study Recommendation

Future studies can be conducted in broader field of spectrum by not limiting the study in Engineering teams. Expanding the area of study can help gather a huge sample of data and get a more general view of the effects of multi team membership variety on individual performance and individual learning together with the moderation effect. Further study into the moderation of the relationship between multi team membership variety with individual learning is required.

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Appendix 1: Measurement of variables

Table 6 contains the measurement items for the constructs of multi team membership variety. Also provided in the Table are the variables being measured, dimensions under concern and multi team membership variety items. Table 7 contains the measurement items for dependent variable. Table 8 contains the measurement items for the moderators.

Table 6: Measurement of multi team membership variety

Variable	Dimension	Items
MTM Variety in Tasks, Procedures, and interpersonal expectations across teams [4]	Skill and training Procedure	Skills individuals, learned by training or experience, to do their job in a team
		Working methods individuals use
	Interpersonal expectations	Expected results of the job the
		Level of collaboration the
		Expectations of the team leader of the individual team members
		Characteristics of principal or client that are part of the team
MTM Variety in Team Members, Team Tasks, Roles, Technologies, locations, Skills, and Ability [9]	Task	To what extent are the tasks in
	Roles	To what extent are your roles
	Technologies	To what extent are the technologies used different in the teams

	Skills and Ability	To what extent are the knowledge, skills, and abilities
	Locations	To what extent are the geographical locations of the teams different
	Team members	To what extent are the people that you work with different

Table 7: Measurement of dependent variables

Dependent variable	Items used
Job performance [11]	Carried out the core parts of my job well
	Completed my core tasks well using the standard procedures
	Ensured my tasks were completed properly
	Adapted well to changes in core tasks
	Coped with changes to the way you must do your core tasks
	Learned new skills to help you adapt to changes in your core tasks
	I am willing to make my efforts for job goals
	I put a lot of energy into my job
	I won't give up my job easily
Innovative performance [4]	Raising new creative ideas and improvements
	Introducing new methods, techniques, or instruments
	Ability to mobilize support for new innovative ideas
	Individual innovative ideas are approved by team members
	Capability to implement their new innovative ideas
	Able to systematically implement new innovative ideas systematically
Individual learning [12]	There are a lot of new things you learn from the tasks you did in the
	It is an important part of being a good team member is to continually improve on your work skills
	Are you very satisfied with making a tough decision
	Is it important for you to learn from your project experiences
	Do you spend a considerable amount of time learning new work
	Are you always learning something new in your work areas
	Is making mistakes part of your learning process
	Is learning how to be a better team member very important to you
	Sometimes do you put effort into learning something new

Table 8: Measurement of moderators

Moderator	Items used
Familiarity [4]	Familiarity is the measure of how long in years an individual team member knows his or her team members. The average number of years an individual has worked with other team members is calculated by adding the number of years the individual has worked with each member then divide by number of team members in the different teams the individual is part of.
External advice [14]	How frequent an individual gets external advice on work related issues. The scale which will be used is 1=monthly, 2=weekly, 3=daily, 4=several times a day
Instant messaging [14]	How frequent do you use instant messaging for work related purposes? on a 0 to 4 points scale, where 0= non-use, 1=monthly, 2=weekly, 3=daily, 4=several times a day.
Emotional skills [15]	Is it difficult for you to find the right words for your feelings
	Are you often confused about what emotion I you are feeling
	When you are faced with an emergency with the capacity to endanger life or major property would it make you nervous
	Are you good at "reading" the feelings of others even when you are in highly stressful situations
	Can you keep yourself calm even when you are in highly stressful situations
	Do you usually know what it takes to turn another person's boredom into
	Do you try to think about good thoughts even if you are feeling badly
Cognitive skills [16]	The individual likes to have the responsibility of working in a situation that needs a lot of thinking
	The individual enjoys doing tasks which involves generating new solutions to problems
	The individual prefers working on complex problems compared to simple
	The individual prefers doing tasks which require little thought once the individual learned them
	The individual is excited with learning new ways of thinking
Social skills [17]	The individual can identify when other team members are having challenges with performing their tasks
	The individual can notice that another team members is in a bad mood
	The individual can realize how other team members feel by looking at their facial expression and or gestures
	The individual knows when other teammates are not in a good mood
	The individual has ability to put them self in other's team members place

Appendix 2:

Table 9: Moderators and their effects

Moderator	Definition	Moderating effect
Familiarity	Familiarity at an individual level is the average number of years an individual member has worked with every other member in the team. [4]	High individual familiarity has positive effect on coordination skills, this is done by reducing the challenges associated with coordinating multi team membership. High individual familiarity can foster disclosure of problems by

		team members because of helping to locate, sharing and application of knowledge. This helps in making the relationship between multi team membership variety and individual performance less negative at high individual familiarity. [4]
External advice	Advice from colleagues that help to successfully complete work.[14]	Knowledge that is obtained from informal social networks and combined from different sources is very important to increase innovative performance. [14]
Instant messaging	Use of collaborative tools such as telephone, email, instant messaging systems and video conferencing systems just to mention a few to complete tasks, support collaboration, foster coordination, transfer information and knowledge amongst individuals within teams. [14]	Instant messaging has both positive and negative impacts on individual performance involved in multi team membership. Positive impact involves getting immediate access to team members and development of both planned and immediate interactions. The negative effect of instant messaging is increased disruptive interruptions in the work environment. [14]
Emotional skills	Strengths that are provided by emotional skills are regulation of emotions while under stressful conditions in a manner that enhances performance of an individual. [16]	Emotional skills positively moderates the relationship between multi team membership variety and individual performance. [22]
Social skills	Individuals who have good social skills can gain social capital which is vital pertaining to work performance. [16]	Social skills positively moderates the relationship between multi team membership variety and individual performance. [24]
Cognitive skills	Cognitive skills are very important for individuals pertaining to gaining of knowledge of facts, procedures, and rules. Cognitive skills give individuals the ability to develop strategies and techniques to get information from the environment. [16]	Cognitive skills positively moderates the relationship between multiple membership variety and individual learning. [13]

ENGINEERING MANAGEMENT EDUCATION: TRENDS AND ADVANCES

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ABSTRACT

Engineering management is an established discipline in engineering practice, and in the academic domain. Many universities across the world offer masters' degrees in engineering management. However, these degrees vary in terms of their academic focus and curricula, target cohort, admissions requirements (including requirements for work experience) and a number of other dimensions. This paper discusses several emerging trends regarding MEM degrees across the world. The case of a recently launched MEM degree is used to explain the main trends in engineering management education namely a focus on early to mid-career engineers and scientists, an exclusively online hybrid delivery mode and an embedded approach to the development of soft skills. This paper contrasts an engineer's undergraduate education with the real job of the engineer (JoE) in industry to highlight how trends in engineering management education can be utilized to design a contemporary MEM programme that produces "better engineers".

Keywords: Engineering management, education, trends, MEM, job of the engineer (JoE)

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1 INTRODUCTION

Engineering management is a recognised, acknowledged and mature discipline practised in industries across the globe. Similarly, engineering management-related academic endeavours are pursued across the globe as an established academic discipline by universities in terms of their research as well as undergraduate and postgraduate qualifications. A number of learned and professional societies focus on engineering management (such as the IEEE Engineering Management Society), many peer-reviewed journals publish engineering management-related articles and numerous conferences have engineering management as a central theme.

Even a cursory scan of the broader field of engineering management quickly confirms exactly that, i.e. the broadness of the field and the porous boundaries between related disciplines. Academic offerings in this domain, for example, include qualifications in engineering management, technology management, innovation management, project management, construction management and different combinations of these, to mention but a few. Each of the different disciplines has developed a significant body of knowledge, many of which necessarily overlap. It is also interesting to observe different approaches depending on whether they hail from either the engineering or management worlds. This also demonstrates the 'dilemma of definitions', where one person's view of innovation, for example, may be included in another's view of technology and vice versa, which is notoriously difficult to define. It would seem that every textbook that ventures into this semantic quagmire formulates its own definitions. The common thread, though, is the emphasis on the term "management" in the context of engineering, a suggestion that this is something central to "what engineers do".

Against the background of wider trends, this paper explores the specific trend of early to mid-career engineers (and scientists) equipping themselves for that part of the "job of the engineer" that was not emphasised in their undergraduate studies, as well as the impact of the post-COVID uptake of remote studying. A case study of a recently launched master's degree in engineering management (the Stellenbosch MEM) which encapsulates these, is presented.

2 MASTERS DEGREES IN ENGINEERING MANAGEMENT

A number of universities offer undergraduate degrees in engineering management, some of which are related bachelor's degrees in industrial engineering. In this paper, however, the focus is on postgraduate degrees in engineering management, specifically masters' degrees in engineering management (referred as MEM degrees) [1]-[3].

The wide scope of definitions of engineering management referred to above is also reflected in academic offerings by universities, where programmes each have their own focus and emphasis, curricula and apparent target audience. MEM programmes across the world are differentiated with regard to a number of dimensions, including:

- Focus, content and desired outcomes
    - The core curriculum: The mix of engineering management, technology and innovation management, project management, general management and technical subjects
    - Credit weight of and number of taught modules
    - Credit weight of the research project/mini-thesis
    - Range and focus of electives
    - Methods of assessment
- Intended audience, e.g. recent graduates, "five years out", mid-management or more senior management.
- Programme duration
- Full-time/part-time

- Delivery method, viz. residential (typically face-face), online, hybrid or blended. Scope and extent of groupwork.
- Internship required or encouraged (as part of the degree), or not
- MEM offered by the Engineering Faculty, Business School or both (and if so, how much by each), and possibly other academic units such as a Medical School or Law School.
- Entry requirements, including academic qualifications, work experience and entry tests (such as the GMAT)

3 WHAT IS THE "JOB-TO-BE-DONE" (JTBD)?

A multitude of variations on the theme regarding the different dimensions of the MEM programmes on offer is of course to be expected. That is the nature of academia, where there is typically "no single right answer, but [most likely] many wrong answers".

The focus of a specific MEM degree is often articulated in its mission statement, from which one can (loosely) determine its focus. For example, Dartmouth's programme is hailed as "an immersive experience for engineering and science graduates who seek to become leaders in businesses and organizations driven by technology" [4], the Master of Science in Engineering Management (MSEM) programme at Johns Hopkins Whiting School of Engineering "bridges the gap between technology and business by equipping students with the technical expertise and leadership skills they need to advance their career in the fast-paced world of technology" [5], Northwestern's Master of Engineering Management (MEM) programme is "designed for experienced STEM professionals who wish to develop management and leadership skills while deepening their understanding of traditional and emerging technologies" [6] and Warwick's MSc in Engineering Business Management is designed for graduates who want to become managers or leaders of technology-based organisations [7].

Mindful of the variations on the theme referred to above, this type of mission statement can [or should be able to] answer the question, "Who will benefit most from this degree, is this the degree that a specific individual will benefit most from and what will the benefit/value-add be?"

Another way to pose this question is, "What is the job to be done ?"[8], which in turn will inspire the choices that are made with regard to the dimensions referred to above in order to develop a qualification that is fit for purpose for a specific target cohort.

3.1 Framing the problem

As an example of a MEM focussing on a specific cohort, consider now the educational and career trajectory of a typical engineering student, who is pursuing a 4-year undergraduate engineering degree at a university. During these four years of study (and sometimes a little more), the student is exposed to a core bundle of basic science topics, including mathematics and applied mathematics (which preferably includes statistics), physics and often some chemistry. The student then moves on to more applied sciences which can include electromagnetics, thermodynamics and materials. Somewhere during the student's studies (s)he will be exposed to programming and coding. Thereafter the student will explore applications, specifically engineering applications, which build on and are underpinned by the foundational knowledge gained during the initial period of study. Gradually the student is also exposed to design and more applied engineering topics such as processes and manufacturing, maintenance, and reliability. Theory lectures are typically complemented by practical tutorials and laboratory work. During the undergraduate years, the importance of developing communication abilities is stressed, and there may be a little exposure to "business and industry". Contemporary undergraduate engineering education often includes exposure to ethics and sustainability topics. The degree usually requires the student to complete a comprehensive capstone project in the final year, where the student must demonstrate that (s)he can apply the engineering principles and practices of the engineering discipline in which (s)he specialises such as electrical, mechanical, civil, chemical or industrial, for example.

To be registered as a Professional Engineer, the young graduate engineer must complete work prescribed by the Engineering Council of South Africa (ECSA), or similar statutory body in other countries, for a period of circa three years. This is where our young graduate experiences the excitement and challenges of the world of work, under the guidance of an experienced Professional Engineer. A few professions have a similar practice, including law, accounting and medicine.

This model for educating engineers and preparing them to contribute professionally and independently is tried and tested and followed in many countries in the world. In fact, the Washington Accord regulates the recognition of signatory countries' Engineering Councils professional registration by other signatory countries.

3.2 Characteristics of the tried and tested model

To arrive at one specification for a fit-for-purpose MEM degree, specifically for the early to mid-career cohort, it is useful to consider a few characteristics of the model referred to above, viz.

- The lion's share of the undergraduate work is devoted to phenomena and processes that are dictated by the Laws of Mother Nature. These laws are absolute and can be expressed as formulas. They are also unforgiving and are not "open for negotiation". Should a student, for example, be overcome by the urge to philosophise and come to the conclusion that he will henceforth "not believe in gravity" anymore, he will quickly discover that gravity doesn't really care whether he "believes" in it or not – gravity will continue to "happen" irrespective. The same with "time" and many other natural phenomena.
- In this world, "things work" and are "predicable". Calculations based on the formulas explain the natural phenomena and underpin designs, and they support future "forecasts and estimates" (which is another way of explaining a design). This world can be described as one where the student engages with the "beautiful things of life".
- During the undergraduate years, the student is immersed in a world in which the truth is defined by something that is "always true" – if someone can show one case where it is not/true or is false, then the proof/law is invalid. This approach to what is the truth, what is a fact and how things are proven is inculcated into the student. However, it is typically presented as way of "proving mathematical theorems" and other "laws of nature", rather than as a way of thinking about and describing "the truth".
    - Some engineering students may, however, begin to suspect that "not everything is predictable" or easily calculated in closed form, and that Mother Nature is also fond of uncertainty, randomness and even chaos (manifested as the Lorentz effect and as fractals).
- "Problems" are structured and are to be found at the end of a chapter in a textbook, where they are clearly formulated and contain all the information necessary to solve them. Very often the answer is conveniently provided at the back of the book. This may be useful as part of the learning experience in that it enables the student to verify their answers, one should be careful not to assume that this is the case in the "real world". It is not.

Living and growing up (professionally and socially) in the world populated by "beautiful things" and governed by the Laws of Nature, literally day and night (as engineering studies go), the student develops an "engineering mindset". At the same, (s)he is probably not thinking about/is oblivious to the fact that others grow up in a different world and develop a different mindset (including about "the truth", and how "a fact is proven"); and that the real (beautiful) world has significantly more randomness, uncertainty and risk than (s)he ever anticipated.

3.3 Welcome to the real world

After graduation, our young engineer starts his/her first job in the "real world of work". Very soon (probably before the first tea break, if any) (s)he realises that something is amiss. The realisation that the "tried and tested model" is either somewhat incomplete at best or totally misleading at worst. This comes as a shock. (S)he notices that very few (if any) engineers are sitting at their desks eagerly solving partial differential equations. (S)he is required to "work with people" – many of whom come from a very background, i.e. not the beautiful world governed by Mother Nature. They have a different perception of "the truth", and instead speak of "the truth, the whole truth and nothing but the truth" as opposed to "the truth". They assume something is true if you can show one case where it is, but under certain conditions (which are often difficult or impossible to replicate) – as opposed to something is false if you show one case where it doesn't hold. It becomes obvious that these "other people" live in a world governed by the "Laws of Man (and Women)", inspired by the norms of society and changed when the "majority no longer deem them" to be applicable. These laws are subjected to the "democratic will of the majority", they can be contested, negotiated, changed and repealed. Even if these laws are manifested in more subtler forms, such an unwritten company culture, their transgression can still have dire consequences.

Apart from contributing to multi-disciplinary teams in his/her own organisation, the young engineer needs to work with customers, suppliers and engage with competitors as well as learning the skills to "manage your boss". Very soon (s)he will be expected to take leadership and management rolls, which include leading, managing and taking responsibility for other people.

In addition to getting to grips with the "people issues", our young engineer soon also learns that (s)he must also be able to contribute to and take a leadership role in the management of projects, budgets, organisational development, technology and innovation – most of which are far removed from the beautiful world governed by Mother Nature's Laws.

In essence it soon becomes evident to our young engineer that the "job of the engineer" (JoE) entails much more than what (s)he was exposed to during undergraduate studies, together with the discovery of an entire new world – the "other part of the job of the engineer". A large element of the value of the undergraduate qualification is instilling an engineering mindset. However the practicing engineer will probably very rarely be "doing the calculations" that were so prominent in his/her undergraduate studies in this new world of work. (S)he will probably be spending most of his/her time and effort on the "other part of the job of the engineer".

It is at this stage that the young engineer articulates this dilemma and starts seeking solutions. Initially this will probably include reading "management books" and instinctively copying his/her boss's (bad) habits - none of which are ideal. It is important to stress again, that the young engineer will (hopefully) learn much about the JoE "on the job" as a practising young engineer. This is essentially the aim of the requirement for several years' experience to register as a Professional Engineer.

The broader problem can be summarised as follows:

- The undergraduate education is a necessary component of the education and training of the engineer (as discussed above), including the instilling of an engineering mindset.
- However, the "job of the engineer" entails much more than what is formally addressed in undergraduate studies. The undergraduate education is hence necessary but not sufficient.
- There is a "clear and present" need for the young engineer to gain the knowledge and skills necessary to conduct the "other part of the JoE". A case can be made that a structured MEM degree designed specifically for early to mid-career engineers can contribute significantly towards preparing them for this. It adds (many of) the aspects

required for the other part of the JoE which were not addressed during the undergraduate years in a formal postgraduate educational setting that will accelerate and augment their (early) work experience. In this regard, the aim of the MEM is to produce “better engineers”.

4 AN MEM FOR EARLY TO MID-CAREER ENGINEERS

Assuming that there is a need (and market) for an MEM specifically designed to address the requirements of early to mid-career engineers, one can surmise the following would be the characteristics of such a qualification:

- It must address significant elements of the JoE, specifically those not addressed in the undergraduate education, and empower the student to equip him/herself to deal with current job demands as well as those that will arise in the future.
- It must enable the young engineer to acquire skills and knowledge required for the job (s)he is doing now, including the leadership roles (s)he is required to take on.
- At the same time, it also necessary to enable the student to build the skills and knowledge foundations that will serve him/her throughout their career. This principle inspires another vantage point on the nature of “soft skills” that need be cultivated.
- Recognising that young engineers have a high degree of mobility and travel often, the delivery mode and interaction with lecturers and other students needs to be flexible. In addition to having recently commenced on career trajectories, many of them will also recently have started families, which further complicates tumultuous lifestyles.

4.1 Soft skills…. the next generation

There is general agreement that people in the workplace (including young and more mature engineers) must have a number of soft skills… and the ability to apply them. The “usual suspects” of these soft skills typically include people and interpersonal skills, communication skills, the ability to work in teams, various element of emotional intelligence and (very important) professional ethics. It is not unusual for these skills to also be addressed in a more or lesser degree in the undergraduate engineering education.

The MEM degree would also strengthen these. Requiring students to conduct a number of assignments in groups, is particularly useful to develop practical teamwork skills. These include experiencing the manifesting of the 80/20 principle about “who (really) does the work”, taking the lead and convincing others of a viewpoint. In a post-COVID world, it is also necessary to hone online cooperation skills, not only regarding the technicalities of online platforms such as Teams and Zoom, but particularly also online meeting etiquette and behaviour.

However, there is also another range of soft skills which young early to mid-career engineers need to be exposed to. The sort of skills which a senior end-of-career engineer might comment, “I wish someone had pointed these out to me when I was young(er)”.

The first of these is the principle of the “importance of proactively contributing towards shaping a better future, rather than merely reacting to a world dictated by others”. This principle has several profound implications. It is underpinned by the notion that the “future will happen” whether we want it to or not (just as gravity), but that we (as engineers) can and must make a difference towards creating a better world – proactively (i.e. recognising the importance of dynamics in terms of “timing is everything”). This notion leads to the understanding that many of the things that will happen, exist and be important in the future are not known today – and we would be foolish to think and act otherwise. It is important to proactively “anticipate the future” – particularly also the technological future - even though we might not be able to really predict it (i.e. recognising the importance of uncertainty and risk).

On a personal level, the implication is to recognise the importance of "lifelong learning", and that you are responsible for your own lifelong learning. The underpinning principles are captured in a 2x2 knowledge framework that distinguishes between "know knowns, know unknowns, unknown unknowns and unknown knows" [9], [10] coupled with the fact that new knowledge is being created at an astonishing rate whilst "old" knowledge becomes obsolete; and we discover that things we "thought were true/facts", just aren't (anymore) [11].

This being the case, it is important to develop the skills and the discipline to continue learning "in perpetuity". In fact, Jack Welch (former CEO of GE) argued that the ability to learn faster than one's competitor (and have the ability to act on it) is the ultimate sustainable competitive advantage [12].

Attaining a formal qualification such as a degree – be it undergraduate, masters or doctoral – is not the end of the "educational journey". Instead, it signals the start of a new journey. The difference being that once the formal education is completed, you no longer have the "academic luxury" of a lecturer that will present you with a structured curriculum, selected readings and carefully crafted assignments (even though they may be unstructured). As part your responsibility for your own lifelong learning (whether it leads to a formal qualification or not), you need to identify "what is new and what is important" (mindful of the increasing volume of "fake knowledge" that abounds) and then what to learn. You also need to know when you have actually learnt something (i.e. recognising the impact of the Dunning-Kruger effect [13]).

A case can therefore be made that an essential soft skill is "learning how to learn", and the habit of practising the discipline that this requires (i.e. "if you want to be a leader, you have to be a reader"). One of the major objectives of the MEM is thus to enable the student to develop a "Personal Learning Strategy" (PLS), so that by the time (s)he graduates, professional lifelong learning has become a natural element of his/her professional lifestyle.

A similar approach applies to decision-making. Every waking (and often also non-waking) moment, every individual makes conscious decisions, be it in their personal or professional lives.(i.e. recognising that "the decision not to a make decision is also one"). Some decisions are made as individuals, some as part of a group. Increasingly, engineers are also creating machines that will make autonomous decisions. The practicing engineer should conscientiously master the challenges and opportunities presented by all of these. The sooner the better.

A further case can therefore be made that another essential soft skill is to "enhance the quality of decision-making". This not only requires a better understanding of the neurological processes involved, but also of a wide range of biases and heuristics that may impact on the quality of decision-making. There are many techniques and decision-support mechanisms that can promote better decisions and moderate bad decisions. In a similar manner to the development of a Personal Learning Strategy, the MEM student should also be encouraged to develop a Personal Decision-making Strategy (PDS).

Taking a more holistic view of the PLS and the PDS, one can envisage the notion of a personal "EM Toolbox", which the student will populate with "EM tools" to be used throughout his/her career. Some of these tools will be developed/acquired proactively, such as the PLS and PDS, others, as the engineer comes across them (perhaps as part of his/her quest for lifelong learning) and still others as the need arises (i.e. rather than relying on the principle of "if you have a hammer every problem is treated as a nail", search for and acquire appropriate EM tools for your personal EM Toolbox). Part of the associated learning is to develop the insight to know when each tool is preferred/appropriate, or not.

Whereas the PLS and PDS are obvious tools for the engineer's EM Toolbox, it is also helpful to encourage MEM students to cumulatively populate their EM Toolboxes with a range of other tools. EM tools can be categorised as concepts, laws, and methods. This would ideally also become a lifelong professional habit. Table 1 shows a number of typical examples of potential tools for the EM Toolbox.

Table 1: Typical example of tools for the EM Toolbox

Concepts		
Competitiveness and resilience	Effectiveness, efficiency, productivity and resilience	Economies of scale and scope; and scalability
Sunk costs	Tipping points	Dunning-Kruger effect
Laws		
Murphy	Parkinson	Goodhart
Campbell	Diminishing returns	Large numbers
Methods		
2x2 Matrices (incl. Knowledge, Eisenhower, BCG, SWOT, Ansoff)	Sensity analysis	Failure Modes Effect Analysis (FMEA)
TRIZ	Pareto 80/20 principle	Theory of Constraints
TQM and 6 Sigma	Cost-Benefit analysis	McKinsey 7S
Balanced Scorecard	5 Why(s)	Starburst

5 THE MEM VIS-À-VIS THE MBA

As indicated above, the young engineer who finds him/herself increasingly being immersed in management roles will undoubtedly have a need to understand and undertake these management tasks “at the coal face”. As suggested above, many will recognise the value of a formal qualification, specifically on the masters’ level, that will support their goals.

The MEM degree is an obvious choice, mindful that the aim of the MEM is to deliver “better engineers”, by preparing engineers for the “other aspects of the job of the engineer” that were not addressed in their undergraduate education. To be clear, the “job of the engineer”, includes the management of many things, including people, budgets, processes, technologies, innovations and many related issues. Should an engineer be called to manage a company, for example, then (for that engineer) it is also part of the “job of the engineer”.

Having recognised the need for more formal management training, many young engineers are faced with the decision of whether to pursue and MEM or an MBA. Eventhough the aim of this paper is not to discuss the nature of MBA degrees, we point out to students that (as we see it), the objective of the MEM is to make you a better engineer and with that doing the “job of the engineer” (which includes many aspects of management”. The objective of the MBA is to make you a better manager. Many MBA degrees also emphasise the portability of their degree. This is understood to imply that the principles of management are universal and can be applied across many industries and companies (i.e., “if you can manage something, you can manage anything”).

In our research, particularly regarding the juxtaposition of MEM degrees versus MBA degrees, we came across a number of interesting and enlightening insights, including the following:

- The Master of Engineering Management Programs Consortium (MEMPC) is a "dedicated group of forward-thinking universities in the US working together to promote engineering management programs to students and organizations. MEMPC is devoted to sharing best practices in engineering management education and creating a knowledge and talent pipeline between students and employers through outreach and partnerships". The members of the MEMPC are all highly regarded and reputable universities in the US, consisting of Cornell University, Dartmouth College, Duke University, Johns Hopkins University, the Massachusetts Institute of Technology, Northwestern University, Purdue University, Tufts University and the University of Southern California [14].

  The MEMPC notes that, "While MBA and MEM programs share some similarities in shaping capable leaders through a core curriculum in economics, marketing, and operations. Students with MEM degrees are a better fit for today's technology companies simply because an undergraduate degree in a STEM field is a prerequisite for admission. Since it is not a prerequisite for an MBA, a majority of candidates graduate with a non-technical education…. In a world where technology touches almost all aspects of life and business, students with a MEM degree fit seamlessly into today's high-tech companies that need tech-savvy leaders for data-driven decision making and innovation-driven global strategy and growth".

- Dartmouth College (one of the eight Ivy League universities in the US) noted that "Upon graduation, a Dartmouth MEM degree-holder commands, on average, a starting salary 36% higher than a holder of a BS degree in engineering, and this difference increases with the number of years past graduation. Ten years out, the Dartmouth MEM grad enjoys a compensation that rivals or exceeds that of an MBA degree holder with the same seniority"[4].

6 CASE STUDY: MAKING IT REAL – THE STELLENBOSCH MEM

The Faculty of Engineering at Stellenbosch University recently established a new MEM degree specifically aimed at early to mid-career engineers and scientists. The design of the degree was guided and inspired by the principles discussed above and in section 4.1, careful examination of MEM trends and curricula of world-leading universities as well as extensive discussions with industry and potential students to determine what they want and need – now and in the future. An example of this is embedded in the MEM is that each student is tasked with developing their own Personal Learning (PLS) and Personal Decision-making Strategy (PDS) in Introduction to Engineering Management in the first semester of their first year. Decision making in the face of uncertainty is a central focus of the module Quantitative Management for Engineers. Various important industry-relevant soft skills including interpersonal, team, leadership, change management and communication skills are taught in the module Advanced Engineering Management. The students' management abilities are developed and enriched by the modules Advanced Strategy Management, Technology Management, Innovation Management and Project Management. Students are encouraged to select an elective module from a comprehensive list based on their own unique interests and industry context. Several electives are exclusive to the MEM programme and are taught by industry experts.

The Stellenbosch MEM (SU MEM) is a structured masters' degree, with eight modules (15 credits each), of which seven are required and one is an elective; as well as a Research Assignment (60 credits). Mindful of the clearly expressed preferences of the target cohort segment, the degree is delivered in an hybrid online format only [15].

During the COVID pandemic, the world was forced to go online, and technologies that enabled this developed at apace. Not only was it demonstrated that mass remote working was possible, but in many cases it became (and remains) a preferred mode. The same technologies that powered remote working were also adapted for remote learning. It was demonstrated that remote learning on a university level, specifically for structured masters' degrees such as the MEM, provide a feasible route for a quality education.

All the SU MEM students are employed and study part-time. The online format and the integrated nature of the modules allows for great flexibility and enables the students to structure their academic activities to dovetail into their work schedules and personal lives. The curriculum has been designed for a hybrid online delivery mode from the outset, supported by a grant from the University specifically for this purpose.

Now in its second year, early indications are that the degree resonates with the target audience and is very well received by students and their employers. On the whole, the feedback from our students have been very positive and encouraging. More than 8o students were enrolled in the first year of offer (2022), more than 100 in the second year (2023) and applications for the third year (2024) are encouraging.

The hybrid online delivery mode enables students from all over the world to enrol, and students from all across the globe have done so. Currently students from/based in South Africa, Namibia, Zimbabwe, Lesotho, eSwatini, Rwanda, New Zealand, Australia, the US, Canada, the UK, Ireland, France, the Netherlands, Switzerland and Saudi Arabia have enrolled. In addition to students with an engineering background, the degree is also open to students who hold BSc-type science type qualifications and it has attracted students from academic backgrounds which include architecture, quantity surveying, physics, metallurgy and computer science.

Although the primary target cohort is early to mid-career engineers and scientists, it is interesting to note that many mid-career to senior engineers have also enrolled and find the degree useful. A number of our students already have PhD and MBA degrees, and they tell us that the SU MEM brings dimensions to their education which they did not experience elsewhere. A further interesting observation is that many of our students have moved location and to new employers since commencing their studies, in a number of cases to different continents; they travel to exotic locations for work; and a number have gotten married. They tell us that the flexibility of the delivery mode has enabled them to continue seamlessly with their MEM studies, despite all of these changes.

7 CONCLUSION

Engineering management is an established discipline in engineering practice, and similarly in the academic domain. Many universities across the world offer academic qualifications, specifically also masters' degrees in engineering management. The degrees vary in terms of their academic focus and curricula, target cohort, admissions requirements (including requirements for work experience) and a number of other dimensions. The degrees are typically offered by engineering schools, in some cases by engineering schools who collaborate with business schools, medical schools and law schools; and in some cases by business schools. The notion of "management" is a common thread.

A number of emerging trends with regard to MEM degrees are discussed in this paper. The focus is on early to mid-career engineers and scientists, an exclusively online hybrid delivery mode and a fresh look at soft skills requirements. A case of a recently launched MEM degree which encapsulates all of these is presented, viz. the Stellenbosch MEM. It is noted that early indications are that the Stellenbosch MEM is well received by students and their employers.

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AN INTEGRATED APPROACH TO REDUCE OPERATING COST FOR GOLD MINES.

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ABSTRACT

The mining of gold ore is a lucrative industry, but it is virtually difficult to regulate the fluctuations in currency and commodity prices caused by the world economy. However, miners have control over their operations by eliminating inefficiencies, reducing operating expenses, and boosting output. The difficulty most businesses confront is how to reduce their operating expenses, move away from impulsive cost cutting, and develop long-term initiatives for cost management. This study aims to analyze and provide an integrated method for gold mining operating cost optimization or reduction. It goes over how operational efficiency gaps can be found and closed using benchmarking and the implementation of Lean/Six Sigma approaches. We adopted a quantitative study, it utilized the analytical approach to provide guidelines and examples of where achievable and measurable reductions in operating costs and increased efficiencies are obtainable for mobile loading equipment, conveyor systems, transport equipment and infrastructure.

Keywords: Gold mining, Efficiency, Operating costs, Equipment utilization.

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1 INTRODUCTION

The gold mining industry is well-known for being highly profitable, but it is influenced by unpredictable changes in currency and commodity prices caused by the global economy. Miners cannot directly control these external factors, but they can make their operations more efficient by getting rid of waste, reducing expenses, and maximizing their output. However, mining businesses face a persistent challenge of finding long-term solutions for cost management instead of just making quick cuts. In order to succeed in this fast-paced industry, it is crucial for mining companies to reduce their operating expenses. This requires a comprehensive approach that goes beyond short-term fixes. By taking a strategic view, mining companies can identify and address inefficiencies and wasteful practices in all aspects of their operations, such as exploration, extraction, processing, and transportation. This way, they can find ways to optimize costs without compromising safety or quality.

Furthermore, it is important for mining companies to move away from reactive cost-cutting measures and focus on long-term strategies that prioritize efficiency, productivity, and innovation. This includes investing in advanced technologies and equipment, implementing strong maintenance and asset management systems, streamlining supply chain processes, and fostering a culture of continuous improvement. By integrating these initiatives into their operations, mining companies can achieve sustainable cost reductions while also improving their overall performance and resilience.

This study aims to investigate and propose integrated strategies to lower operating costs in gold mining operations while ensuring productivity and safety. By analysing various aspects of the mining process, including equipment utilization, energy consumption, labor management, and supply chain efficiency, the research seeks to identify areas for improvement and develop practical solutions. This integrated approach may involve leveraging advanced technologies, optimizing production processes, streamlining workflows, and implementing cost-effective maintenance strategies. Additionally, the research will examine resource utilization to minimize waste and reduce environmental impact. The goal is to provide gold mining companies with a comprehensive framework for reducing operating costs, enhancing production output, increasing profitability, improving sustainability, and strengthening their competitive position in the industry.

This paper is organized as follows: In Section 1 this study introduced the research topic and defined a problem statement, in section 2, we review relevant literature and describe the research methodology. In Section 3 we analyzed and discussed the finding, Section 4 outlines the guidelines for the proposed integrated approach and concludes the paper.

1.1 Problem statement

In gold mines, there are problems with the efficiency of equipment used for loading, transporting, and moving materials. This causes higher costs and a need for improvement. The inefficiencies are caused by outdated technology, not maintaining the equipment properly, inefficient workflows, not using resources effectively, and not providing proper training. To solve these problems, it is important to use newer technology, maintain the equipment well, improve coordination between different tasks, use resources efficiently, and train workers properly. By doing this, gold mining operations can become more efficient, save money, and be more successful.

1.2 Aim

The aim of this study is to investigate and propose an integrated approach to address efficiency gaps in mobile loading equipment, conveyor systems, and transport equipment within gold mines. The study aims to identify specific strategies and interventions that can optimize operations, reduce operating costs, and enhance overall cost-effectiveness in gold mining activities.

1.3 Major Objectives

- Identify the specific inefficiency gaps in mobile loading equipment, conveyor systems, and transport equipment within gold mines.
- Propose an integrated approach that addresses the identified inefficiencies and aims to optimize operations, reduce operating costs, and enhance cost-effectiveness in gold mining activities.

1.4 Minor Objectives

- Analyze the impact of inefficiency gaps on operating costs in gold mines.
- Evaluate existing practices and technologies used in mobile loading equipment, conveyor systems, and transport equipment within gold mines.
- Propose specific interventions and strategies to improve efficiency and reduce operating costs in the identified areas.

1.5 Significance of the study

This study is important because it can help gold mining companies become more efficient and reduce their operating costs. By finding ways to improve mobile loading equipment, conveyor systems, and transport equipment, the study aims to make mining operations better and save money. This research can also promote sustainability by reducing waste and using resources more wisely. The findings can benefit mining companies, industry professionals, policymakers, and local communities. Mining companies can save money and grow, policymakers can make better rules, and local communities can have more jobs and a cleaner environment. Overall, this study is significant because it can bring positive changes to the gold mining industry by making it more efficient, saving money, and being better for the environment.

1.6 Scope

The study will investigate the problems related to inefficiency in mobile loading equipment, conveyor systems, and transport equipment within gold mines. It will focus on understanding the causes of these inefficiencies and how they affect operating costs. The study will analyze the current practices, technologies, and processes used for these equipment systems. It will also explore different ways to improve efficiency and reduce operating costs. The study will select specific journals, research papers and websites to examine, and it will mainly look at the operational aspects of gold mining operations and their costs. The goal is to find solutions that can improve productivity, safety, and environmental sustainability in a straightforward manner.

2 LITERATURE REVIEW

2.1 Introduction

The literature review is an essential component of the study as it provides valuable insights and knowledge related to improving operating costs in gold mines. By reviewing existing research, studies, and publications, the researchers can gain a comprehensive understanding of the current state of knowledge and identify the most effective strategies and approaches used in similar contexts. This review will establish a theoretical foundation by examining relevant theories and models, helping guide the research methodology. Additionally, it will identify best practices and successful case studies in the mining industry that have reduced operating costs while maintaining productivity and safety standards. The literature review will also highlight research gaps, enabling the study to contribute new knowledge and insights to the field. By building on existing knowledge, the study can validate previous findings, extend theories, and propose innovative approaches. Overall, the literature review will ensure the study is grounded in existing scholarship, inform the research design, and contribute to the advancement of knowledge in gold mining cost optimization.

2.2 Cost optimization strategies in the mining industry

The mining industry is facing increasing pressure to reduce operating costs and enhance cost-effectiveness, particularly in the context of gold mining operations [16]. As a result, there is a significant amount of literature available on cost optimization strategies in this industry. One key approach that has been widely studied is the use of advanced technologies and automation to reduce labor costs and improve operational efficiency. For example, research has shown that the use of autonomous mining equipment can lead to significant cost savings, as well as improved safety and productivity. In addition, the use of real-time data analytics and predictive maintenance can help to identify potential equipment failures before they occur, reducing downtime and maintenance costs [3].

Another important strategy is the optimization of supply chain management, including the use of advanced analytics and modelling techniques to streamline procurement, transportation, and inventory management. This can help to reduce waste and minimize costs associated with delays and disruptions in the supply chain [18]. In addition, many mining companies have focused on improving energy efficiency and reducing energy costs through the use of renewable energy sources, such as solar and wind power [4].

Several studies have also highlighted the importance of effective cost management and budgeting practices, including the use of activity-based costing and other cost allocation techniques [19]. By accurately tracking and allocating costs, mining companies can identify areas where costs can be reduced and make informed decisions about resource allocation.

Finally, it is important to note that effective cost optimization strategies require a culture of continuous improvement and innovation. This involves engaging employees at all levels of the organization, promoting a mindset of cost consciousness, and encouraging the development of new ideas and approaches to cost optimization [16]. Overall, the literature suggests that a combination of these and other strategies, tailored to the specific needs and challenges of each mining operation, can lead to significant cost savings and improved cost-effectiveness. However, successful implementation requires careful planning and management, as well as a commitment to ongoing improvement and innovation.

2.3 *Lean Six Sigma in mining*

The use of Lean and Six Sigma methodologies in the mining industry has become increasingly popular in recent years as companies seek to improve efficiency, reduce costs, and increase profitability. A literature review on this topic provides insights into the various approaches, methodologies, and best practices used to implement Lean and Six Sigma in mining operations. Lean methodology is focused on eliminating waste and increasing efficiency in processes. In the mining industry, this can involve reducing the time and resources required for drilling, blasting, and transportation of ore. Several studies have highlighted the benefits of applying Lean principles to mining operations, including improved productivity, reduced costs, and increased safety [17][13].

The Six Sigma methodology, on the other hand, is focused on reducing defects and improving quality in processes. In the mining industry, this can involve improving the accuracy and precision of drilling and blasting operations, as well as reducing variability in ore grades. Several studies have demonstrated the benefits of applying Six Sigma principles to mining operations, including improved product quality, reduced rework, and increased profitability [17][2]. The integration of Lean and Six Sigma methodologies, known as Lean Six Sigma, has also been applied in the mining industry with promising results. This approach combines the waste elimination and efficiency improvement of Lean with the defect reduction and quality improvement of Six Sigma. Several studies have demonstrated the benefits of applying Lean Six Sigma principles to mining operations, including improved productivity, reduced costs, and increased safety [17][2]. However, implementing Lean and Six Sigma methodologies in the mining industry can be challenging due to the unique characteristics of mining operations, such as the complex geology, variability in ore grades, and harsh working conditions. Successful implementation requires a tailored approach that takes into account these challenges, as well as a commitment to continuous improvement and a culture of data-driven decision making [13][2].

Overall, the literature suggests that the application of Lean and Six Sigma methodologies, either individually or in combination, can lead to significant improvements in efficiency, quality, and profitability in mining operations. However, successful implementation requires careful planning, management, and a commitment to ongoing improvement and innovation.

2.4 Supply chain management in supply chain

The mining industry has various stages like exploration, production, and transportation, requiring effective supply chain management. Studies show that advanced analytics and modelling techniques can optimize procurement, transportation, and inventory management, reducing waste and improving efficiency. Building strong relationships with suppliers and stakeholders helps build trust and collaboration. Risk management is important to identify and mitigate potential risks, while sustainability practices focus on renewable energy and responsible sourcing. Continuous improvement and innovation are necessary through employee engagement and a mindset of optimization. Regarding mining equipment, studies emphasize the importance of utilization, maintenance, and scheduling for productivity. Effective strategies in these areas can improve profitability, and advanced technologies aid in optimizing equipment usage. Efficient scheduling, supported by communication and collaboration, is crucial for productivity.

2.5 Equipment utilization and optimization

In one of the studies, they looked at measuring the performance of mining equipment, specifically focusing on utilization and availability. They found that how much equipment is used to be an important factor in determining how well mining operations perform. By improving utilization, they discovered that productivity and profitability can significantly increase. The study also emphasized the importance of effective maintenance and repair strategies to optimize equipment utilization [15].

In another study, they explored how equipment utilization and maintenance impact the productivity of gold mines. They found that both utilization and maintenance play critical roles in determining the productivity of gold mines [5]. Effective maintenance strategies were found to improve equipment availability and utilization, resulting in notable enhancements. The study also highlighted the value of advanced technologies like predictive maintenance and real-time monitoring in optimizing equipment utilization and maintenance. A third study [6] focused on optimizing equipment scheduling in underground gold mines. They found that effective scheduling strategies are crucial for maximizing equipment utilization and productivity. The study revealed that incorporating advanced scheduling tools and techniques can lead to significant improvements in scheduling efficiency. Effective communication and collaboration between different departments and stakeholders were also identified as vital for successful equipment scheduling.

2.6 Maintenance strategies for mining equipment

In one study, they looked at using predictive maintenance for mining equipment. They found that predictive maintenance can be helpful in improving equipment availability and reducing maintenance costs by identifying potential equipment failures before they happen [7]. The study emphasized the importance of collecting and analyzing data to develop effective predictive maintenance strategies. In another study [21], they developed a model for making maintenance decisions about mining equipment. The model combines different maintenance strategies like corrective, preventive, and predictive maintenance. It uses a fuzzy analytic hierarchy process (FAHP) to prioritize maintenance activities based on their importance and urgency. The study showed that the model can optimize maintenance activities, reduce downtime, and improve equipment reliability and availability. In a third [10], they focused on using big data analytics to optimize maintenance in mining equipment. The study found that big data analytics can help identify equipment failures and predict maintenance needs. This leads to better equipment availability and more efficient maintenance. The study also highlighted the importance of integrating different types of data, such as sensor data, maintenance records, and operational data, to develop effective maintenance strategies. Energy cost optimal operation of belt conveyors using model predictive control methodology.

Research suggests that there are four levels at which the energy efficiency of belt conveyors can be improved: performance, operation, equipment, and technology (POET). Existing literature primarily focuses on the equipment and operational levels. At the equipment level, efforts are made to make idlers, belts, and drive systems more efficient. The operational level aims to improve energy efficiency by adjusting belt speed, feed rate, operating status, and time in a coordinated manner. These adjustments are usually formulated as optimization problems. Developing an energy model is an important aspect of optimizing energy for belt conveyors. While research proposed a model for energy auditing, it is not suitable for operational optimization. On the other hand, it proposed an analytical energy model based on the ISO 5048 standard, which is more suitable for optimization calculations.

Optimal control is widely used for energy optimization. It has been used to save energy in pneumatic actuator systems and reduce costs in belt conveyor systems by considering time-of-use (TOU) tariffs and coordinating belt status and time for optimization. These approaches have shown significant energy cost reduction. However, the methods proposed by studies are open-loop control methods and have limitations in dealing with practical issues like disturbances and forecast inaccuracies. Therefore, closed-loop control approaches, such as model predictive control (MPC), are preferred as they can handle uncertainties and disturbances better. Another study used MPC to design closed-loop controllers that incorporate near-optimal switching schemes and binary integer programming (BIP) methods to reduce TOU and electricity costs based on maximum demand. One study investigated the application of MPC with linear programming-based optimizers for energy management in production environments. Similarly, another proposed an MPC approach for closed-loop feedback control to improve the operational efficiency of individual belt conveyors. These optimal scheduling problems typically involve implementing optimal solutions periodically over a time horizon, which some classify as a special class of optimal dynamic resource allocation problems.

2.7 Methodology

The study collects information about inefficiencies in gold mines using existing data and literature. The researcher collects data from research papers, reports, and case studies. The study uses statistical analysis to identify patterns and relationships in the data. The findings are presented clearly, and recommendations are made based on the research. However, the study has limitations as it relies on existing data.

2.7.1 Limitations

- The study relies on existing data, which may have limitations.
- Primary data collection and field observations are not included, limiting the depth of analysis.
- The findings and recommendations may not apply to all gold mines.

Despite these limitations, the study can provide valuable insights for future research and practical implementation of cost reduction strategies in gold mining operation.

3 FINDINGS AND DATA ANALYSIS

3.1 Introduction

Within this section, we delve into the comprehensive analysis and insightful discussion of the findings acquired from the collected data. Our primary objective is to identify significant patterns, emerging trends, and explore potential opportunities for cost reduction. To achieve this, the study employed appropriate analytical techniques and tools, enabling us to derive meaningful insights from the dataset. Our analysis entails a thorough comparison of various mining operations, the identification of shared cost drivers, and a critical assessment of the effectiveness of previous cost reduction initiatives. By delving into these aspects, we aim to provide valuable recommendations and strategies for optimizing operational efficiency and enhancing cost-effectiveness within the mining industry.

3.2 Evaluating rules of thumb using conveyor belt.

In a study that evaluated the conveyor haulage versus truck haulage, the focus was on the costs associated with conveyors and the commonly used guidelines in underground mining. The study aimed to demonstrate how Sherpa for Underground Mines, a software tool provided by Cost Mine, can enhance confidence in these guidelines. Sherpa's speed and engineering capabilities enable a more comprehensive assessment of De la Vergne's rules of thumb, which were chosen for analysis. Below are some of the key rules/assumptions that were examined in the study.

a) An underground mine is more economically served by a belt conveyor than railcars or trucks when the daily mine production exceeds 5,000 tons.
b) As a rule, a belt conveyor operation is more economical than truck haulage if the conveying distance exceeds 1 km (3,280 ft.).
c) The ton-mile cost of transport by belt conveyor may be as low as one-tenth the cost by haul truck.
d) The installed capital cost of a long belt conveyor system to be put underground is approximately equal to the cost of driving the heading in which it is to be placed.

In the study, different mining projects using cut and fill, sublevel long hole, and room and pillar stopping methods were simulated in Sherpa for Underground Mines. These simulations considered typical deposits and varying production rates. As per rule of thumb No. 1, conveying distances were set at 1 km. The analysis, depicted in Figure 1, supported de la Vergne's rule of thumb, which suggests that using a conveyor is economically favorable compared to rail or truck haulage when production rates exceed 5,000 t/d (tons per day). The results aligned with this rule, indicating that conveyor systems are advantageous at higher production rates. The analysis of sublevel long hole and room and pillar methods exhibited similar trends overall. However, in comparison to the cut and fill models in Sherpa, the cost variations above 5,000 t/d were more significant in the sublevel stopping analysis, while the room and pillar analysis showed narrower cost variations.

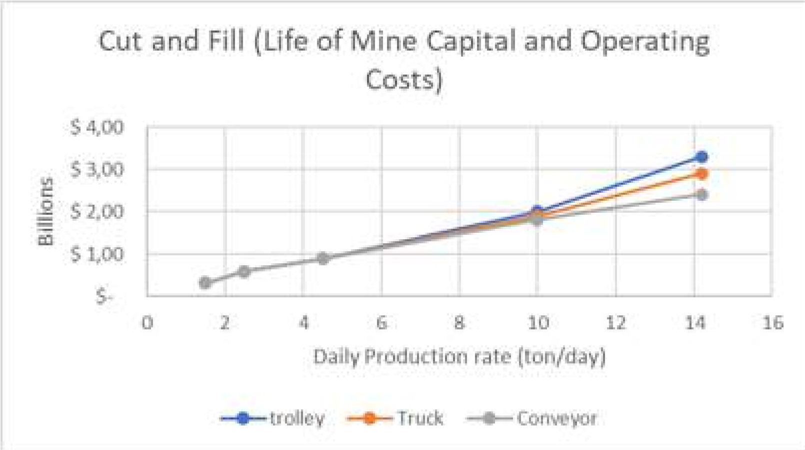

Figure 1: Cut and fill haul method, production rates and LOM costs.

The results show that haul length is a primary factor when comparing the costs of truck and conveyor transport. Production rates also have a significant impact, and above a certain production rate, it is more cost-effective to use a conveyor to transport ore over a specific haul distance. The study also points out the benefits of more detailed analysis, as the finite availability of machine sizes can affect cost per ton. The evaluation shows that conveyor transport costs are typically about 39% of those for truck transport, including the costs of diesel, electricity, maintenance, repair parts and labour, tires, lubricants, and operator for the truck. The results of the analysis indicate that while trucks offer high flexibility and lower upfront capital outlay, conveyor haulage offers a better measure of performance on all three metrics of measuring equipment performance, namely, utilized time, operating time, and valuable operating time. The conveyors achieved an average of 3,509 hours in valuable operating time compared to the average valuable operating time of 2,638 hours for the truck fleet.

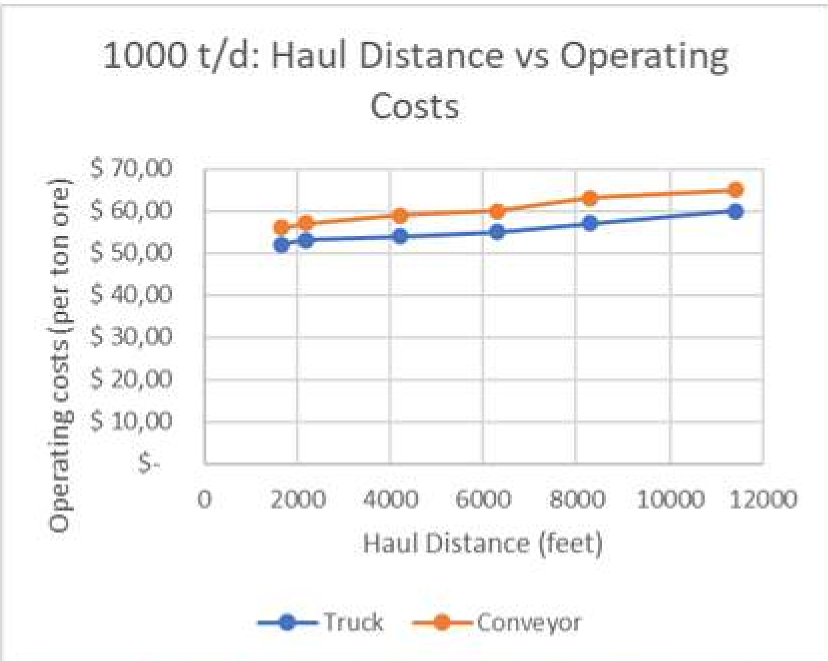

Figure 2: 1000 t/d Haul Distance vs Operating Costs

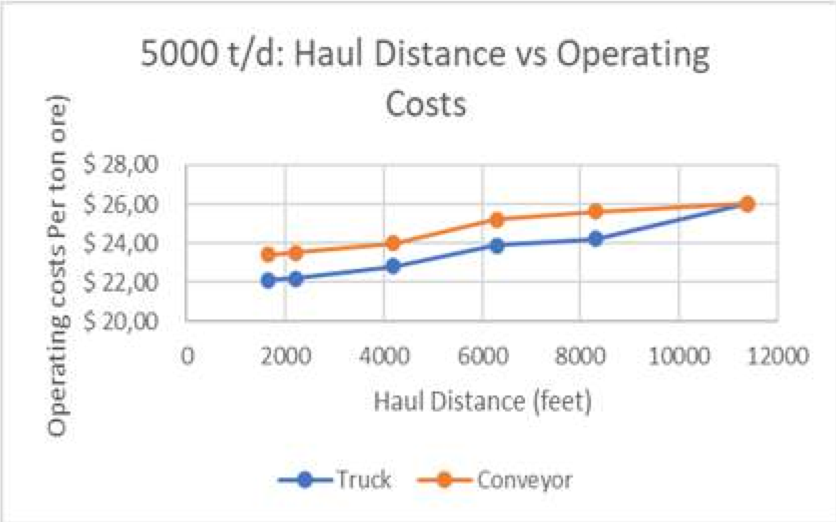

Figure 3: 5000 t/d Haul Distance vs Operating Costs

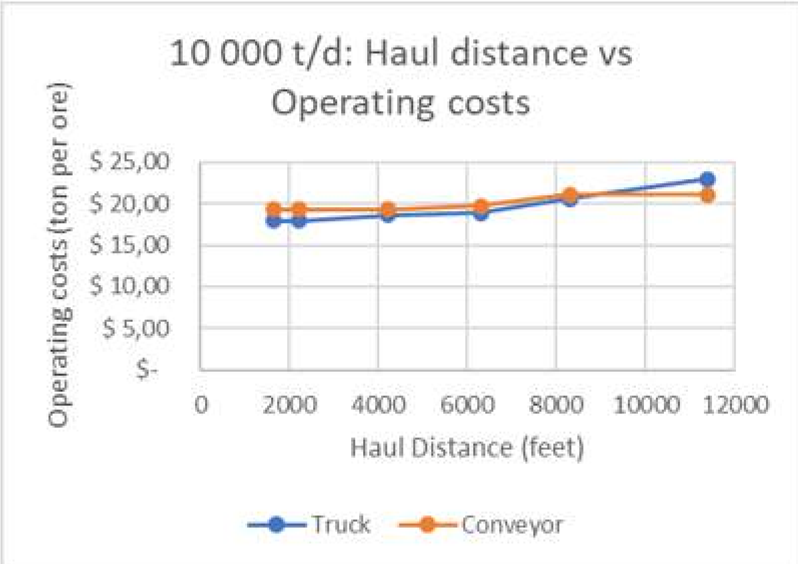

Figure 4: 10 000 t/d Haul Distance vs Operating Costs

3.3 Energy costs and conveying

Determining the lifespan of a motor used in conveyor systems can be challenging since there is no fixed definition for a "typical" motor lifespan. However, Leeson, a manufacturer of electric motors, has developed a rule of thumb for motor life expectancy based on horsepower. For example, a 5 hp motor generally has a life expectancy of approximately 17.1 years, while a 10 hp motor may last up to 19.4 years. This means that a conveyor system installed in 1999 could still be in operation today with its original equipment. Although the conveyor might be technically functional, it is likely to be less energy-efficient compared to newer systems. Therefore, upgrading to more efficient motors and equipment can not only improve energy efficiency but also extend the lifespan of the conveyor system.

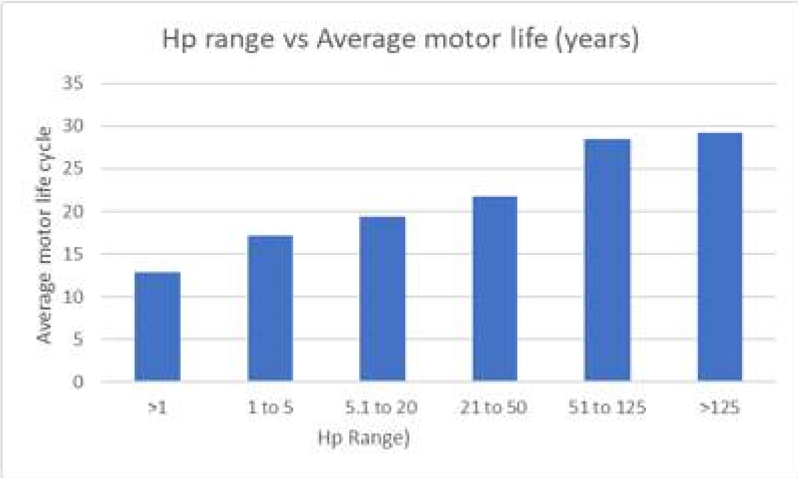

Figure 5: Hp range vs average motor life cycle

4 FRAMEWORK

Based on the findings from the literature review and data analysis, the following framework or set of guidelines can be developed to outline an integrated approach to reducing operating costs in gold mines:

4.1 Advanced Technologies and Automation:

- Implement autonomous mining equipment to reduce labor costs, improve operational efficiency, and enhance safety.
- Utilize real-time data analytics and predictive maintenance to identify potential equipment failures before they occur, reducing downtime and maintenance costs.

4.2 Supply Chain Optimization:

- Apply advanced analytics and modeling techniques to streamline procurement, transportation, and inventory management, reducing waste and minimizing costs.
- Develop strong relationships and partnerships with suppliers, distributors, and other stakeholders to improve communication and collaboration in the supply chain.
- Implement effective risk management strategies to identify and mitigate potential risks, such as natural disasters and supply chain disruptions.
- Incorporate sustainability practices, such as using renewable energy sources and responsible sourcing of raw materials, to meet social and environmental demands.

4.3 Lean Six Sigma Methodologies:

- Apply Lean principles to eliminate waste and increase efficiency in mining processes, such as drilling, blasting, and transportation of ore.
- Implement Six Sigma methodologies to reduce defects, improve quality, and increase productivity in mining operations, including drilling accuracy and ore grade variability.
- Integrate Lean and Six Sigma methodologies (Lean Six Sigma) to optimize efficiency, quality, and profitability, considering the unique characteristics and challenges of mining operations.

4.4 Cost Management Practices:

- Utilize activity-based costing and other cost allocation techniques to accurately track and allocate costs, identifying areas for cost reduction and resource allocation optimization.
- Foster a culture of continuous improvement and innovation, engaging employees at all levels of the organization and promoting cost-consciousness.

4.5 Equipment Utilization and Optimization:

- Focus on improving equipment utilization through effective maintenance and repair strategies, as well as the use of advanced technologies like predictive maintenance and real-time monitoring.
- Optimize equipment scheduling through the use of advanced scheduling tools and techniques, considering effective communication and collaboration between different departments and stakeholders.

4.6 Maintenance Strategies:

- Implement predictive maintenance to optimize equipment availability and reduce maintenance costs by identifying potential equipment failures before they occur.
- Develop maintenance decision-making models using a prioritization approach, such as fuzzy analytic hierarchy process (FAHP), to optimize maintenance activities based on importance and urgency.
- Utilize big data analytics to identify equipment failures, predict maintenance needs, and improve equipment availability and maintenance efficiency.

4.7 Energy Efficiency:

- Consider upgrading to more energy-efficient motors and equipment in conveyor systems to improve energy efficiency and extend the lifespan of the system.
- Evaluate and optimize the energy costs associated with different modes of transportation, such as trucks and conveyors, considering factors like haul length and production rates.

These guidelines provide a comprehensive framework for reducing operating costs in gold mines, covering various aspects from technology adoption to supply chain management, lean six sigma methodologies, cost management practices, equipment utilization, maintenance strategies, and energy efficiency considerations. By implementing these strategies and approaches, mining companies can enhance their cost-effectiveness, sustainability, and overall profitability.

4.8 Conclusion and recommendations

The paper discusses the challenges faced by the gold mining industry in reducing operating costs and improving efficiency. It emphasizes the need for a comprehensive approach that goes beyond short-term fixes and proposes an integrated approach to address inefficiency gaps in mobile loading equipment, conveyor systems, and transport equipment within gold mines. The major objectives of the study include identifying specific inefficiencies, proposing strategies to optimize operations and reduce costs, and analyzing the impact of inefficiency gaps on operating costs.

The literature review highlights various cost optimization strategies in the mining industry, including the use of advanced technologies, automation, supply chain management, and Lean Six Sigma methodologies. It also emphasizes the importance of effective equipment utilization and maintenance, as well as equipment scheduling. The review identifies best practices, successful case studies, and the challenges associated with implementing these strategies in the mining industry.

The findings and data analysis section focuses on evaluating the effectiveness of rules of thumb in conveyor belt haulage and the impact of energy costs on conveying systems. The study utilizes Sherpa for Underground Mines software to assess the guidelines and demonstrates the economic advantages of using conveyor systems over truck haulage at higher production rates. It also discusses motor life expectancy and provides insights into optimizing energy costs in conveying systems.

Based on the research findings, the study recommends implementing the proposed integrated approach to address inefficiencies in mobile loading equipment, conveyor systems, and transport equipment within gold mines. It suggests adopting advanced technologies, automation, and predictive maintenance for improved efficiency and cost reduction. The study also emphasizes the importance of effective supply chain management, equipment utilization, maintenance strategies, and equipment scheduling. Furthermore, it highlights the need for continuous improvement, innovation, and a data-driven decision-making culture in the mining industry.

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A SCOPING REVIEW OF LITERATURE RELATING TO INFRASTRUCTURE COMPONENTS FOR WHOLESALE FOOD MARKETS

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ABSTRACT

Wholesale Food Markets (WFMs) play an important role in the food supply chain by providing storage and distribution facilities that help to preserve food quality. However, WFMs and their infrastructure have received relatively little research attention. This current study presents a scoping review of the literature on WFMs and their infrastructure to identify infrastructure components that may be considered for infrastructure maturity assessment. The PRISMA-ScR approach was used, and bibliometrics data was analysed using Bibliometrix and VOSviewer software. The study found that the physical flow of products, information flow, and cash flow are the infrastructure components reported in the literature. The paper proposes further work to develop a WFM infrastructure maturity model composed of identified infrastructure components to aid in the assessment of WFM infrastructure maturity.

Keywords: Wholesale Markets, Infrastructure, Maturity model, Scoping Review, Literature Review

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1 INTRODUCTION

In rapidly growing economies [1], agricultural value chains ultimately become more diverse to cater to the evolving nature of economic demands [2]. Thus, the complex relationship between agricultural production and consumer consumption is linked through various facilities, such as Wholesale Food Markets (WFMs) across the food supply chain [3]. WFMs are defined as logistic hubs and facilities coordinating and controlling food distribution [4].

WFMs across the globe were reported to employ an estimated 1.5 billion people and have a total value of US$1.5 trillion in 2022 [5]. Globally, WFMs are renowned for improving access to and availability of healthy food while enabling a space for sustainable and resilient food systems development. WFMs create a platform that fulfils the needs of producers (creating a trading place for profit maximisation) and consumers (contributing to food security) [6] by providing efficiency and quality in food distribution [7].

The ability of WFMs to operate effectively might depend on their infrastructure's maturity and readiness to adapt to the changing business environment. According to [8], infrastructure is defined as a collective term encompassing physical, financial, technological, social, legal, and regulatory infrastructure; this is the definition adopted in this study. The concept of maturity in the infrastructure of WFMs refers to the level of development and efficiency that the market infrastructure portrays.

Poor infrastructure usually imposes prohibitive costs [8], ultimately hindering WFM systems' performance and negatively impacting food access, an element of food security. Food security is enhanced through infrastructure development [9] in sectors such as agriculture, which promotes economic growth [10]. Infrastructure development ensures effective interactions between farmers, food processors, food traders, and consumers [11] along the food supply chain. Through infrastructure, WFMs are generally accepted as hubs for economic growth [12]; they play a catalytic role in enhancing the agricultural sector's potential. WFMs are enhanced through innovations such as infrastructural innovation, which prompt the need for exploring infrastructure components.

A maturity model is a technique/tool used to measure different aspects of an organisation [13]. Maturity models describe the development process of selected features, such as an organisation's infrastructure [14]. Maturity models usually encompass four to six maturity stages, whereby each preceding stage portrays greater competency than the previous stage [14] of each feature. This review's main objective is to uncover the components of infrastructure that can be considered in making an infrastructure maturity model, as maturity models can help determine the competency [13] of infrastructure in WFMs. This research will benefit WFMs nationally and internationally.

This review paper seeks to identify some of the components of infrastructure for WFMs by addressing the following formulated research questions:

I. What WFM infrastructure components are reported in the literature body?
II. What are the key concepts in the literature related to WFMs?
III. What are the advantages of using high infrastructure maturity levels in WFMs?

2 METHODOLOGY

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) methodology guided this Scoping review. The systematic approach offers structure to the scoping review, magnifies the study's reproducibility, lowers bias, and assures that the investigation is exhaustive enough to capture scientific value [15].

This Scoping review followed a sequence of techniques shown in Figure 1, starting with identifying keywords related to the topic through a preliminary literature review to avoid theoretical deviation.

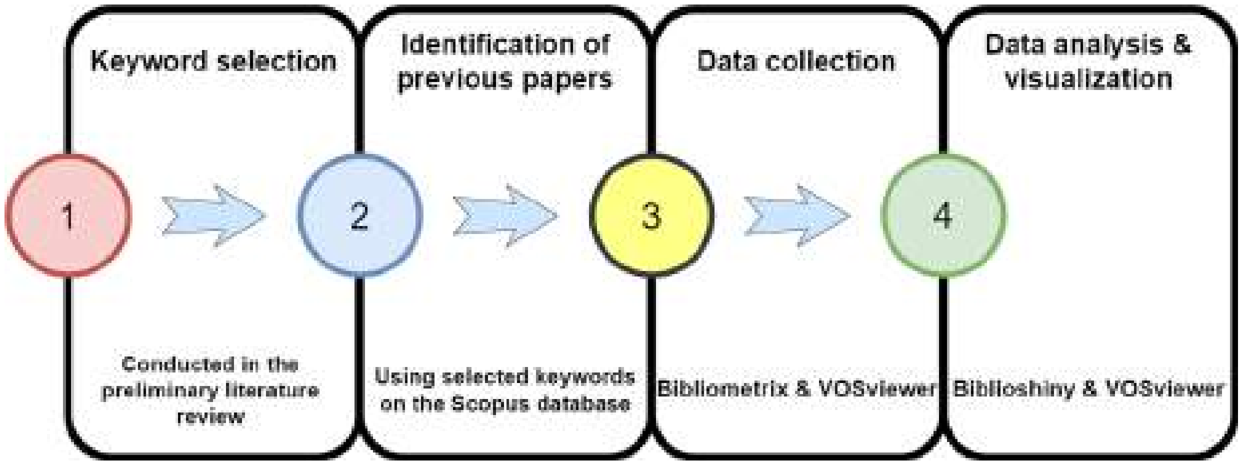

Figure 1: Methodology Process

The preliminary literature review assists in positioning a research concept [16] to the existing body of knowledge. All identified keywords were subsequently used to generate and access peer-reviewed articles and other relevant research papers, such as conference papers from the Scopus database. The Scopus database was chosen because it is a repository of a significant range of research contributions relevant to our research questions [17].

This scoping review conducted a bibliometric analysis of research publications using multiple bibliometric tools, such as Bibliometrix, an R programming package and its user interface, Biblioshiny, and VOSviewer. The tools were utilised for data collection, analysis, and visualisation. Bibliometrix helps perform a manageable workflow for bibliometric analysis [18]. Moreover, the Bibliometrix tool programmed in R is flexible and advanced, making it significant in a rapidly changing science [19]. In addition, Bibliometrix programmed in R is preferred over other tools because it offers effective statistical algorithms and access to high-quality numerical routines, which makes it the strongest in scientific computation [20]. VOSviewer is a software with the same functions as Bibliometrix. However, it was used in this study because it has text-mining capabilities that can construct network maps, such as keyword co-occurrence maps [21].

The keywords identified in the preliminary literature review stage were grouped into Wholesale Food Markets, Infrastructure, and Producer and consumer relations. All are presented in Table 1.

Table 1: Search keywords

Category	**Search keywords**
Wholesale Food Markets	"Wholesale food market*" OR "Fresh food market*" OR "Food wholesale market*" OR "Produce centre" OR "Food hub" OR "Food distribution centre*"
AND	
Infrastructure	"Logistics facility*" OR "Warehousing equipment" OR " Infrastructure*" OR "Logistics asset*" OR "Hardware*" OR "Technology*"
Producer and customer relations	"Wholesaler*" OR "Food distributor*"

The eligibility criteria in Table 2 were used on the Scopus database while searching for research papers using keywords in Table 1. The selection criteria are crucial as they narrow a diverse range of research papers to the only significant ones. The goal of relevant research-based literature is to connect past knowledge to current knowledge while maintaining relevancy.

Table 2: Eligibility criteria

Eligibility criteria	
Language	English
Subject areas	Engineering; Social Sciences; Business, Management, & Accounting; Agricultural and Biological Sciences; Economics, Econometrics & Finance; Decision Sciences

The review used the selected subject areas as they are more relevant in covering a broad scope of business and economics that contributes massively to business-related models such as the one the present study aims to research for WFMs. In addition, the selected subject areas also ensure the viability of literature, promoting the probability of acquiring adequate and reliable results in analysis following the conceptual framework process depicted in Figure 2.

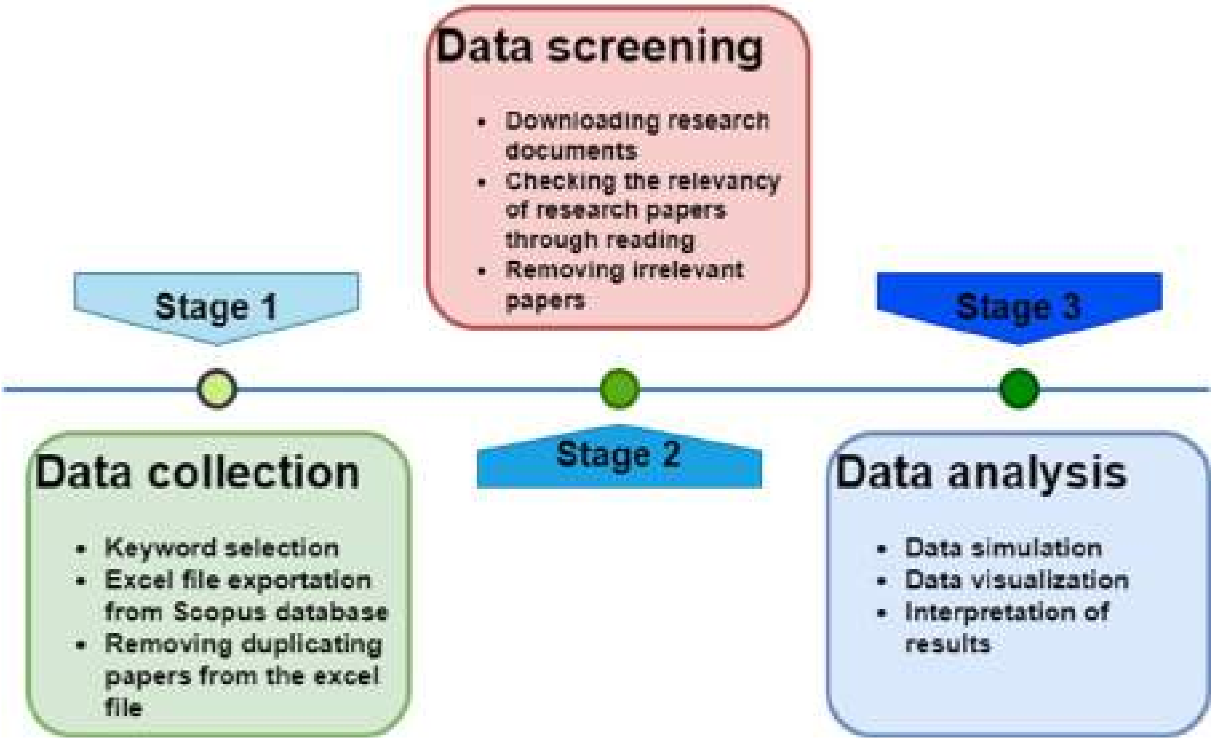

Figure 2: Conceptual Framework of Analysis

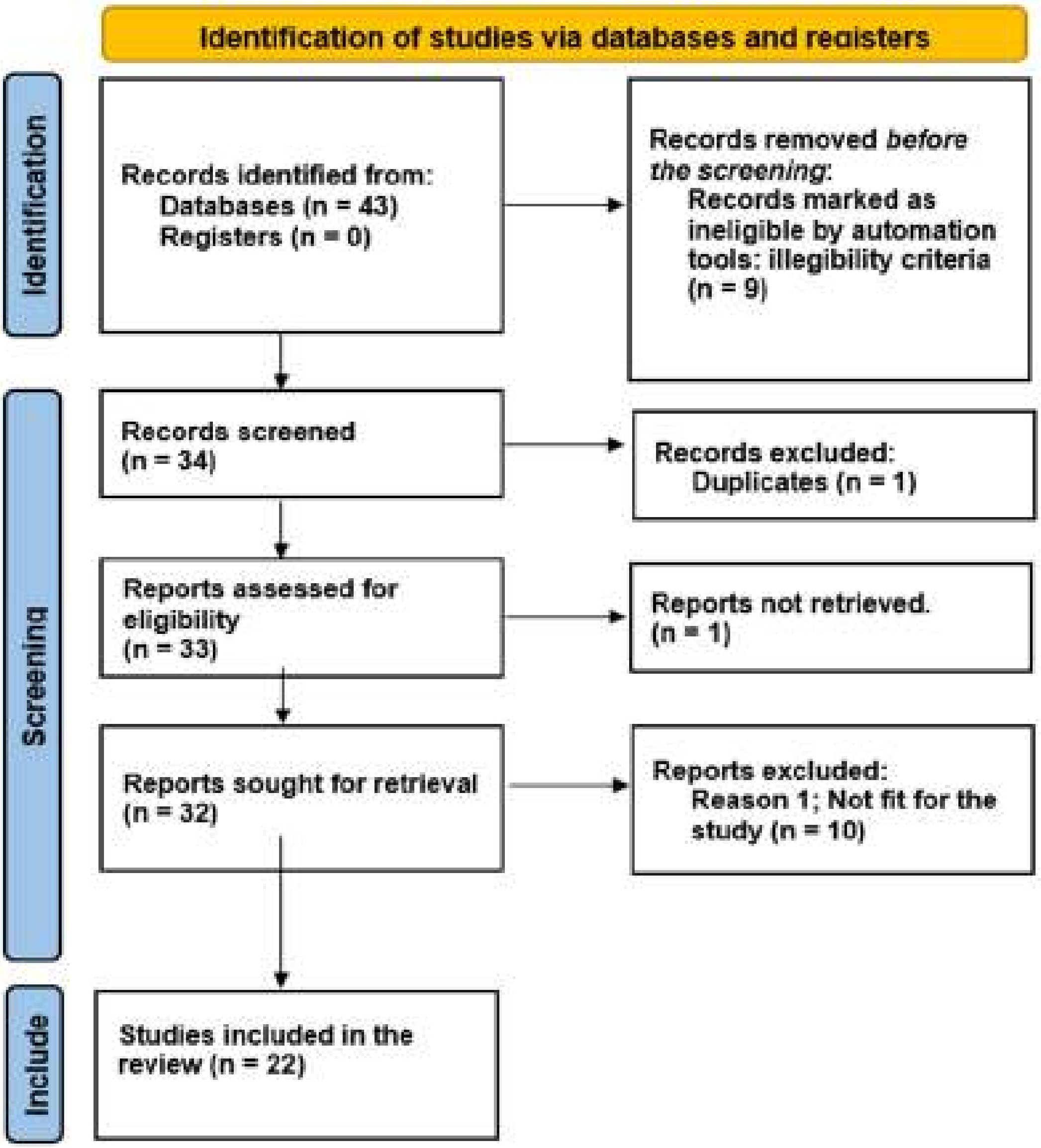

Figure 3. PRISMA-ScR Flow Diagram

The dataset is relatively small (22), however, the use of bibliometrix and VOSviewer for small datasets like the one in this study is supported in literature such as [20], [22]-[24], which used the tools to analyse datasets with studies between 20 and 40. The use of bibliometrix in the current study is also motivated by its usefulness in analysing the keywords while running algorithms on the paper's bibliometric data [25].

The rest of this paper is arranged as follows: Section (3) gives the analysis results through visualisation and discussion, and Section (4) presents conclusions and recommendations based on the paper's results.

3 RESULTS AND DISCUSSION

This section is divided into two subsections: Subsection 3.1 gives and discusses descriptive statistical results, and Subsection 3.2 discusses the conceptual results of the database of research papers for this review.

3.1 Descriptive results & discussion

In this scoping review, 22 of 43 research papers were obtained from the Scopus database following the PRISMA methodology, as shown in Figure 3. The included papers in this present study are 13 peer-reviewed journal articles, 6 conference papers, and 3 books. The variety of literature resources helps to explore different opinions, theories, and models established by previous scholars in different research settings for related market infrastructure problems.

The annual scientific production of research papers fluctuated in the period from 1983 to 2023. However, the scientific production trend is growing gradually. This finding implies the growing relevance of research regarding WFMs globally. The annual scientific production trend is depicted in Figure 4.

Figure 4: Annual Scientific Production

Various fields have contributed to this work area, as depicted in Figure 5. The findings show that fields such as Business, Management, & Accounting; Decision Science; Engineering; and Economics, Econometrics, & Finance are significant contributors (all significant fields were selected in the eligibility criteria shown in Table 2). Most literature in these fields assessed WFM components and their potential in the economy.

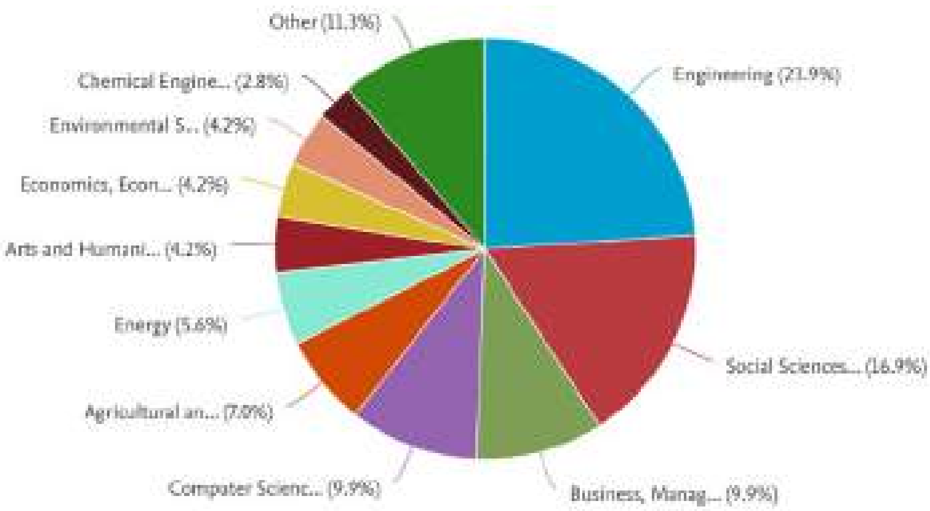

Figure 5: Subject Areas

Figure 6 shows the thematic map with four quadrants: Motor themes, Niche Themes, Emerging Themes, and Basic Themes. Motor themes are well-established in research while emerging themes are unestablished but new to research. Niche themes weigh the slightest relevancy in literature, while basic themes serve as a base for the research topic. All the themes are measured based on density and centrality, whereby the density shows occurrence frequency and centrality indicates importance. From Figure 6, the most populated quadrants are Motor and Emerging themes. This indicates that literature about WFMs and WFM infrastructure explores a few well-established concepts and has branched out towards emerging new themes.

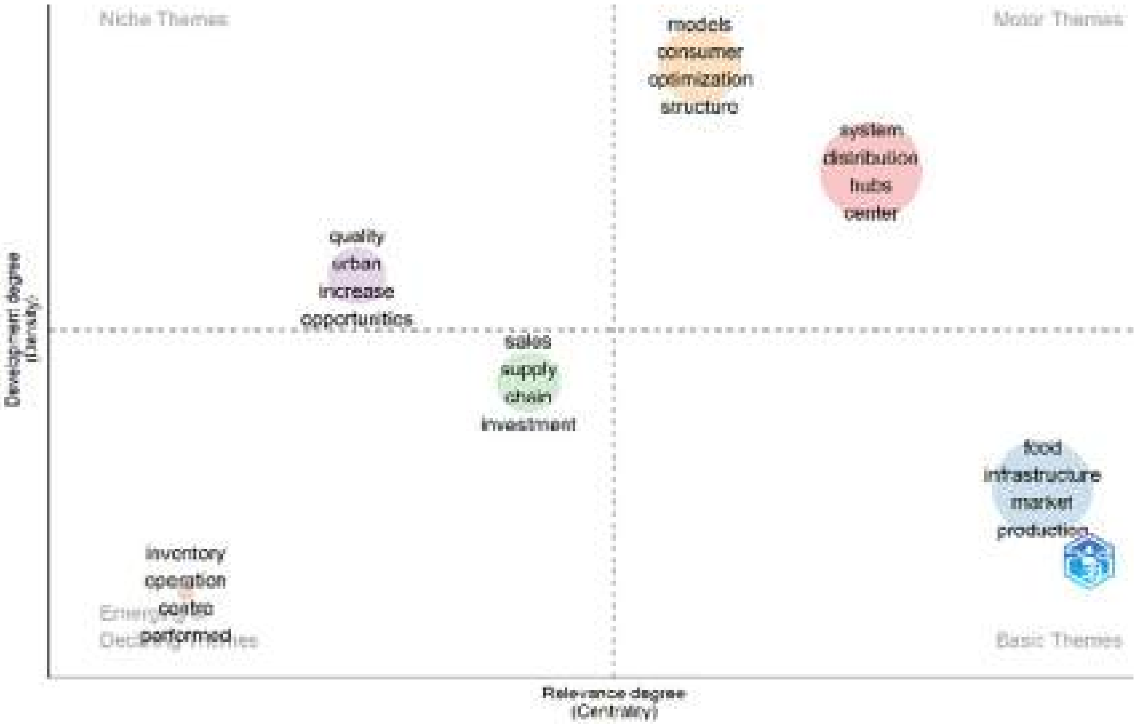

Figure 6: Thematic Map

Well-established research themes are generally expected to branch out to niche themes. Themes such as distribution, hubs, and models are in the Motor themes quadrant, while themes such as infrastructure, food, and market are in the Basic theme quadrant. The thematic map proposes that themes such as sales and inventory are emerging.

Research papers included in the analysis of this scoping review were produced globally. Figure 7 shows the country's collaboration with other countries while highlighting the level of each country's scientific contribution based on the colour blue (from light to dark blue).

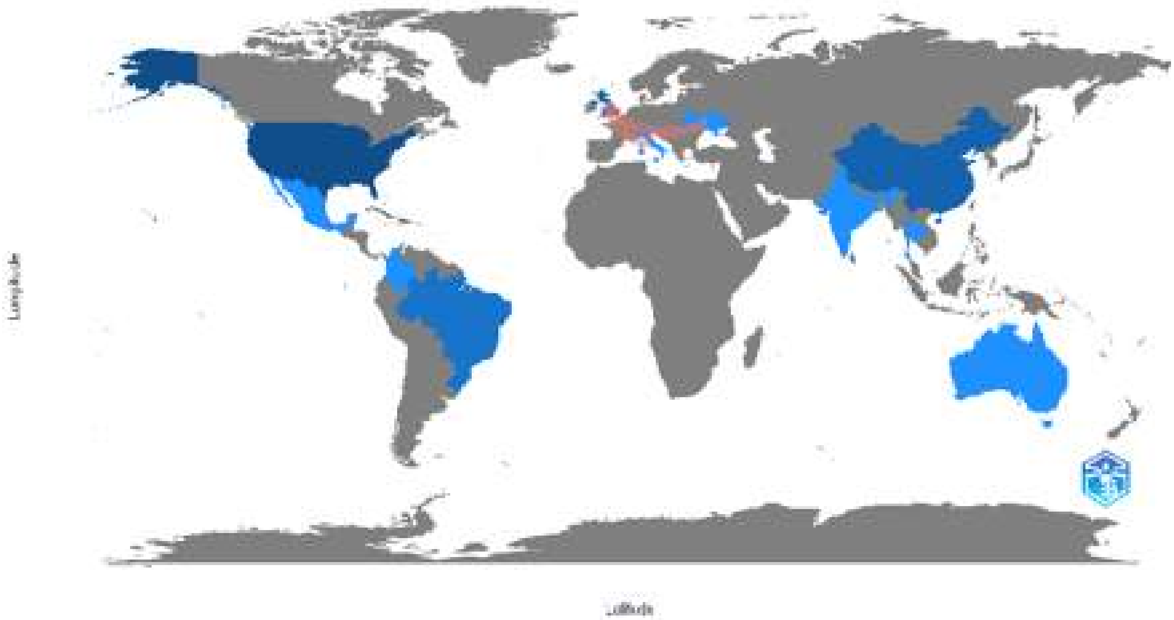

Figure 7: Countries' Collaboration World Map

The United States of America, Alaska, and China are significant producers of research papers, followed by Brazil. Figure 7 reveals the paucity of evidence-based research in the African continent, which indicates an opportunity to prioritise this research scope in the present and future. As a result of research interests, researchers from different parts of the world collaborated on some of the papers through projects and academic partnerships. Figure 7 further shows that most collaborations are among researchers from the United Kingdom and Ukraine.

VOSviewer helped to visualise results for the co-occurrence of keywords. The importance of keyword co-occurrence analysis is derived from the need to establish the strengths of relationships between keywords [26]. The keyword co-occurrence was made based on research titles and abstracts, and the results are shown in Figure 8.

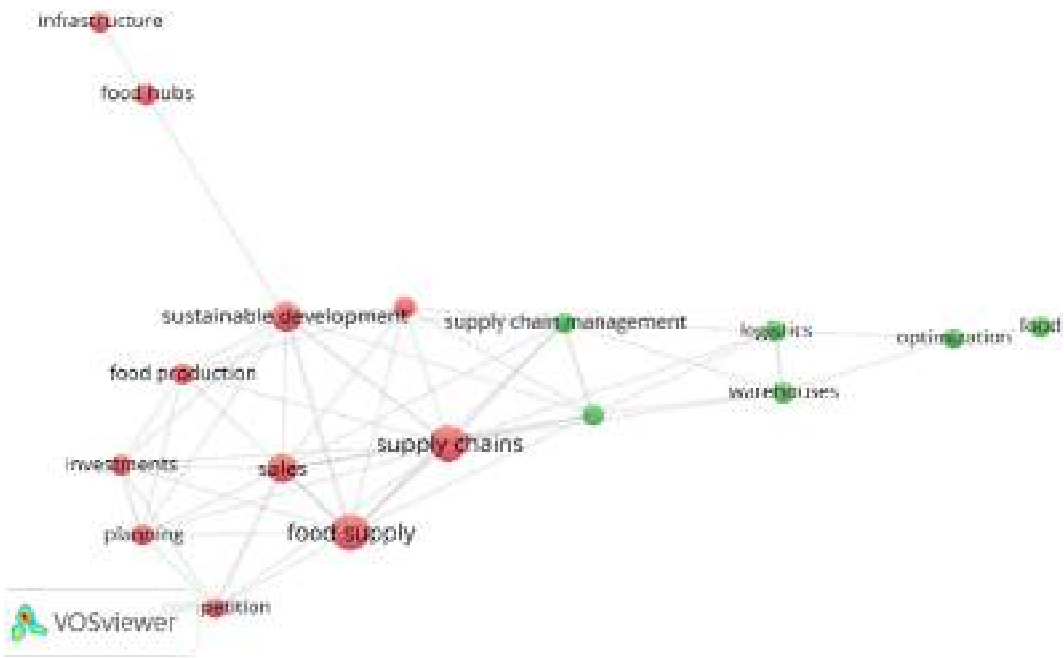

Figure 8: Co-occurrence Network

The co-occurrence illustration was made using VOSviewer with specifications: Co-occurrence (all keywords), minimum co-occurrence (2), 17 keywords met the threshold, clusters (2; shown as red and green), links (53), total link strength (65), max length (0), max line (500). Figure 8 shows that the most co-occurring keywords of articles in our database are food supply and supply chains, which are in the same cluster. Figure 8 further shows that there is a strong relationship between keywords such as infrastructure and keywords such as food hubs, food supply, food production, supply chain, and investment, as they are in the same cluster; this finding implies that food hubs such as WFMs are pendant to infrastructure components, essentially controlling food distribution [4]. On the other hand, managerial terms such as supply chain management and optimisation are in the same cluster, entailing a strong relationship between them.

3.2 Further discussion of results

Although infrastructure was featured in some of the 22 research papers deemed eligible for this study, none focused on infrastructure maturity models for WFMs (creating a gap in research to be explored in future). This gap was also identified in the results of the study areas presented in Figure 5. This gap in research has led to harm in WFMs worldwide. According to [27], most regional and local WFMs have old and neglected infrastructure. This results in WFMs managers needing the necessary infrastructure maturity models and practical tools to help them make infrastructure innovation decisions while assessing the infrastructure maturity level. Based on the logistics and business models [28]–[31], which have already proven to be effective, there is a high possibility that infrastructure maturity models can have the ability to advance WFMs. Furthermore, literature such as [32]–[35] shows that the link between WFMs and consumers is the market's ability to connect with consumers through efficient infrastructure.

4 CONCLUSIONS AND RECOMMENDATIONS

After conducting the study through a scoping review oriented to identify some of the components of infrastructure for WFMs, the following conclusions and recommendations can be made.

This scoping review found that infrastructure-related research is yet to be established for WFMs, particularly in themes such as sales, supply, investment, and inventory which form part of infrastructure dimensions.

The African continent is yet to have significant research on infrastructure for WFMs. Thus, the lack of research-based information that WFMs can rely on causes a slow formation and poor infrastructure management in WFMs in most African countries. This negatively affects the relationship between WFMs, consumers, and other food supply chain stakeholders because they are all connected by various components [36] of infrastructure. Figure 9 sheds light and answers question one of this study on the reported infrastructure components in the literature [37].

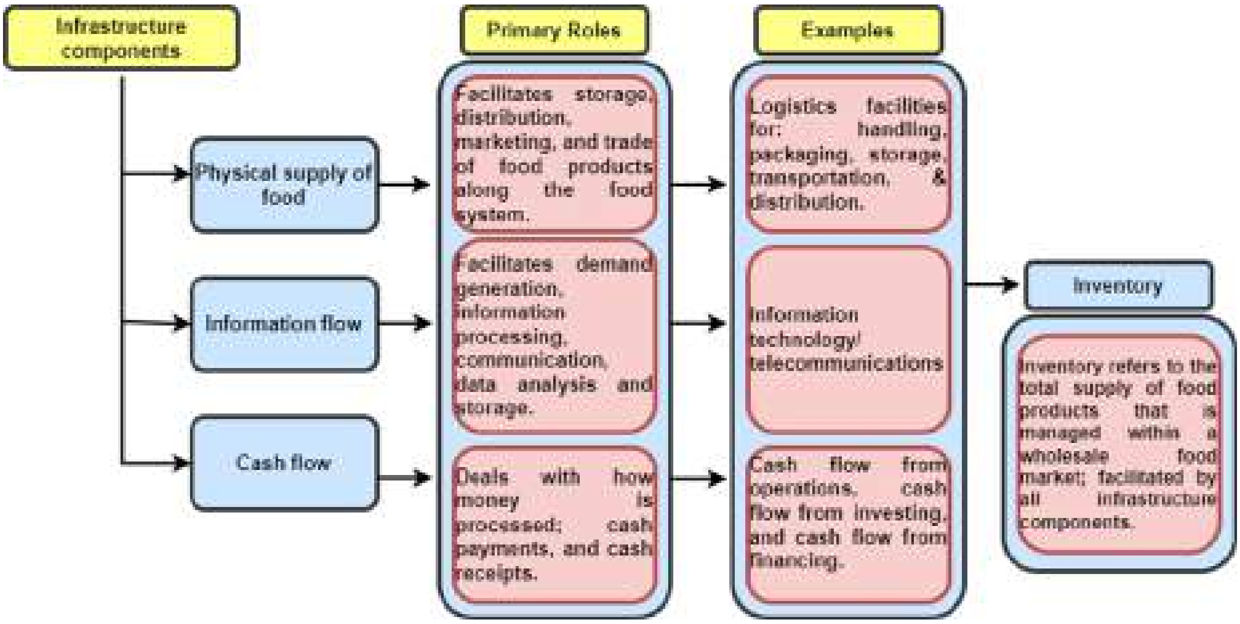

Figure 9: Infrastructure Components

Figure 9 portrays 3 components of infrastructure: the Physical supply of food, Information flow, and Cash flow. All these components perform different roles, and all their performances are recorded as an overall inventory. Inventory is horizontal to the three components. However, these components have a typical role: connecting a WFM with the rest of the food supply chain, comprising farmers, food processors, food traders (consisting of distribution and retail), and consumers.

When infrastructure components are in a poor state (in low maturity levels), there is likely to be a vicious cycle between poor infrastructure and WFM development [32]; most WFMs in Africa are experiencing this dilemma [39]. This might result from a need for more quality-based research on infrastructure for WFMs, as reported in Figure 7. The vicious cycle is shown in Figure 10.

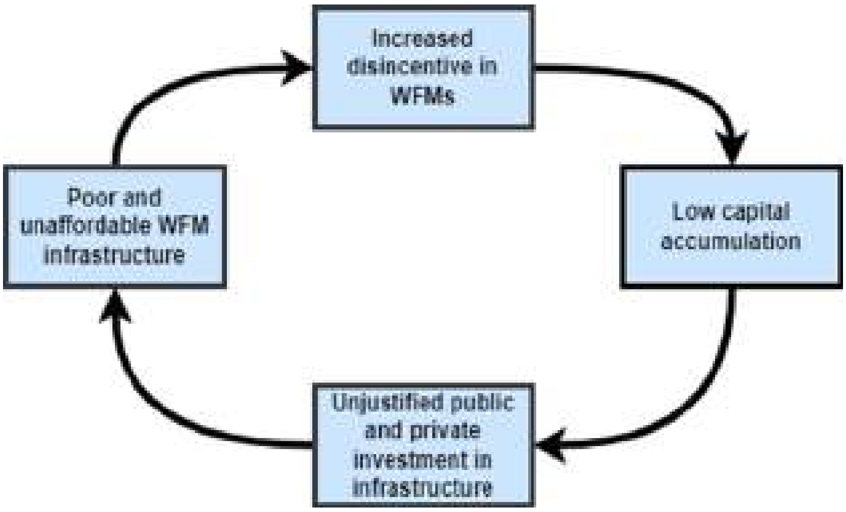

Figure 10: Vicious Cycle (Poor Infrastructure & WFM Development)

The vicious cycle between poor infrastructure and WFM development negates the minimisation of food waste, improved food quality, proper formation of market prices, and financial and information support (from all stakeholders along the food supply chain).

With the consensus that most WFMs have unreliable infrastructure, there is a need for infrastructural innovation. The first step to such a positive change is configuring a suitable WFM infrastructure maturity model. This model may allow easy access for WFMs managers and relevant stakeholders to assess the maturity of their infrastructure and reveal which part of it to improve to move to use high maturity levels. High maturity levels in infrastructure can ensure better transparency, security, and efficiency in WFMs.

5 LIMITATIONS

The scoping review used studies from the Scopus database only. Thus, neglecting non-scientific reports from databases such as FAO, WFP, and food-related NGOs worldwide (limited time led to this limitation). The scoping review also did not research related maturity indexes to attempt to make a new conceptual maturity model focused on WFM infrastructure; thus, opening a door for future research on this aspect.

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BEYOND FINANCIAL VALUE: A SCOPING REVIEW ASSESSING THE USE OF BLENDED VALUE ACCOUNTING- AND IMPACT EVALUATION METHODS TO ALLEVIATE FOOD INSECURITY

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ABSTRACT

This scoping review explores the utilization of impact evaluation (IE) and blended value accounting (BVA) tools to support organizations within the Non-profit (NPO) sector. The Non-profit sector plays a vital role in addressing societal challenges, and understanding how impact evaluation tools are employed to enhance the effectiveness and accountability of NPOs is essential. This review aims to identify key themes and trends in the application of the IE- and BVA tools. Furthermore, the review highlights the challenges and opportunities NPOs encounter when employing these tools, including limited resources, varying organizational capacities, and the need for adaptable frameworks. This scoping review contributes to the understanding of how IE, IR, and BVA practices are adopted in the NPO sector and provides insights into ways to enhance the effectiveness of impact assessment approaches for non-profit organizations.

Keywords: Impact Evaluation (IE), Impact Reporting (IR), Blended Value Accounting (BVA), Non-profit organisations (NPO),

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1 INTRODUCTION

In a world facing an increasing set of complex social-, economic-, and environmental issues, the role of Non-profit Organisations (NPOs) is becoming imperative. On these organizations' missions to create meaningful change, the ability to accurately assess and communicate their impact possesses the potential to present significant benefits to them. Impact evaluation (IE) methods have emerged as powerful tools that enable NPOs to systematically measure and demonstrate the outcomes of their initiatives. This study assesses the current body of literature to determine the different applications of IE tools and methods on NPOs, with a focus on food banks.

The nature and relevance of food banks:

Food insecurity is a consequence of insufficient food security, which encompasses the availability of adequate food to support a healthy and active lifestyle, access to nutritious and safe foods, and the assurance that these foods can be obtained in a socially acceptable manner [1]. Research has linked food insecurity to numerous negative impacts on cognitive, social, and physical human development and performance, especially in children [2], [3]. The State of Food Security and Nutrition in the World for 2021 report stated that 2,36 billion people faced food insecurity due to inadequate access to food during 2020, an increase from 2 billion people in 2019 because of the effect COVID-19 had on the global food supply chain. The United Nations' second sustainable development goal, Zero Hunger, aims to eliminate hunger and malnutrition by 2030, reiterating this issue's importance and relevance.

Food banks are not-for-profit organisations (NPOs or NGOs) that collect, organise, and distribute food to individuals and member agencies to alleviate food insecurity [4]. Food banks play an integral part in the way that individuals experience food insecurity. It has been found that a large benefit of food banks is that they alleviate the intensity of food insecurity experienced by individuals [5]. The operations of food banks, however, have a wider impact than only addressing food insecurity. Food banks play a crucial role in addressing the paradox between food waste and food insecurity by bridging the gap between surplus food supply and the needs of the underprivileged [6]. Since food plays such an integral part in the daily lives of humans, numerous social benefits are generated by the interventions that food banks initiate [7], [8].

Over the past 20 years, the usage of food banks has dramatically increased, and a vast amount of the population is becoming increasingly dependent on them [5]. The demand for food banks is growing at a higher pace than what food banks can support, which indicates that a re-evaluation of the current food supply chain of food banks is desperately needed. Until then, improvements in the supply chain of food banks are required to sustain the increased demand [5]. Researchers have found that people have become less likely to donate after the world resumed its normal activities compared to before COVID-19 appeared [9]. This presents food banks with a major sustainability problem. Food banks are therefore required to find ways to ensure continued donations and use their donations more efficiently to compensate for the lower volumes received.

Impact evaluation

Evaluations in general can provide answers to three, broad questions: [10]

i. Descriptive questions: They are concerned with what is taking place;
ii. Normative questions: They are concerned with both what is taking place, and what should be taking place; and
iii. Cause-and-effect questions: They are concerned with identifying the contribution that an intervention makes to outcomes.

There are numerous different types of evaluation studies and methods, of which Impact Evaluations are the focus of this study. IE is concerned with the 3rd question. The concept of

IE is concerned with assessing how interventions affect certain outcomes [10]. The most general categorisation of IE methods are: i) retrospective, and ii) prospective. Retrospective evaluations are conducted to determine the impact of a program after the program has been implemented, whereas prospective evaluations are conducted during the design period of the program and, therefore, before implementation. Retrospective evaluation studies are known to produce more accurate and conclusive results since accurate data is usually available for these studies, whereas prospective evaluation studies are useful to guide the design of programs and to guide decision-making between choosing the most relevant program. There are many different methods of IE that are all created to deliver certain outcomes. This study is concerned with the concept of IE and will therefore not limit the literature under review to only certain IE methods. [10]

Blended value accounting

Since NPOs are responsible for a wide range of impacts, quantifying and describing their performance can be challenging, and extremely resource intensive. Blended Value Accounting (BVA) methods have been created for this reason: to evaluate and report on an action, organisation, intervention, or policy's ability to generate a blend of financial, social, and environmental value [11], [12]. BVA methods have been proven to be effective at improving NPOs' cases for funding [11]. The industry standard regarding BVA methods is the Social Return on Investment (SROI) model. This model is concerned with translating its subject's economic, social, and environmental impact into monetary terms depicting the donation as a social investment [12]–[14]. It draws on the accounting method, Return on Investment (ROI), to display the total social return that the subject will deliver. BVA methods, therefore, have the potential to be of great help to food banks' quest to attain a more sustainable way of existence.

Both IE- and BVA methods provide definite, yet distinct, benefits to organisations. This study is concerned with determining the maturity and nature of the current body of literature regarding the use of IE- and BVA methods on food insecurity-related interventions, like food banks. The relevant literature will be assessed to determine the different ways in which these methods have been applied, with the goal of providing researchers with future research opportunities. This study will therefore be a scoping review (SR).

2 METHODOLOGY

The methodology for this SR is based on the PRISMA-ScR approach. The PRISMA-ScR approach consists of a 22-point checklist that acts as a guide to ensure sufficient quality, which acted as the review protocol of this SR [15]. To collect, analyse, and visualise data, the study used an R programming package, called Bibliometric, and its accompanying user interface, Biblioshiny. The Scopus database was chosen for its variety of peer-reviewed literature. To ensure that non-relevant papers were filtered out, this SR considered the intersection and combination of multiple terms through a preliminary literature review. The available literature about the current use of BVA- and IE methods and techniques on any subject that is aimed at alleviating food insecurity was investigated. Subjects that were not tasked with directly addressing food insecurity, but rather closely related topics, e.g., nutrition, were also included. An iterative approach was followed to find the search string which produced a sufficient number of relevant papers. Table 1 displays the search strings used for this study.

Table 1: Search strings

Scope	Search terms
Impact- evaluation and/or reporting on interventions to reduce food insecurity. (n=147)	TITLE-ABS-KEY (("food banks" OR "food pantry" OR "pantry" OR "food rescue" OR "food programs" OR "food security" OR "food insecurity") AND ("SROI" OR "social return on investment" OR "blended value accounting" OR "impact evaluation" OR "impact reporting"))

The evaluation of the publications was done in two phases: 1) evaluation before- and 2) after full-text reading. The literature was evaluated before full-text reading using bibliometric to gain a view of the maturity and diversity of the concepts, factors, and themes involved. The full-text evaluation was done with the goal of gaining a better insight into the available content of the publications. These two phases determined which publications were included in the preliminary list of publications. The list of publications was then subject to four constraints before they were subject to full-text analyses. The four constraints were: 1) language, 2) availability, 3) duplicity, and 4) relevance. Figure 1 depicts this logic. The four constraints eliminated 83 of the 147 publications from the search string to produce the final set of 64 publications.

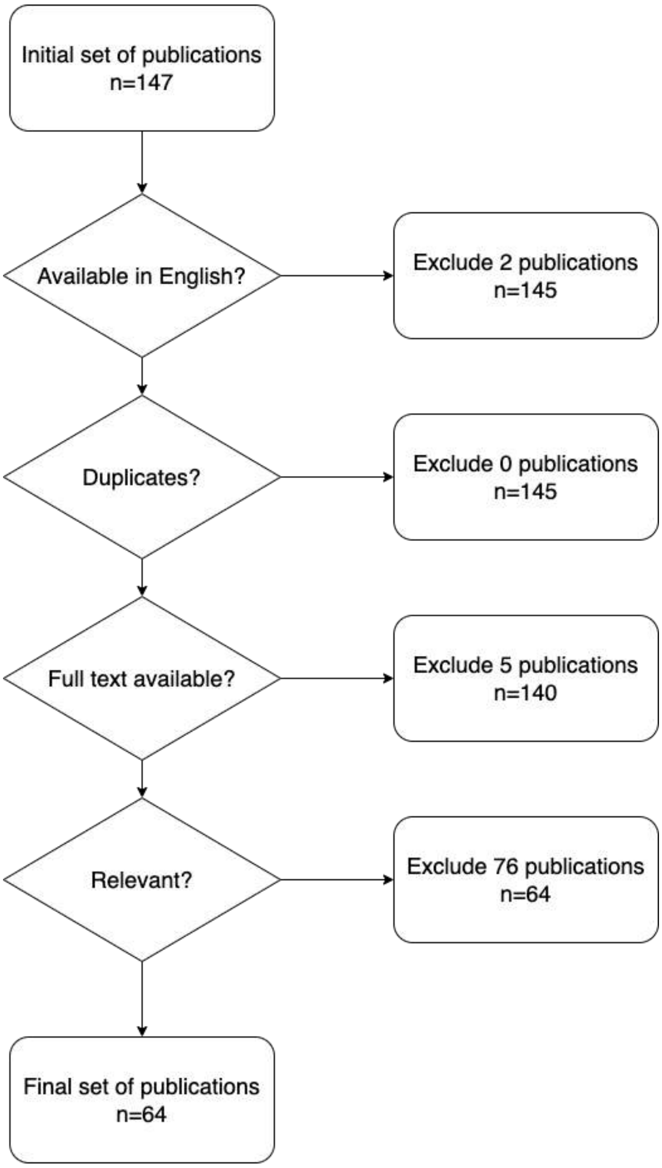

Figure 1: Publication inclusion logic

3 RESULTS

The compiled lists of articles provided key insights into the trends and nature of this topic. Figure 2 displays the wide variety of subject areas in which BVA-, IE-, and IR methods were applied to alleviate food insecurity. The three most relevant subject areas, in descending order of relevance, were: i) Social Sciences, ii) Agricultural and Biological Sciences, and iii) Environmental Science. The fourth most relevant subject area – Economics, Econometrics, and Finance – also deserves mention since it comprises 14.1% of the publications. This still represents one of the most relevant subject areas compared to the remaining topics. While the most relevant subject areas can all be expected due to their close relation to both concepts under inspection: i) food insecurity and ii) IE- and BVA methods, the figure further displays the diverse nature of this topic.

Figure 2: Subject areas of SROI publications

Bibliometric Analysis

Figure 3 is a depiction of the total publications made on this topic per year. The graph depicts a general upwards trend indicating the increasing relevance and popularity of this topic. The topic endured a slow introduction to the academic world. The first publication appeared in 2002, while for the next 6 years, no publications were made. The topic only seemed to gain traction after 2013. The topic's popularity peaked in 2021 with 12 publications. 2023 sees a large drop-off to 3 publications, which is due to the year still being in progress during the time of this investigation. This graph clearly shows an increase in this topic's popularity. This indicates the increasing relevance of the topic and affirms that the problem identification for this scoping review is in-line with current trends.

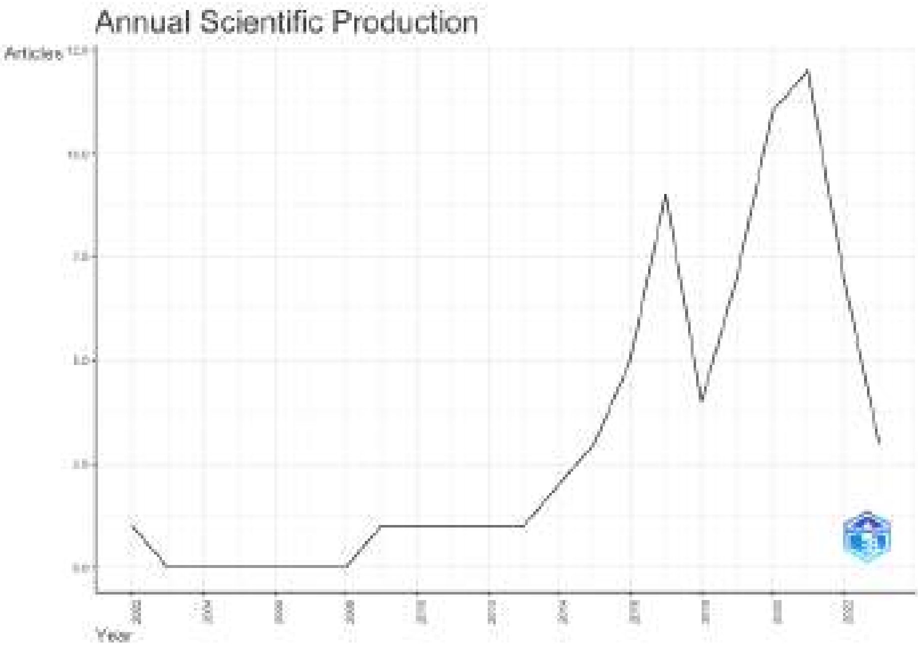

Figure 3: Articles published per year, as found on Scopus.

Figure 4 depicts the number of publications produced per country. The United States has the highest publication rate with 20 publications made, followed by Italy (13), and finally, then the United Kingdom (12) to complete the top three publication-producing countries. It is worth mentioning that of the chosen 64 publications, the top three countries were involved in 45 of them, which represents 70% of the publications under investigation. All three top-producing countries can be classified as High-Income Countries (HIC). This topic has however also been covered by Newly Emerging Economies (NEE), with the African countries of Kenya and Ethiopia leading the line with 8 and 7 publications, respectively. Food insecurity is infamously more relevant in NEE than HIC, especially in African countries which experience a combination of societal instability and natural disasters.

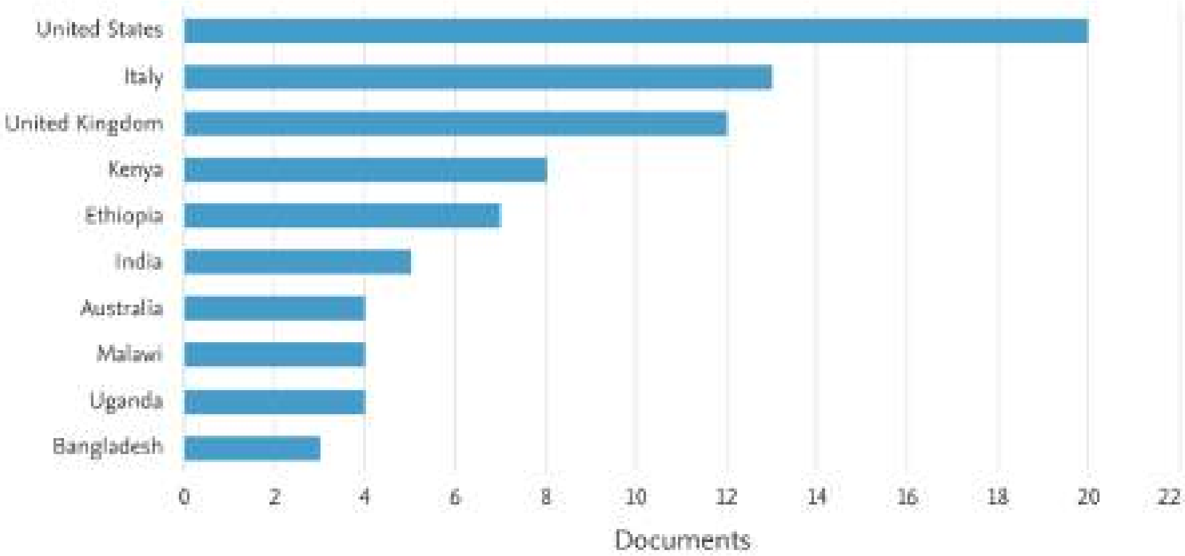

Figure 4: Documents produced per country

A large portion of these publications exists as collaborations between countries. This provides the studies with a larger diversity of input which can be beneficial to the quality of the publications. Figure 5 displays the collaborations between countries from the sample of publications used. Countries that are connected by a line represent a collaboration that occurred, and the thickness of the line represents the frequency of collaborations between the countries. The United States is a participant in most of the collaborations with both African and European countries, which can be expected since the USA is also the country with the highest number of publications. HICs are known to fund research conducted in NEE, the depiction in Figure 5 can therefore be expected.

Figure 5: Country Collaborations

The conceptual structure of these publications was also reviewed and analyzed analysed to indicate the maturity of the topic. This analysis resulted in two figures: i) Figure 7: Thematic map, and ii) Figure 8: Keyword co-occurrences.

The four quadrants of the thematic map have been defined as Motor themes, Niche Themes, Emerging Themes, and Basic Themes. The themes that are most deeply rooted in the field of the available literature, are found in the Motor Themes quadrant. These themes are foundational to the available literature. The new and unestablished themes are represented by the Emerging themes represent the new and unestablished themes, while the sequestered and minor relevance themes are represented by the Niche themes. The basic themes are foundational themes to the observed topic.

There are two metrics used to measure the themes, namely centrality, and density. The density indicates the frequency of occurrence, while centrality indicates relevance and importance. Generally, frequently occurring themes are well established [16].

From this study, the highest populated quadrant is the Motor Themes quadrant, followed by the Basic Themes quadrant. What this indicates, is that the literature concerning this topic explores only a small number of well-established concepts. The topic has barely branched out into niche themes. Niche themes are, as the name suggests, highly refined themes, that do not carry a lot of significance. Experimentation is known to occur within the Nice Themes quadrant.

These findings dictate that this topic consists of a few, well-established themes and is still a relatively new concept. Little experimentation has taken place, and the Motor themes are primarily concerned with nutrition, agriculture, and regional studies.

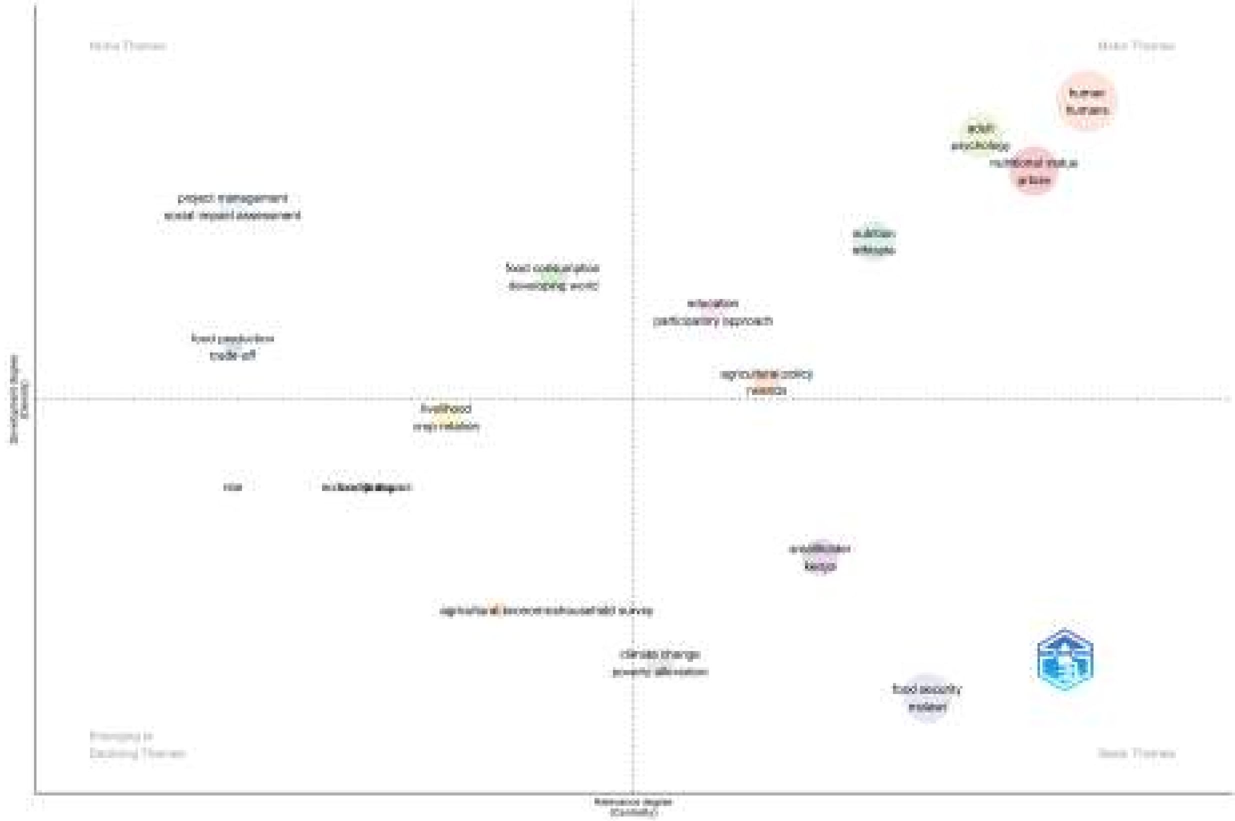

Figure 6: Thematic Map

4 CONTENT ANALYSIS

The publications were thoroughly reviewed to gain insight into how BVA- and IE methods were applied to different interventions tasked with alleviating the effects of food insecurity. This was done to identify possible gaps in the current literature. The observed trends in the literature are discussed in this section.

Out of the 64 publications, 1 publication was concerned with utilising a BVA method for a food insecurity intervention and 63 publications were concerned with solely utilising IE methods for food insecurity interventions. The BVA method that was applied, was the social return on investment (SROI) method [17]. This method is currently viewed as the industry standard regarding BVA methods [11]. This method contains aspects of both IE and impact reporting (IR) concepts [12]. This method was concerned with identifying and describing the theory of change (ToC) that describes how the inputs generate the identified outcomes, which eventually lead to certain impacts. This entails the IE aspect of the method. Once all the impacts were identified, they were assigned financial proxies that were tasked with translating the total social impact to a composite financial ratio, known in the financial world as a return on investment (ROI) ratio. This ratio was used to report to potential donors and social investors – the IR aspect of the method. This study was applied to a food bank and was tasked with identifying and quantifying all the impacts generated by the food bank. The food bank was therefore not measured against its ability to address food insecurity. This resulted in a very wide scope regarding impact identification. The defined goal of this method was to improve the food bank's case for funding by depicting the social value which they generated, in financial terms.

The basic approach of this method is depicted in Figure 9. The method started by defining the inputs generated by the food bank. Once this step was complete, the outputs-, then outcomes- and eventually the impacts were identified that were all directly, or indirectly, caused by the inputs. The last step of this study was to quantify the impact in financial terms. This was done by assigning financial proxies to each impact and then calculating the total financial value of the impact generated by the food bank's inputs.

Once all the impacts were identified and quantified in financial terms, there were four factors introduced to ensure that the total impact calculated was solely caused by the food bank's inputs: i) deadweight – indicates the value that would have been generated without the food bank's input, ii) displacement – indicates whether the food bank displaced any of the undesirable outcomes to a different group that was not observed in this study, iii) attribution – acknowledges the total impact that was attributed by a different intervention, and iv) drop-off – how the impacts will diminish over time. The worst case for each of these factors would be to discount the identified impact to 0, which indicates that the food bank cannot take responsibility for any of the value created. The lowest total social impact that the subject of this study could achieve is therefore 0. This indicates that the study neglects any negative impact that the subject of the study could generate. This represents a limitation regarding the method's ability to evaluate the total impact. It neglects any negative impacts caused by the food banks and cannot be viewed as an evaluation of the total impact, but only the positive impact.

Once the final, discounted financial impact estimation has been calculated, this value was compared to the total capital used to generate the impact to deliver the result – the social return on investment ratio.

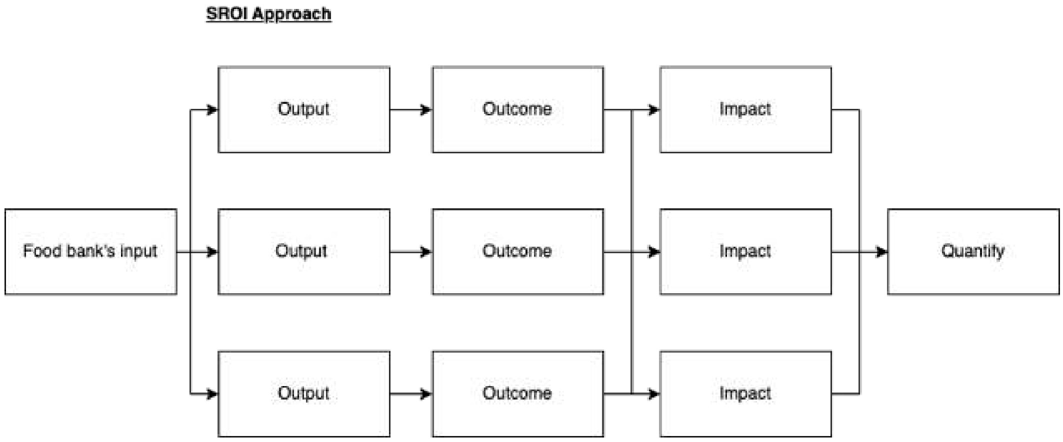

Figure 7: SROI approach

The IE methods used within the final set of publications contained noticeable differences from the SROI method. They were all applied to programs, interventions, or policies, where the subjects were measured against their ability to address a single social issue. The social issues under focus for this paper were all closely related to the issue of food insecurity. The IE method was not applied to any organisations. The most widely used IE methods in the list of publications are depicted in Table 2. The general, shared nature of the IE methods will be discussed in this paper, and not the nature of each individual IE method. This will be referenced as the concept of IE.

The general approach that was followed by the IE methods is depicted in Figure 10. Many of these evaluations started by identifying key indicators related to the state of a chosen social issue experienced by individuals [18]-[40]. The concept was therefore not concerned with identifying where the impacts lie, but rather with evaluating the subjects' effect on the social issue it impacts. The method then measured the effect that the subject had on the social issue by monitoring the state of the indicators. The focus was therefore on evaluating whether the subject was effective at alleviating the effects that social issues had on people. This represents a difference in the desired outcome of the BVA- and IE methods. The BVA method

– SROI – was aimed at quantifying the social, economic, and environmental impact by translating the total impact to a composite score, while the IE methods were more concerned with the binary question of effectiveness.

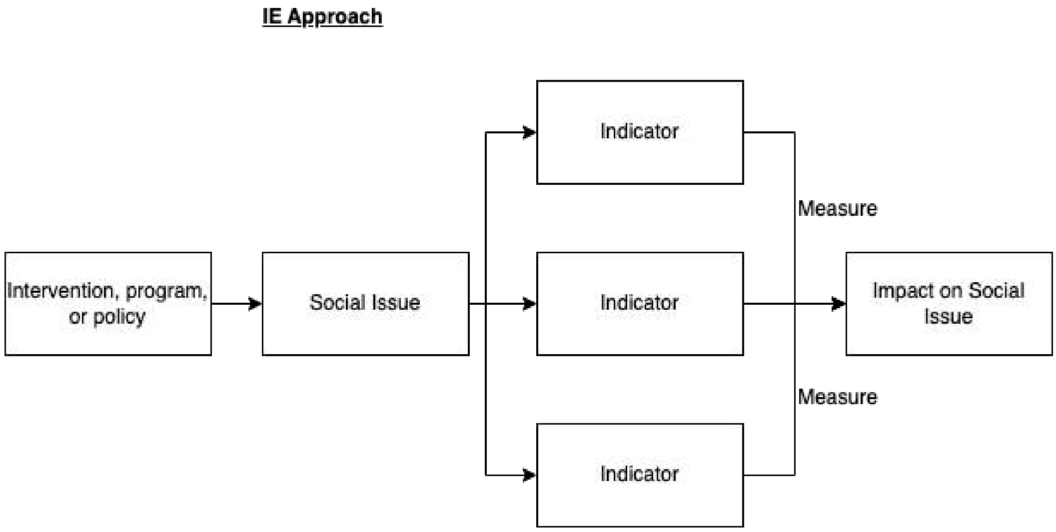

Figure 8: The IE approach

A significant difference between the IE concept and the BVA concept was the comparability aspect. The comparability of the results is a known limitation of the SROI method due to its inherent subjectiveness [12]. The results are therefore limited in their use. Numerous IE methods were used to compare subjects' effectiveness to eventually aid the user in their decision-making quest [29], [41]-[44]]. This points towards the difference in desired results and outcomes from these two concepts.

Table 2: IE method utilised in the publication list

IE Method	**Description**
Propensity Score Matching (PSM)	*Propensity Score Matching (PSM) is a quasi-experimental technique in which statistical methods are employed by researchers to form a synthetic control group by pairing each treated entity with a non-treated counterpart possessing comparable attributes. Through these pairings, researchers can gauge the effects of an intervention. Matching serves as a valuable tool within data analysis for approximating the effects of a program or occurrence where ethical or logistical constraints prevent randomization.* [45]
Quasi experimental difference	*Quasi-experimental methodologies encompass research frameworks that seek to discern the influence of a specific intervention, program, or event (referred to as a "treatment") by contrasting entities subjected to the treatment (such as*

	households, groups, villages, schools, firms, etc.) with control entities. Distinct from experimental methodologies, quasi-experimental techniques utilize a control group, yet diverge in that they do not employ randomization to establish this control group. These methodologies prove invaluable in approximating the effects of a program or occurrence in situations where ethical or logistical constraints hinder the possibility of randomization. [46]
SROI	This model is concerned with translating the economic, social, and environmental impact of its subject into monetary terms depicting the donation as a social investment [12]
Own adaptations	Own methods to determine the impact on project subject.
Contribution analysis and process tracing procedure	Both contribution analysis and process tracing share the aim of drawing causal conclusions about cause-and-effect relationships through methods that do not rely on counterfactual approaches. These approaches are underpinned by analogous analytical tools, including causal mechanisms and theories of change.[47]
Economic surplus model (MODEXC)	*The MODEXC model facilitates the computation and examination of the advantages resulting from technological advancements, quantified as the economic surplus experienced by producers and consumers. Additionally, the model assesses metrics indicative of societal benefits arising from research investments.*[48]

5 CONCLUSION AND DISCUSSION

The goal of this study is to contribute to the understanding of how IE- and BVA methods are currently applied to food insecurity interventions. This is done to aid food insecurity interventions in becoming more sustainable by improving their case for funding and optimizing their effectiveness. The literature surrounding BVA methods to aid food insecurity interventions was analysed to determine its maturity and relevance. As portrayed by the bibliometric analysis, the methods under consideration have not been widely applied in the area under focus. This leads to the conclusion that there is a gap in knowledge regarding the application of BVA methods to aid food insecurity interventions.

Regarding the content analysis, the first noteworthy observation is the lack of utilisation of BVA methods when it comes to the subject area of food insecurity and related fields. IE methods were the only methods that were adequately covered in the list of publications. This can be due to a wide variety of reasons, which can include both concerns with the methodology of the BVA methods and the lack of research covering the usage of this concept in this topic.

Research should be launched into uncovering the reason behind the lack of utilisation of these concepts in this field.

Regarding the studied SROI method, to increase its accuracy and validity, the total impact of the intervention should be considered, and not only the positive impacts. The desired outcomes of the different IE methods were all concerned with the question: is the subject effective at achieving its goals? The BVA method assumed the answer to this question is 'yes'. The BVA method was aimed at quantifying the effectiveness, i.e., determining its efficiency. These two methods should therefore be used in conjunction with each other to present the most accurate results. The suggested logical sequence of application of these two methods is: first apply an IE method to the subject to determine whether it is effective at achieving its defined goals, after which the BVA methods can aid the subject in quantifying the efficiency of the subject. This will present food banks with two distinct benefits: i) it can increase the effectiveness of the food bank in achieving its goals through evaluating and comparing the desired outcomes with the real outcomes, and ii) it can improve the food banks' case for funding through presenting them with a method to report their total impact in a way that is relevant to donors and investors.

Both concepts, the IE and BVA concept, can be valuable in addressing the food insecurity problem but are not well-represented in the literature. Both concepts address separate, yet relevant problems for food banks. It was identified that food banks require the optimization optimisation of their supply chain as well as increases in donations to be able to support the growing demand. This presents an opportunity for future research: the introduction of IE methods into BVA methods, and vice versa, to aid food banks in more effectively, and efficiently achieving their defined goals.

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PRODUCTIVITY ENHANCEMENT THROUGH LEAN PHILOSOPHY APPLICATION IN A SERVICE ENVIRONMENT

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ABSTRACT

The application of lean principles and tools in the manufacturing sector has widely been acknowledged for its undeniable benefits. However, the service industry, experiencing significant economic growth, presents a promising opportunity for the implementation of lean philosophy. This has the potential to enhance organisational competitiveness, improve customer satisfaction, and reduce waste. This study aims to investigate the application of lean philosophy and tools to the Monitoring and Reporting Process within Company A's internal function, with the goal of enhancing productivity. A company analysis revealed high levels of operational inconsistency and inefficiency in executing this process, leading to low productivity levels, delayed outputs, and excessive workload pressure. To address these issues, the Soft Systems Methodology is employed and adapted as the research methodology for pursuing the research aim and facilitating function-wide improvement, resulting in a 27.7% increase in process execution time and improved overall process efficiency.

Keywords: Lean services, soft system methodology, monitoring and reporting

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1 INTRODUCTION

Lean philosophy or "lean thinking" is inclusive of a set of lean practices, principles and tools, which can be applied to a process to achieve waste reduction and value enhancement through the involvement of all relevant parties [1]. Lean was initially developed around its application in the manufacturing industry, specifically the Toyota production system, with majority of the thinking and approach being based on that industry. However, applying lean philosophy to the services industry is a relatively recent endeavour, and ongoing evolution of current lean approaches and techniques is necessary to effectively meet the unique requirements of a service environment[2][3].

Lean philosophy will be applied to the monitoring and reporting process of Company A's function, to both identify and address the operational inconsistency and inefficiency experienced by the function. This particular service environment is not only diverse and dynamic, with high volumes of document processing and analysis required, but is also strongly dependent on human factors, which makes way for issues and challenges which may not be clearly defined within the current lean manufacturing principles [2]. As a result, the ideology, principles, and implementation strategies, which form part of the lean philosophy, must be adapted to address the issues identified in this service-based function.

2 LITERATURE REVIEW

The concept of lean originated from the early 20th century in the Japanese car and automotive industry, which gained high market leadership and later resulted in the discovery of 'lean production' [4]. Organisations have henceforth viewed lean as more of a process as opposed to a philosophy, a way of thinking, with tools, processes and principles that establish the thoughts of Bhasin and Burcher [5] who define lean as a philosophy that when implemented reduces the time from customer order to delivery by eliminating sources of waste in the production flow.

2.1 Forms of waste in lean service

Waste identification in the service environment is slightly more complex considering that the operations are somewhat intangible and based on the customer's experience [6].

Table 1: Forms of lean service waste

Service waste	Description	Equivalent manufacturing waste
Overproduction	Execution of more work than what is required by the customer or performing the work prior to customer demand.	Overproduction
Delay	Employees/customer waiting for information/services to be delivered.	Waiting
Unnecessary motion	Resources (people or items) being moved around unnecessarily both physically (one room to another) or virtually (methods and approaches).	Motion
Duplication	Additional activities/processes being performed even though they do not address a need or adding more value than what the customer is willing to pay for.	Over-processing

Service waste	Description	Equivalent manufacturing waste
Lack of standardization/ Variation in task execution	Processes and procedures not being done in a uniform and efficient manner or using outdated methods.	Inventory
Demand failure	Failure to conform to the customer's expectation/need, which will result in loss of customers or missed opportunities.	Defects
Under-utilized resources	Not taking advantage of employees' skills, knowledge, and creative abilities.	Unutilised talents
Manager resistance to change	Management personnel being opposed to improvement suggestions and operations.	

2.2 Effective Lean Service Implementation Tools

Lean philosophy is concerned with not just the eradication of waste, but ultimately changing the culture of the organisation to consistently apply lean daily at every level of the service delivery process [5][7][8]. A way in which this can be successfully achieved, according to Bhasin and Burcher, (2006) is through:

- Communicating a clear vision to all employees and their respective roles[9].
- Communicating the benefits of the change and encouraging employee input.
- Running a pilot program for a set period, as a means of gradually introducing the transformation and gaining buy in from the employees.
- Creating and embracing an environment of learning and personal development by facilitating trainings and workshops[10].
- Promoting lean leadership within the different departments, at different levels.

The tools shown below can and have been adapted and applied to allow for the effective implementation of lean service [2][11]:

- Pull System
- Total Quality Management
- 5S or Workplace Organisation
- Value-stream mapping
- Just-In-Time (JIT)

3 METHODOLOGY: MODIFIED SOFT SYSTEMS METHODOLOGY (SSM)

A modified approach on the Soft Systems methodology is used in this project to clearly understand and analyse the process of monitoring and reporting in Company A's internal function and ultimately developing a solution to the issues that have been identified. The soft systems methodology (SSM) was derived from research conducted at Lancaster University, with the intention of solving management/business problems concerned with efficiency and effectiveness [12], [13] . The methodology accommodates the idea of ill-defined problems based on human driven systems and developing a practical solution for a problem viewed from different perspectives by different individuals. The methodology allows for an in-depth analysis of the real-world situation, while looking to improve it [13], using a 7-step approach as illustrated in Figure 1:

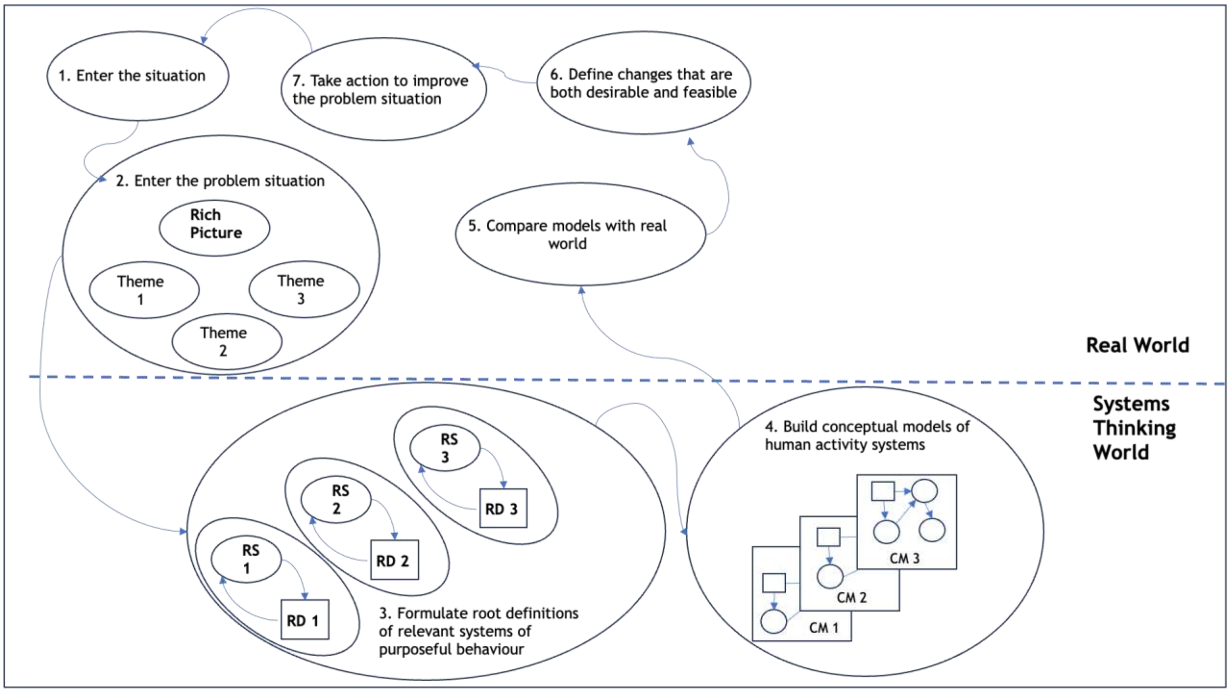

Figure 1: The 7 step soft systems methodology ([12])

This study groups certain steps of SSM to accommodate the needs and specifications of this project, while incorporating the fundamental concepts and elements of SSM.

Table 2: Detailed project methodology breakdown

Problem description and definition clarification (step 1 and 2)
• Literature Review • Research objective
Conceptual model construction and root cause analysis (step 3 and 4)

• As-is process modelling and analysis
  - Stakeholder workshops
• Root cause identification
  - Cause and effect diagram (Fishbone diagram)
  - 5 Why's
• Waste identification
  - Lean service wastes
  - Lean service waste impact

Feasible and desirable change construction (Step 6)

• Improvement opportunities identification
  - Total quality management
  - KANBAN
  - Just-In-Time (JIT)
• Developing an action plan to achieve the higher production and lead time reduction.
  - Scope of improvement solutions

Action to improve the situation (Step 7)
• Improvement solutions development

Problem description and definition clarification (step 1 and 2)

• Proposed to-be process model
  - Evaluating the proposed improved "future state vision"
• Solution validation
  - Qualitative
  - Quantitative

4 CONCEPTUAL MODEL CONSTRUCTION AND ANALYSIS

Through stakeholder engagements and process time studies, a consolidated 'world view' is laid out in this section for a more detailed analysis. The current 'real-world' state of the monitoring and reporting process is mapped out to analyse the process workings and understand the key problem areas from all stakeholder perspectives.

4.1 As-is process model and description

The figure below aims to communicate the monitoring and reporting process at a high-level, to determine the process inputs, outputs and end users (sometimes referred to as customers), to create a clear understanding of the process objectives and requirements as a function, before the process can be further broken down into process tasks and roles.

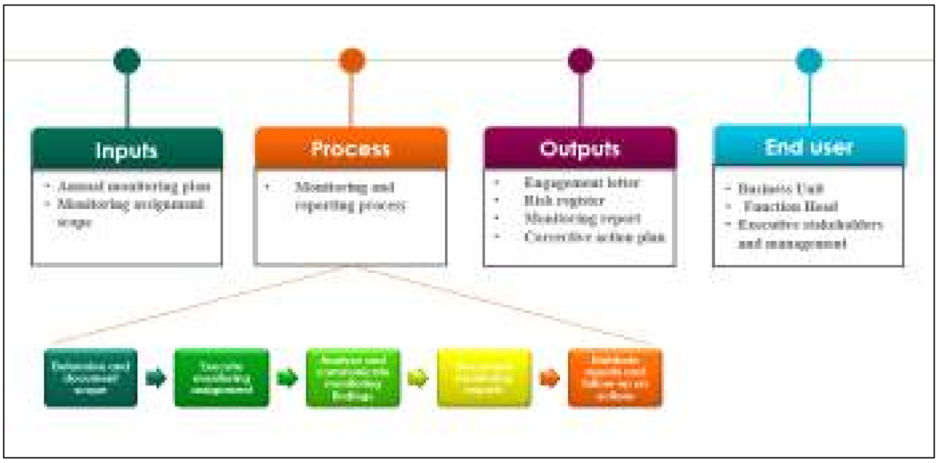

Figure 2: High level process breakdown

The map shown in Figure 3 below, provides a step-by-step visual representation of how the internal function's team carries out their monitoring and reporting on a quarterly basis.

The process is triggered by the function's annual plan which states all the activities that the function should complete within the year. Once the monitoring period date stated on the annual plan approaches, the respective Relationship Managers (RM) will inform the relevant business units (BU) of the upcoming monitoring engagement.

The entire team will then, schedule a meeting to determine the scope of the monitoring engagement and draft an engagement letter, which is then sent to the relevant manager for review. If the manager does not approve the monitoring plan, it is sent back for rework and update, however, if it is approved, the relevant RM's will send out emails to their BU's requesting specific data which the RM will analyse and draw conclusions from. The RM will then meet with the BU to discuss the monitoring results and later compile the first draft monitoring report, consisting of information concerning the regulations monitored, the data received, the monitoring period and identified problem areas. The RM them compiles a risk register which consists of the risks identified, level of impact and severity and controls put into place. An additional remedial action plan is put together, which lays out suggestions from the RM on remedial actions that should be implemented by the BU before the next monitoring period, to address the risks mentioned. The RMs draft the reports individually but usually schedule internal group review session meetings, to offer advice and improvement suggestions for the individual reports before submitting to the manager for review. If the reports have not been correctly prepared, they will be sent back for correction and update, otherwise the reports are distributed to the BU and all relevant stakeholders. The RM then has the responsibility to follow up on the implementation of the action plans, after which, the monitoring assignment is complete.

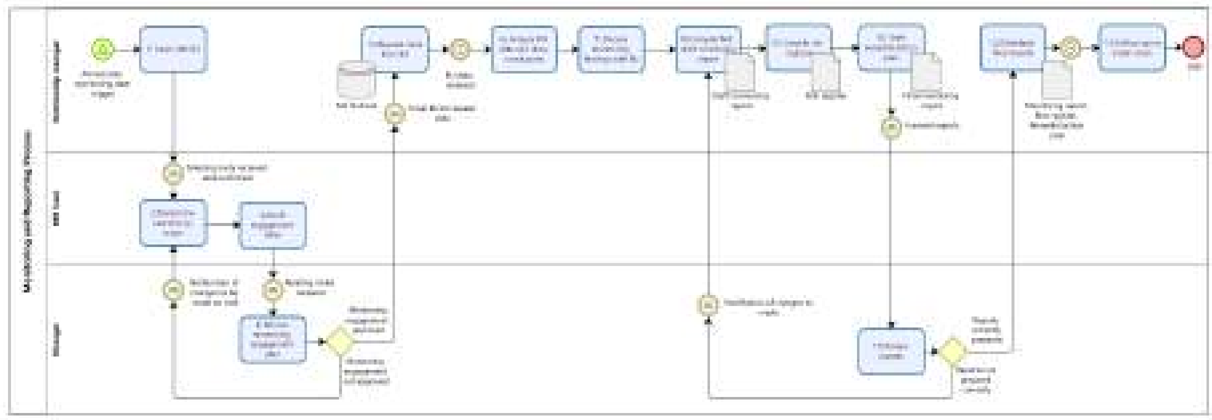

Figure 3: As-is process model

4.2 As-is process model and description

The process times have been documented as part of the analysis of the current state process, with the purpose of identifying the most time-consuming tasks, that require immediate attention for waste elimination.

The data concludes that the current-state process duration is 34.5hrs long, performed over 43 working days, every quarter. Of the 43 days spent on this process, only 51.16% of those are productive working days, while the rest are spent idle or waiting.

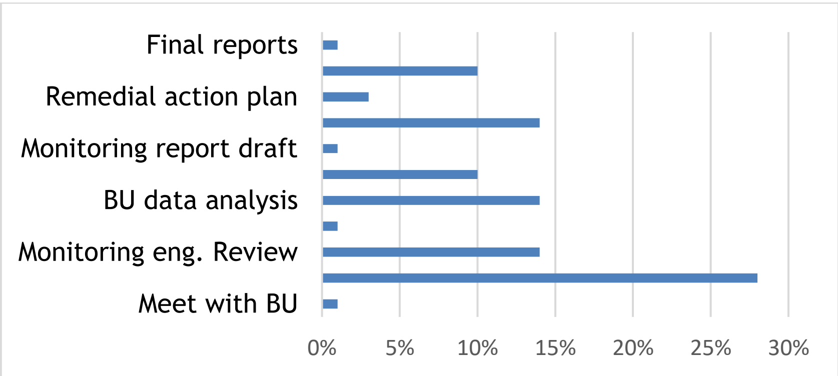

Figure 4: Process task execution times

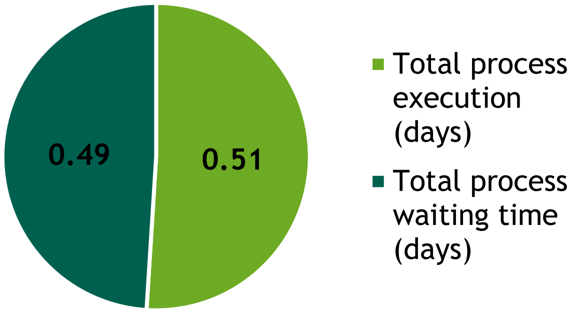

Figure 5: Process execution and waiting time

The data displayed in the figures 4 and 5 also indicates that requesting data from BUs and the drafting of all the required reports, acts as a bottleneck in the process, with long task duration and long waiting/idle time. This immediately draws attention to these tasks as being sources of waste within the process, and main focal areas for lean implementation, to decrease total process duration and waiting time.

5 ROOT-CAUSE ANALYSIS

The following section aims to determine the main causes for inefficiency and waste within the process using lean waste identification tools.

5.1 Cause and effect analysis

The purpose of using this tool is to determine the contributing factors to the key problem areas identified in the process. Figure 6 shows the causes that may be potentially contributing to the main issues experienced, organised into sub-categories (people, process, system and environment), to determine the relationship and inter-dependencies between these factors as well as the level of contribution, to the overall unproductiveness of the team. The operational inconsistency and inefficiency of the team is the main reason for the team's experience of excess workload pressure and late deliverables.

- People – factors that involve/are a result of human resources.
- Process – factors that involve/are a result of the actual process structure and execution.
- Systems – factors that involve/are a result of the enabling systems used in the process, or the lack thereof.
- Environment - factors that involve/are a result of the company/team culture and behaviour, including certain company policies or rules.

Figure 6: Cause and effect diagram

5.2 Lean service waste identification

Table 3 discusses the wastes identified within the process and compares the wastes to the equivalent manufacturing waste type. The team can only fulfil their work requirements with the cooperation of the respective Business Units. Therefore, more often than not, the RM's have to wait for the requested feedback from the BU's, before proceeding with the process, resulting in wasted time. As a method of quality control, the RM's are also required to have their reports reviewed by the managers. However, if the managers do not respond on time, the RM's are unable to proceed with the rest of the process.

The team has also become accustomed to group/collaborative report drafting/review sessions which result in lengthy meetings with very little progress made, a waste of time and unnecessary motion of the team. Another form of unnecessary motion is seen in the emailing of reports back and forth between the team members, for editing and reviewing, with no central edit and storage repository.

The RM's are required to produce three different reports in this process, the monitoring report, risk register and remedial action plan; containing similar and complimentary information. The reports are also presented in different formats to suit the needs/requests of different Business Units, which makes it difficult for all Relationship managers to follow a standard operating procedure for the process execution. The result of these practices is severe waste, in the form of duplication, overproduction and lack of standardization of reports and process implementation.

Company A has provided all functions within the business, with access to Microsoft Office, and recently introduced a system specifically aimed at automating certain aspects of the team's work and processes. However, this system is not yet in use, while only limited functions of the software are being used by the team to assist them in being more efficient, which is a waste; under-utilized resources which are being paid for by the company.

Table 3: Process service waste identification

No.	Lean service waste identified	Equivalent manufacturing waste	Process waste description
1	Delay	Waiting	Late report submissions
2			Waiting BU or managerial response and data
3	Unnecessary motion	Motion	Entire team meeting together to determine monitoring scopes, draft engagement letters or review reports when requested.
4			Back and forth emailing of documents between different individuals
5	Overproduction/ Duplication	Over-production/ processing	The production of three different reports that give feedback on a singular monitoring report for one BU

No.	Lean service waste identified	Equivalent manufacturing waste	Process waste description
6	Lack of standardization	Inventory	Reports containing similar data presented on different reporting formats, tailor made to BU preference
7			No standard or formal monitoring and reporting process structure within the team
8	Under-utilized resources	Unutilized talents	Not making full use of systems and software already available to the team as a form of an automated enabling mechanism

5.3 Five Why's

The 5 Why's is an analysis tool used to discover the underlying reasons for challenges faced within a system or organisation. With the help of the information provided by the team during workshopping sessions and the 5 Why's analysis tool, four main root causes were uncovered, as displayed in Figure 7.

However, some of the root causes, such as company culture, misconstrued perception of the RRC's role, the regulatory analysts' confidence in their work and the overall working environment cannot be actively addressed and solved using lean and engineering techniques and are far removed from the scope of this project. Therefore, certain preceding issues will be selected to form part of the root causes that can aid in developing a measurable and practical solution.

The selected root causes are now:

- Lack of planning or organisation within the team.
- Collective drafting of sessions and managerial review of documents.
- The same information required by different BUs, presented in different formats.
- Lack of training on software/system use and capability.

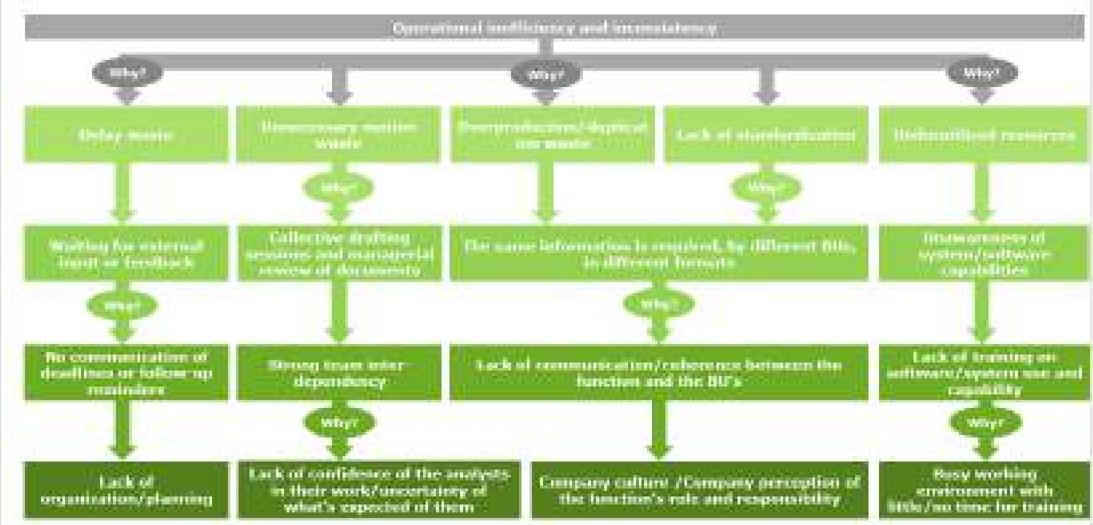

Figure 7: Five Why's analysis

6 SOLUTION PROPOSITION

The following section discusses the potential solutions and improvement ideas that the author has proposed to the function. The improvement suggestions are derived from the documented problem areas, as a means of directly addressing the issues discussed, eradicating all forms of waste identified in the process and forming part of a modified and improved process for the monitoring and reporting process.

Change opportunity identification

- Introduce standard process steps and a documented operating procedure manual.
- Create a standardized and consolidated monitoring report template.
- Eliminate group sessions to determine monitoring scopes, draft engagement letters or review reports.
- Introducing a central data repository and work platform.

6.1 Proposed to-be process model and description

The following process map, shown in Figure 8, serves as a visual representation of the proposed monitoring and reporting process.

The process is still triggered by the function's annual plan which states all the activities that the function should complete within the year. The respective RM then determines the scope of the monitoring assignment and proceeds to populate the engagement letter, which contains all the necessary information and requirements for the monitoring assignment and uploads the letter onto the team's OneDrive folder for the manager to review. The manager will then receive a notification of the upload and proceed to review the engagement letter to ensure that it is complete and populated with all the required information. All corrective commentary should be made on the live document and once the letter is approved, the manager sends a notification of approval to the RM.

The RM downloads the engagement letter from the OneDrive and emails it to the relevant Business Units and the BU responds to the RM with the requested data and information. The RM then proceeds to analyse the BU data, identify, and take note of any risks and exposures. The RM will then meet with the BU, to discuss the monitoring findings, discuss all the points of concern and agree on corrective actions. The RM then has the responsibility of populating the standard monitoring report template, as a draft version and uploading it onto the OneDrive.

The manager will receive a notification of the upload and proceed to review the draft monitoring report, ensuring that it is complete and populated with all the required information. All corrective commentary should be made on the live document and once the report has been approved, the manager sends a notification of approval to the RM. The Relationship manager then distributes the report to all relevant stakeholders and over the course of an agreed upon duration of time, follows up on the implementation of the documented corrective actions.

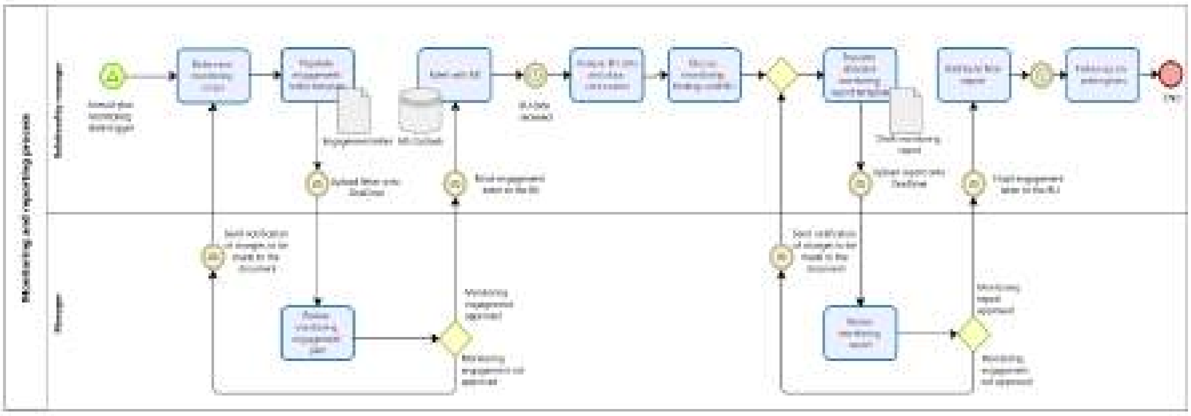

Figure 8: Proposed to-be process model

6.2 Standard process steps and documented operating procedure manual

The purpose of the Standard Operating Procedure is to establish a standardized procedure and create a step by step understanding and breakdown of the monitoring and reporting process. The process is initiated by the annual monitoring plan dates and executed by the Relationship Managers and managers, involving the cooperation and input of certain business units. As illustrated in Table 4, the manual highlights the Process activity, Role responsible and system used to implement the task as well as a detailed activity description.

Table 4: Extract of the to-be process SOP manual

No	Activity Role System	Activity description
	Determine monitoring scope Relationship manager Manual OneDrive	1.1) As soon as the Annual plan monitoring date trigger occurs, the Relationship manager is access the team OneDrive, navigate to the ‘monitoring plan and documentation’ folder, to access the annual monitoring plan, relevant policy and legislative documents and download all process document templates. 1.2) The RM is then required to determine and finalize the scope of the monitoring engagement that is to take place: • Monitoring sample dates • Monitoring objective • Legislation/Act being monitored • Business Unit/s being monitored • Information submission date • Monitoring interaction meeting days

6.3 Standardised monitoring report template

An essential output of the monitoring and reporting process is the information included in the reports produced. The author designed a new and updated report, based on the three major reports: the risk register, monitoring report and corrective action plan, produced by the monitoring and reporting process.

The new report allows for all the necessary information required from the three reports, to be consolidated into one concise report.

The report template and format presented remains the same across all BU's and stakeholders, eliminating the variance in duration of populating the report, between different RM's and conserving time when populating report information.

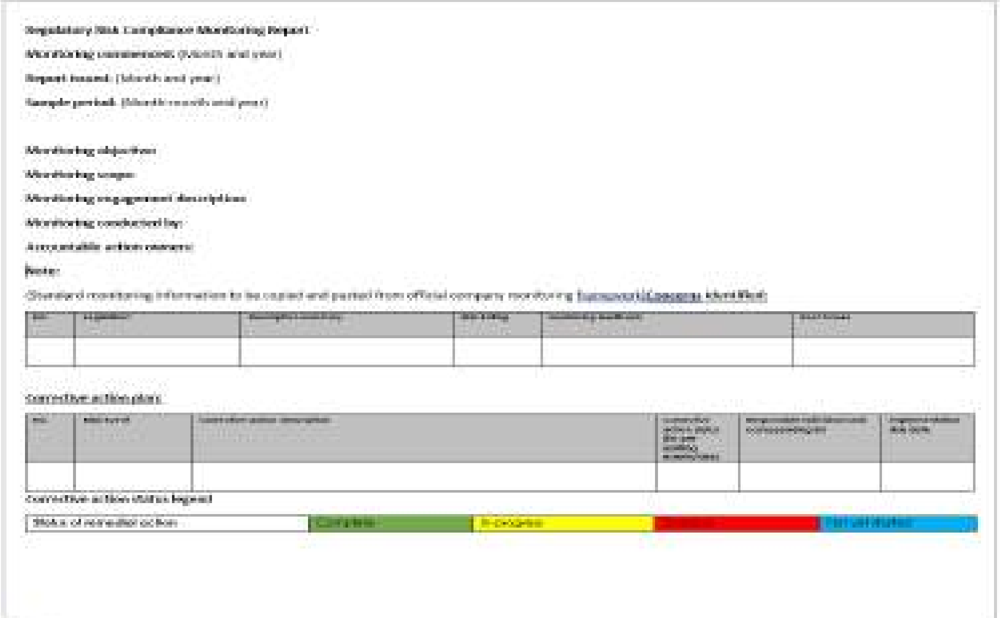

Figure 9: Standardised monitoring report template

6.4 Central storage and editing repository: OneDrive

The team has been granted access to the complete Microsoft Office 365 suite, as provided by Company A. A combination of desktop applications designed specifically for business use by Microsoft, including OneDrive.

OneDrive is a Microsoft cloud service which acts as a connecting interface for all files in the MS Office suite. Through the use of MS OneDrive, the user has the ability to store, share and access live documents. This has been an unutilised tool or resource within the team that has consequently resulted in other forms of waste that can be addressed by the full use of the capabilities of the cloud service at no additional costs to the company.

OneDrive capabilities include the ability to share common folders among users and co-author and annotate documents, which means team members can draft documents or edit one another's work (should there be a need), without having to physically meet. All changes and structural changes can also be tracked to show who made the alteration to the document and when this was executed, which allows for accountability and ease of follow-up on the side of the manager, should specific changes be questioned.

OneDrive also allows for the user to restrict access to certain folders, which ensures that confidential information will only be accessed and altered by the relevant users [14].

The team requires a central platform that will allow them to store documents in an orderly and organised fashion, update document information in real-time by different individuals, and access the most recent version of documents without having to email documents between team members. Microsoft OneDrive caters to these requirements and more.

The author set up the team OneDrive folder, as shown in Figure 10, to act as a central edit and storage repository.

Figure 10: OneDrive folder structure

The structure of the OneDrive folder is created in a way as to allow for segregation of documents for storage purposes as well as a Kanban system for review and approval of the monitoring report. Once the RM has completed the documentation of the engagement letter and the monitoring report, the documents are moved to the 'review' folder. Documents in the review folder act as a Kanban signal for the Manager, indicating that the next review step, should take place. Once the manager has approved the document, the move of the document from the 'review' folder to the 'approved and submitted' folder, is a signal for the RM to distribute the letter or the report, to the relevant BU's and stakeholders.

All monitoring results documented are to be stored according to the relevant BU being monitored as well as all internal monitoring documents, such as policies and legislations, annual monitoring plan and monitoring document templates. This ensures that there is a central storage location for easy access of all documents that would be required in future for auditing or reference purposes.

7 SOLUTION VALIDATION

The purpose of this section is to validate the process solutions and to-be process proposed by the student to the OMI RRC team for the monitoring and reporting process.

As a result of time and policy constraints within the business environment, the proposed process could not be implemented throughout the function for the monitoring period. Therefore, a pilot project was executed by selected team members, while the rest of the RRC team proceeded to perform the monitoring and reporting process as usual. The pilot process execution was carried out over a reduced monitoring period and reduced scope, as a means of testing the validity and practicality of the proposed process.

7.1 Quantitative result analysis

The data collected concludes that the future-state RRC monitoring and reporting process duration time is 24.5hrs long, performed over 22 working days. Of the 22 days spent on this process, only 72.72% of those are productive working days, while the rest are spent idle or waiting, as indicated in Figure 11 and Figure 12.

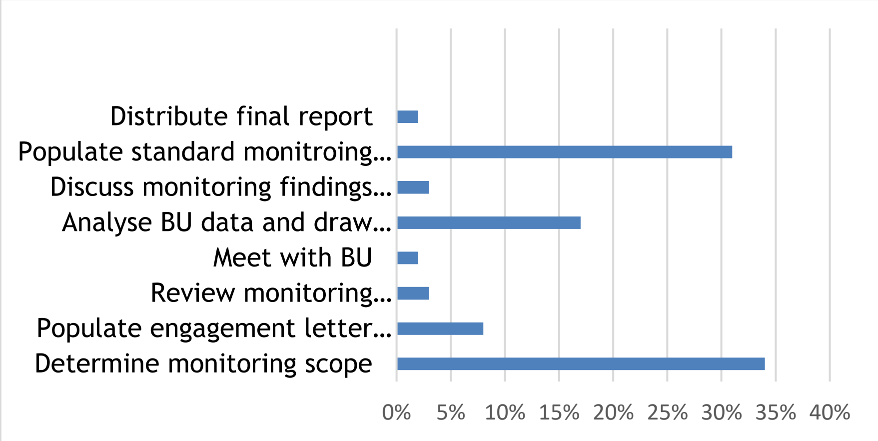

Figure 11: To-be monitoring and reporting task execution times

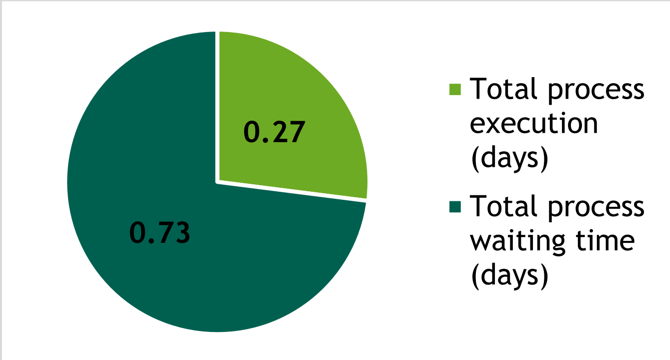

Figure 12: To-be monitoring and reporting execution and waiting time

The To-be process executed resulted in reduced process duration time in hours as well as reduced waiting time resulting in 72.27% of the process duration time in days, being productive.

Percentage reduction on process task execution time (hrs): (34.5-24.5)/34.5 = 28.99%

Percentage improvement on productive process duration time (days): (22-16)/22 = 27.

Comparing the As-Is process execution time of 34.5 hrs, to the To-be process execution time of 24.5 hrs, a percentage reduction of 28.9% is observed for process execution time.

Waiting time in the To-be process has been recorded to have reduced from 21 days in the As-is process, to 6 days in the To-be process, which results in a 27.27% percentage improvement on the productive process duration time in days.

7.2 Qualitative result analysis

The team involved in the process pilot trial provided insightful feedback on their personal experience and input on the execution of the proposed process, the benefits experienced as well as observed challenges and concerns for future function-wide implementation.

7.2.1 Process implementation benefits

The Team expressed that the standard operating procedure (SOP) manual introduced, acted as both a training tool and a process embedment tool as well, ensuring that all RM;'s executing the process, were doing so in a uniform and standardised manner. The use of new report template not only made it easier to capture all the required information for the monitoring task, but created clarity from the start of the monitoring period, as to what information and documents would have to be finalized before the report template is populated. This resulted in minimal report population and rework time for the RM and report review time for the manager. Similarly, the elimination of group draft and review sessions also resulted in more time for the RM's to execute other process tasks and allowed for a smoother flow of the process. Lastly, the central data repository and work platform introduced an organised way of storing all the most recent documentation, relevant to the monitoring engagements making it very easy to navigate.

7.2.2 Process implementation challenges

To ensure successful process execution, stakeholder, and BU buy-in and approval is required, to ensure that they are all aware of the role in which they play within the process. Company culture and the 'old way of doing things' becomes an issue in the introduction of a new process or way of executing tasks. Once a BU or stakeholder is unfamiliar with the role they play in the process or is reluctant in executing said task, such as submitting all required information and documentation in a certain format by a certain date, creates delay and rework within the process. The introduction of the new report, resulted in a substantial amount of rework for BU's to translate the information presented in the report, for their own managerial reports. Due to the ripple effect of the changed reporting structure, the updated monitoring report needs to undergo an executive approval process within Company A, before it can be implemented within the function.

8 CONCLUSION

The project identifies the approach and techniques that can be adopted in industry to apply lean philosophy, not just in a manufacturing environment, where lean is most used, but in a service environment. The project translates the principles and tools of lean to apply to an environment that has high human dependency for process execution and no standard process structure.

The lean service wastes identified and documented in this project can be applied to other functions, that do not deal with physical products, but rather provide a service both internally and externally to the general public. The approach adopted in increasing process efficiency and eliminating process inconsistency and waste, can also be modified to apply to industries that would typically not consider lean as an applicable productivity enhancement approach, industries in the health sector, legal sector and financial (banking, accounting, and insurance) sector. The project further highlights a need for more research and applications of lean philosophy to be documented in the service industry and specifically the financial and legal sector.

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ADDING NEW PUZZLE PIECES: IMPROVED CATTLE HANDLING FACILITIES FOR IMPROVED FLOW

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ABSTRACT

Well-designed cattle handling facilities play a crucial role in simplifying handling procedures, ensuring smooth flow, and minimising stress for animals, thereby positively impacting their experience and production. However, there remains a challenge in achieving optimal facility designs. In response, this study aims to integrate industrial engineering principles with animal psychology to propose concept designs for cattle handling facilities on case study farms. Through a narrative literature review and a current state analysis, the study identifies key factors such as gentle handling methods, curved passages- and high-solid sides, that enhance overall flow in cattle handling facilities. Concept designs tailored to each farm are presented, emphasizing the importance of optimising facility layouts, equipment locations, and operational procedures to enhance cattle flow. While the study provides valuable insights, further research is needed to assess the feasibility, effectiveness, and potential impact of implementing these concept designs in existing cattle-handling facilities.

Keywords: Cattle, handling facility, Temple Grandin.

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1 INTRODUCTION

Applying industrial engineering principles in agriculture has proven beneficial in enhancing productivity, improving efficiency, and optimising processes [1]. Industrial engineering techniques, such as work research and quality management, offer valuable tools for analysing and improving work processes in various industries, including agriculture. These principles can boost resource utilisation and overall process optimisation by identifying bottlenecks, eliminating waste and optimising workflow [2].

One area in agriculture where industrial engineering principles can be applied is in cattle handling facilities. Cattle handling facilities are structures that are designed and constructed to facilitate the management and movement of cattle in a safe, efficient, and humane manner. These facilities are essential for livestock producers to manage their herds and provide a controlled environment for performing tasks such as weighing, sorting, and medical treatment. The design and layout of cattle handling facilities are critical to their effectiveness. Good facility design considers the natural behaviour of cattle, their movement patterns, and their reactions to stress [3]. These facilities also play an important role in cow-calf operations where effective handling and management practices are essential for maintaining the health and productivity of the herd and the quality of the calves produced [4]. Just as in a factory/manufacturing setting, bottlenecks in cattle handling facilities can hinder the flow of operations, leading to inefficiencies, increased stress for the animals, and reduced productivity.

Understanding the behaviour and temperament of cattle is also important for effective handling and management [5]. Cattle temperament can significantly affect how they react and the level of stress they experience. Calmer cattle tend to exhibit less fear and anxiety during handling, making them easier to manage [6]. Conversely, hyperactive cattle can be more challenging to handle, leading to increased stress for both the animals and handlers.

Cattle experience stress which is caused by various environmental factors, including temperature, lighting, and noise levels [7]. Stress in cattle can affect their behaviour and overall well-being, which, in turn, influences their production [3]. The cattle handling facility, being the primary location where cattle are subjected to handling procedures, represents a significant source of stress for the animals [8]. Therefore, designing handling facilities with a focus on minimising stress is crucial for enhancing animal welfare and optimising production outcomes.

The importance of an efficient layout and flow dynamics in cattle handling facilities is highlighted by Grandin’s research [6, 3, 9, 10, 11, 12]. According to Grandin [13], curved or circular designs, as opposed to sharp corners, can promote smoother cattle movement and reduce the risk of animal injury. The width, height, and type of flooring in the chutes can all have an impact on the behaviour and stress levels of the animals during handling [14]. For example, squeeze chutes and head gates can be used effectively to lessen animal suffering and increase worker safety [15]. By considering layout and flow dynamics, chute systems and equipment, lighting and environmental considerations, cattle handling facilities can be improved to provide efficient, secure, and humane handling procedures.

The intersection of cattle handling facilities with industrial engineering principles underscores a significant synergy aimed at optimising the management of cattle and enhancing operational efficiency. Just as in industrial engineering, where methodologies are employed to streamline processes and maximise productivity, the design and operation of cattle handling facilities demand similar attention to detail and systematic planning. The management of cattle through these facilities parallels engineering management, both aiming to achieve efficiency, safety, and the desired outcomes. The key to this connection is found in the idea of facility design, where the positioning of the workflow in the working area—the pens, chutes, and crushes—is mirrored by the layout of the workspace frequently found in industrial environments. The main idea of process optimisation in industrial engineering is directly aligned with improving the flow in cattle handling facilities. The use of data-driven decisions, as evidenced by the analysis of the case studies, mirrors the empirical approach often taken in industrial engineering to refine and enhance systems. Integrating insights from Temple Grandin's principles further enhances the scalability and adaptability of these facilities, akin to incorporating innovative strategies in industrial processes to ensure continuous improvement. Furthermore, considerations such as space utilisation and equipment placement resonate with facility design principles, ensuring efficient resource utilisation and overall functionality. This convergence underscores the value of applying industrial engineering methodologies to cattle-handling facility design, resulting in streamlined operations, reduced stress for animals, and improved production outcomes.

Handling facilities consist of different sizes of sorting and holding pens leading up to a straight or curved chute. The single-file chutes allow cattle to move one-by-one behind each other towards the working area. The working area consists of different types of crushes including head gates, squeeze crushes, box crushes and or scales as indicated in Figure 1.

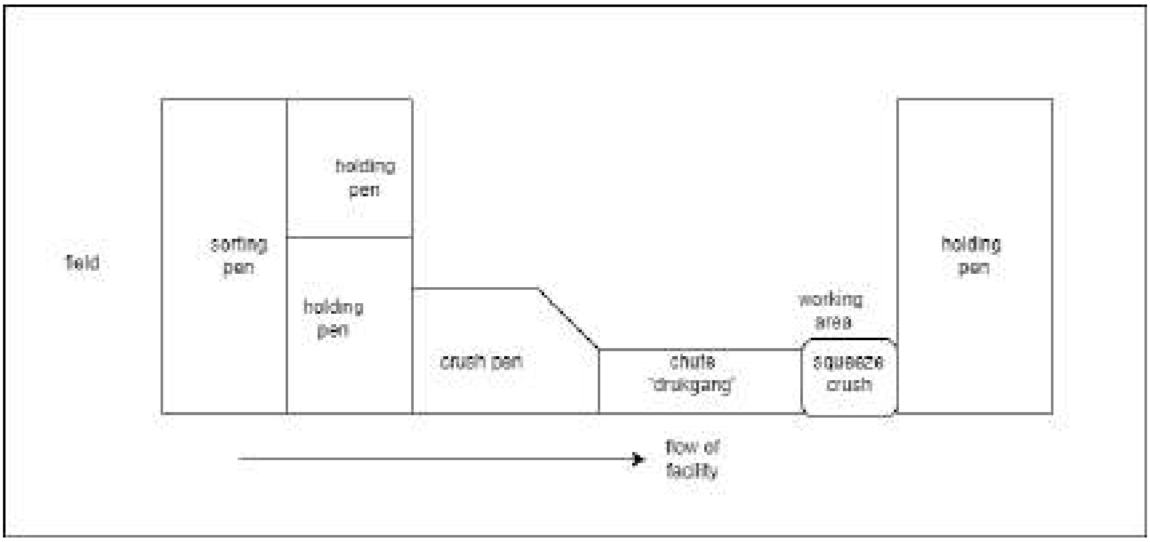

Figure 1: General handling facility layout

The problem is that existing South African cattle handling facilities often lack efficient layouts and flow dynamics, leading to poor handling practices and increased stress on the animals. This results in compromised animal welfare, increased risk of injury for both animals and handlers and reduced overall operational efficiency.

Ten case study farms were chosen at random throughout central South Africa, to examine their handling facilities. These first ten farms form part of a larger study. The goal of the larger study is to improve the design and layout of more facilities throughout South Africa to achieve a more effective and stress-free handling process by integrating insights from industrial engineering and animal psychology. The information gained from the case study farms will be valuable in directing future research (of the larger study) and contributing towards workable solutions to enhance cattle-handling facilities across the entire agricultural sector.

The aim of this study is to investigate how many of the theoretical principles are applied on the case study farms and then to apply industrial engineering principles together with animal psychology principles to provide improved concept facility designs for these farms.

The next section will provide relevant literature on the subject and Section 3 explains the research method that was followed. Section 4 provides the current state of analysis and Section 5 stipulates the design requirements. Section 6 provides the improved concept designs for which verification is provided in Section 7. Conclusions and recommendations for future research are provided in Sections 8 and 9, respectively.

2 LITERATURE REVIEW

The relevant literature on facility design principles for cattle handling facilities is presented in this section.

2.1 Best Practices

One area of focus in recent research is the impact of handling techniques on animal behaviour and stress levels. Researchers found that using low-stress handling techniques, such as visual cues and maintaining consistent pressure [9], can significantly reduce animal stress and improve animal behaviour [11, 16, 7, 6, 9]. Other studies have explored the impact of facility design, such as the use of curved chutes and solid walls, on reducing animal stress and improving flow [13, 10, 14, 8].

Another area of research is the use of technology to improve cattle handling [4, 17, 18]. Technologies, such as automated sorting systems, remote-controlled gates, and virtual fences, have been developed to reduce the need for human intervention and improve animal handling. These technologies have shown promising results in reducing stress on animals and enhancing worker safety.

2.2 Review of Temple Grandin's Principles and Their Application

Temple Grandin's principles have revolutionised the design and management of cattle handling facilities [3, 6, 13, 14, 7, 11, 19]. Grandin, a renowned animal behaviour expert and autism advocate, developed principles and guidelines for designing and operating cattle handling facilities based on her extensive knowledge of animal behaviour [19, 20]. According to the literature, Temple Grandin is the leader in the field of animal handling facilities. The collection of her principles served as a useful tool for directing the redesign of the facilities. These guidelines emphasised the significance of reducing stress and fear in cattle, encouraging gentle handling methods, and improving the physical environment to allow for fluid and effective movement. The suggested redesigns provided potential answers to problems in cattle handling facilities.

The main objective of Grandin's design philosophy is reducing animal stress [3]. Furthermore, Grandin's principles aim to improve animal welfare and reduce injuries to both animals and handlers [6, 7]. Grandin also stresses the importance of worker safety in cattle handling facilities [10]. She recommends designing facilities that minimise the need for human intervention, using remote-controlled gates and other technologies to reduce the risk of accidents and injuries [9].

The application of Grandin's principles has been widely adopted in the cattle industry, with many facilities adopting her design principles to improve animal welfare, worker safety, and efficiency [7, 13, 11]. The use of solid walls and curved chutes have been shown to reduce animal stress and improve flow, while the use of visual cues and remote-controlled gates has reduced the need for human intervention and improved worker safety [6, 3, 9].

A summary of principles developed by Grandin is provided in Table 1.

3 METHODOLOGY

The engineering design process was used to develop concept designs of cattle handling facilities for the ten case study farms in the central Free State:

1) Current state analysis and problem identification
2) Literature review

3) Design requirements
4) Final design
5) Verification

3.1 Current State Analysis and Problem Identification

To gain a comprehensive understanding of the existing cattle handling facilities, each farm included in the study was visited. These visits served as an opportunity to gather accurate information about the facility layouts and to observe their operations first-hand. An evaluation of the facilities was done using a checklist based on Temple Grandin's design principles (Refer to the left column of Table 1 for the checklist).

By systematically documenting these aspects, a detailed analysis of the facility layouts was conducted. This analysis aimed to identify problem areas that hindered the efficient flow of cattle and contributed to operational inefficiencies.

The flow of cattle through the facilities, the presence of potential bottlenecks, inefficient equipment placement and other design-related issues were among the main factors considered during the analysis. By closely examining these aspects, specific problems that impeded the smooth handling and movement of cattle, were pinpointed.

The current state analysis is captured in Section 4.

3.2 Literature Review

A narrative literature review (Section 2) was conducted using various search databases such as ScienceDirect, Scopus, and Web of Science. Specific keywords such as “handling facilities”, “cattle psychology”, and “facility design” were used. To ensure the selection of relevant research papers, a set of inclusion and exclusion criteria was applied. The inclusion criteria encompassed research papers that focused on facility layout, handling facilities in a corral set, beef cattle flow and crush/chute systems. On the other hand, the exclusion criteria aimed to filter out non-English literature, topics unrelated to cattle handling facilities (such as slaughter, abattoirs, non-cattle facilities, handling raw meat, rodeo, auction facilities, and flow of blood), transportation handling, and discussions primarily cantered on the human factor with regards of the handling of cattle.

Following the application of these criteria, 58 research papers underwent a thorough quality assessment to ensure their reliability and credibility. This assessment process involved the removal of any duplicate papers and a further narrowing down to 20 research papers. These studies focused specifically on cattle-handling improvements within the corral, emphasising the design aspects of handling facilities rather than the human factor.

The selected 20 research papers were analysed to extract valuable insights and findings related to facility design and cattle handling. This analysis involved comparing and synthesizing the information from different studies to identify common themes, trends, and best practices.

3.3 Design Requirements

Design requirements were established based on the client’s needs and design principles identified from the literature. Refer to Section 5 for the list of design requirements.

3.4 Final Designs

Based on the client requirements and design principles from the literature, the improved concept facility layouts were designed. Refer to section 6 for these concept designs.

3.5 Verification

The concept designs for the handling facilities can be seen in Figure 2-11. The original Temple Grandin checklist was used again to verify that the new concept design of the facilities met the requirements. Refer to the right-hand side of Table 1 for the verification that each principle was addressed in the new concept designs.

4 CURRENT STATE ANALYSIS

During the current state analysis, each facility was visited, drawn, and evaluated against Temple Grandin's principles. The drawings of the current facility layout can be seen on the left-hand side of Figures 2-11.

A checklist of facility design principles was created, based on the important principles found in the literature review. The focus was on investigating the layout of the facilities, specifically the pens, chute, and crushes, to align with best practices for cattle-handling.

During the evaluation, each farm was evaluated against each principle (refer to the middle column of Table 1). If a farm adhered to the principle it was marked with "Y" denoting "yes". When a particular principle was not upheld, an "N" was recorded, denoting "no". If the principle did not apply to the facility a “- “was inserted in the table. The evaluation of the current handling facilities is represented in the middle column of Table 1.

The design of cattle handling facilities varies, but some common features include pens, chutes, and working areas. The designs range from traditional layouts to more modern designs that incorporate Temple Grandin's principles. However, some facilities have insufficient layouts, little room for movement, misplaced equipment and gates, or other design flaws. Congestion, unpredictable cattle behaviour, and elevated stress levels during handling can result from these design flaws.

Several variables were noted in the construction material used for the current cattle handling facilities. Due to their strength and durability, combinations of cables, wood bulks, and steel these materials are frequently employed in the construction of cattle handling facilities While some of the facilities have been constructed from scratch, others have been passed down through generations of farmers or handed over from previous owners, with only simple renovations made over time.

It was noted how the arrangement of cattle handling facilities affect how the handlers and animals move around during the procedure. The configuration of the pens, squeeze crushes, and chutes may present difficulties in their current state. Some facilities have bottlenecks, sharp angles, or dead ends that obstruct smooth movement and add to delays. The quality, accessibility, and usefulness of equipment varied in each facility. The handling process might have been hampered by out-of-date or malfunctioning equipment, a lack of tools, or inappropriate sizes for a certain activity.

In summary, despite the variations in their design and histories, all the facilities of the case study farms had similar flow problems. These difficulties included bottlenecks at the chute's entrance, where cattle may have trouble or be reluctant to enter the designated area. The facilities also experienced cattle crowding in corners, which can obstruct the easy movement of animals inside the facility. The inability of cattle to move through the chute, which could be brought on by things like fear, stress, or discomfort, is another issue that has been observed.

These flow problems in the current state of the facilities hinder efficient cattle handling, compromise worker safety, and may negatively impact animal welfare. Addressing these issues is crucial to improving the overall effectiveness and functionality of cattle handling facilities.

Table 1: Design principles checklist

Design principles	A current state analysis of handling facilities										Verification of the concept design layouts.
	A	B	C	D	E	F	G	H	I	J	
1) The contact surface is smooth, at the chute.	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Earth ground fillers are incorporated into the designs.
2) Sharp corners are padded.	N	N	N	N	N	N	N	N	Y	N	All the sharp corners are removed or padded.
3) Gates had tiebacks.	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y	Each gate has its tie-back on both sides.
4) The indoor facility has nonslip floors.	-	-	Y	-	N	-	-	-	-	-	Diamond groves are designed on concrete surfaces.
5) Is illumination even?	Y	Y	N	Y	N	N	Y	N	Y	Y	The crush is placed North or South in the design, if not cattle should be handled at certain times of the day.
6) No sudden changes in floor level/texture.	Y	Y	N	Y	N	Y	Y	Y	Y	Y	Yes, no sudden changes.
7) No banging metals.	N	N	Y	N	Y	Y	Y	N	Y	Y	Yes, all banging metals were removed.
8) Is loud machinery far away?	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Yes, no loud machinery is near.
9) Can cattle make 180-degree turns inside the pen?	Y	N	Y	Y	Y	N	Y	N	Y	Y	Yes, the pen is enlarged for it.
10) Are the curve pens' inside radii between 3,5 and 6 meters?	N	-	-	N	Y	-	Y	-	N	-	Yes, the radius is changed to match the requirement.
11) Is the crowd gate between 2,44-3,66 meters?	Y	Y	Y	-	N	Y	Y	Y	N	Y	Yes, all the gates are between those dimensions.
12) Is the junction of the crowd pen and single-file non-sharp?	Y	N	N	Y	N	N	N	N	Y	Y	Yes, the junction was changed to ensure smooth flow.
13) Can the cattle see 2 body lengths up the single file?	N	N	Y	Y	Y	N	Y	Y	Y	Y	Yes, chutes are changed to elongate cattle sight.
14) Is the race width between 66-71 cm?	Y	Y	Y	Y	Y	N	Y	N	N	Y	Yes, the races' widths are.
15) Is the fence height 152cm for English breeds, and 167-183 cm for Brahman-type breeds?	Y	N	Y	Y	Y	Y	Y	N	Y	N	Yes, all the fences are adjustable according to cattle breed.

Design principles	A current state analysis of handling facilities										Verification of the concept design layouts.
	A	B	C	D	E	F	G	H	I	J	
16) Is the straight crowd pen funnelling with one side at a 30 angle?	-	N	N	Y	N	N	-	N	-	Y	Yes, all angled fences are at 30-degree angles.
17) Are there no shadows, puddles of water, drain gates and bright sun in the way?	Y	N	Y	Y	Y	Y	Y	Y	Y	Y	Yes, the change in design eliminated these stress factors.
18) No light glaring into their eyes.	Y	Y	N	Y	N	Y	N	Y	Y	Y	Yes, the change of equipment placement, removed the glaring light.
19) Is the single file 3-5 m outside the shade if the chute is under the shade?	-	-	N	Y	N	-	-	-	-	-	Yes, longer chutes are added.
20) Are the sides of the single-file race, loading ramp or crowd gates solid?	N	N	N	N	Y	N	N	N	N	N	Yes, solid sides are added, all gates on designs have solid sides.
21) Are rails not at cow's eye height?	N	N	Y	N	N	Y	Y	N	Y	Y	Yes, the lengths are according to no.15.
22) Squeeze side distances: 16 cm for 113-180 kg calves, 21 cm for 272-360 kg cattle, and 30 cm for most cows and fed steers.	N	N	Y	N	N	N	Y	N	Y	N	Yes, designs are adjustable according to cattle type.

5 DESIGN REQUIREMENTS

The design requirements for the new cattle handling facilities were set by integrating both the client's needs and theoretical requirements gathered from the literature. The client requirements reflect the specific needs and preferences of the farmers, considering factors such as herd size, breed, and management practices. The theoretical requirements draw upon established principles and best practices in cattle handling, incorporating insights from experts in the field.

5.1 Client Requirements

1. Safety: The facility should prioritise both the handlers' and the cattle's safety, reducing the possibility of injuries while handling the animals.
2. Efficiency: To reduce handling time and increase productivity, the facility should allow for a constant and smooth flow of cattle.
3. Animal welfare: By providing a humane and low-stress handling environment, the facility should reduce stress and discomfort for the cattle.
4. Flexibility: The facility should be flexible enough to accommodate a range of handling techniques and activities for cattle of various sizes and breeds.

5. Durability: To withstand the wear and tear caused by cattle handling operations, the facility should be built with durable materials.
6. Accessibility: The establishment must be made easy to access for cattle handlers to move and handle cattle efficiently.

5.2 Theoretical Requirements (based on literature)

1. Flow and Layout: The facility's layout needs to be well-planned to encourage a steady flow of cattle while avoiding bottlenecks, acute angles, and dead ends. It ought to reduce traffic and offer open paths for the movement of cattle.
2. In all pens, cattle should be able to make 180-degree turns [6].
3. Curved Passages: According to Temple Grandin [10], the facility should have curved passages to improve cattle movement and lessen stress. By taking advantage of the natural tendency of cattle to move in arcs, curves can improve cattle flow.
4. If curved pens or chutes are used their inside radium must be between three and a half (3,5) to six (6) meters [10].
5. High-Solid Sides: The building should have high-solid sides to keep cattle from noticing distractions outside the fence, which will lessen stress and help them keep calm while being handled.
6. The chute, loading ramp and crowed gates should have solid sides [10].
7. Proper equipment placement: The facility should make sure that equipment like pens, chutes, and crushes is placed correctly and is functional. Equipment should be positioned carefully to support effective handling procedures.
8. The junction of the chute pen and the single-file chute must be non-sharp, allowing cattle to move in their natural manner [10].
9. Lighting and environmental considerations: The facility should take lighting and environmental factors into account to reduce shadows, reflections, and other elements that could frighten or confuse cattle. To lessen stress, environmental factors like temperature, ventilation, and noise levels should be optimised.
10. Ergonomics: The facility should take the ergonomics of handlers into account, making sure that tools and handling techniques are made to reduce physical stress and fatigue.
11. The contact surface should be level in the chute with no sudden changes.
12. Indoor facilities should have non-slip flooring with diamond groves [10].
13. All sharp corners must be padded to prevent injury.
14. Remove all stress factors such as the noise of metal banging, glaring sunlight, puddles, or other loud machinery [3].
15. All gates used to crowd or move the cattle must be between 2.44 to 3.66 meters [10].
16. When cattle are at the entrance of the chute, they must be able to see two body in lengths in front of them [10].
17. The chute’s race width must be between sixty-six to seventy-one centimetres [10].
18. The fence height should be placed strategically and not in the cattle’s view. For English breeds, the height is 152 centimetres and for Brahman-type breeds 167 to 183 centimetres [10].
19. A straight crowd pen should funnel leading to the single-file chute, with one side straight and the other at a thirty-degree angle [14].
20. The working area, the squeeze chute should be placed North / South to keep glaring sunlight from dazzling the cattle [9].
21. When a cover is over the working area, a three-to-five-meter chute must be outside before leading the cattle into the shade [3].
22. The squeeze crush’s width is dependent on the cattle type, ensure that for 113 - 180 kg calves the squeeze sides should be 16 cm apart at the chute floor, 21 cm for 272 - 360 kg cattle and 30 cm apart for most cows and fed steers [3].

6 CONCEPT DESIGNS

In Figures 2-11, the current state design is presented on the left and the new design is presented on the right. To distinguish the working area, it is highlighted in purple, while all the gates are represented in pink. The flow of cattle is indicated by arrows, showing the desired movement within the facility. The single lines in the design indicate open sides, allowing visibility and some degree of movement, while the double lines represent solid sides, providing a barrier and preventing the cattle from seeing other animals or handlers. The problem areas are circled with a dashed red circle.

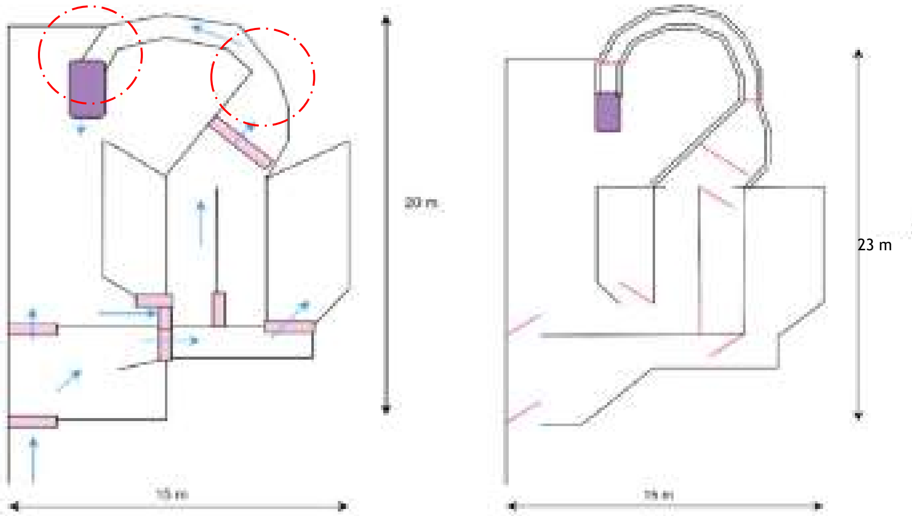

Figure 2: Farm A current vs ideal facility design

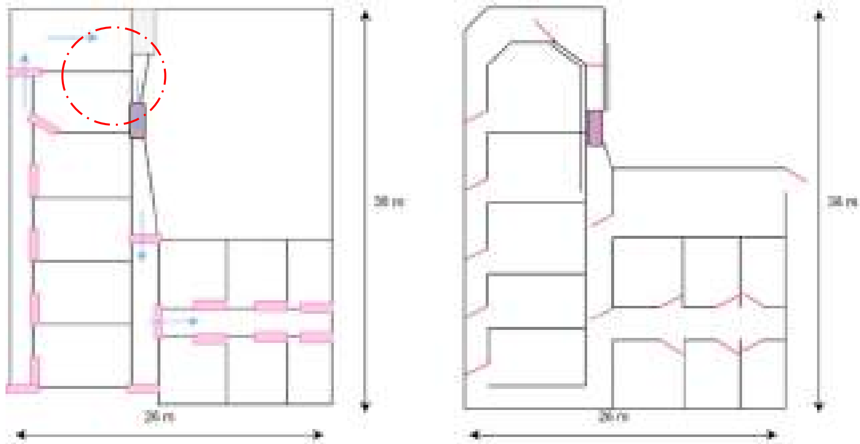

Figure 3: Farm B current vs ideal facility

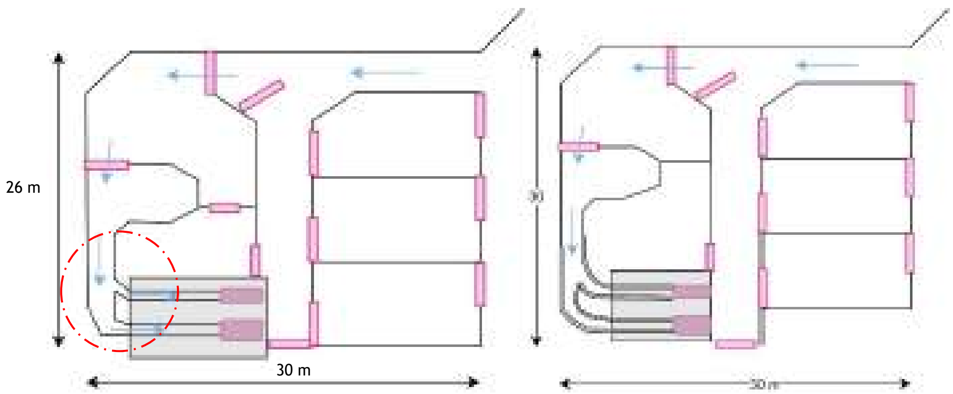

Figure 4: Farm C current vs ideal facility

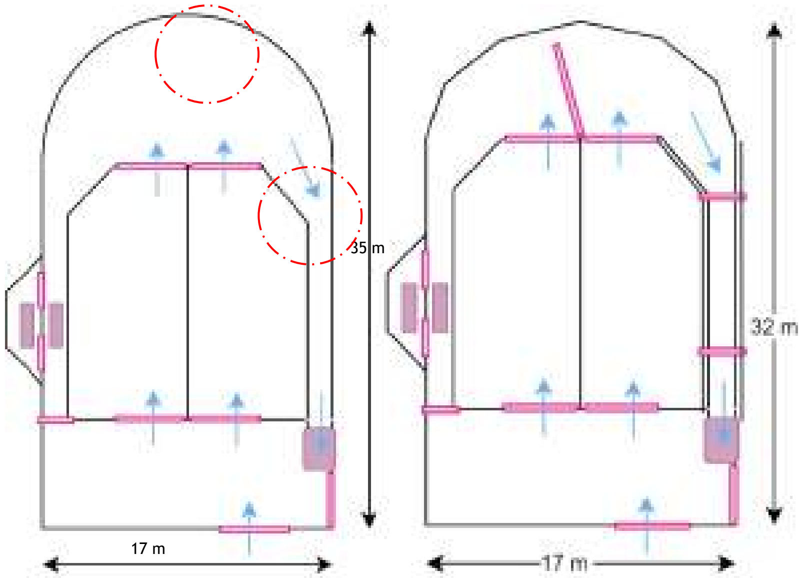

Figure 5: Farm D current vs ideal facility

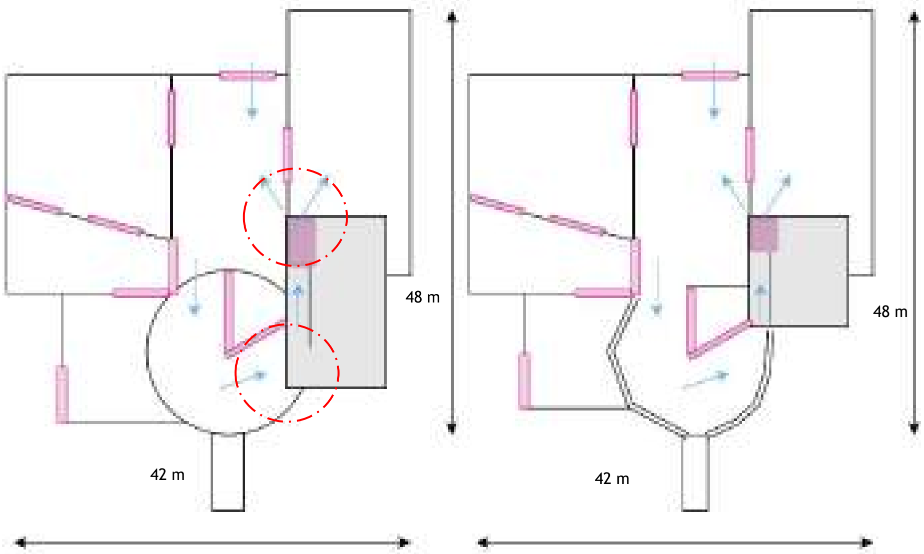

Figure 6: Farm E current vs ideal facility

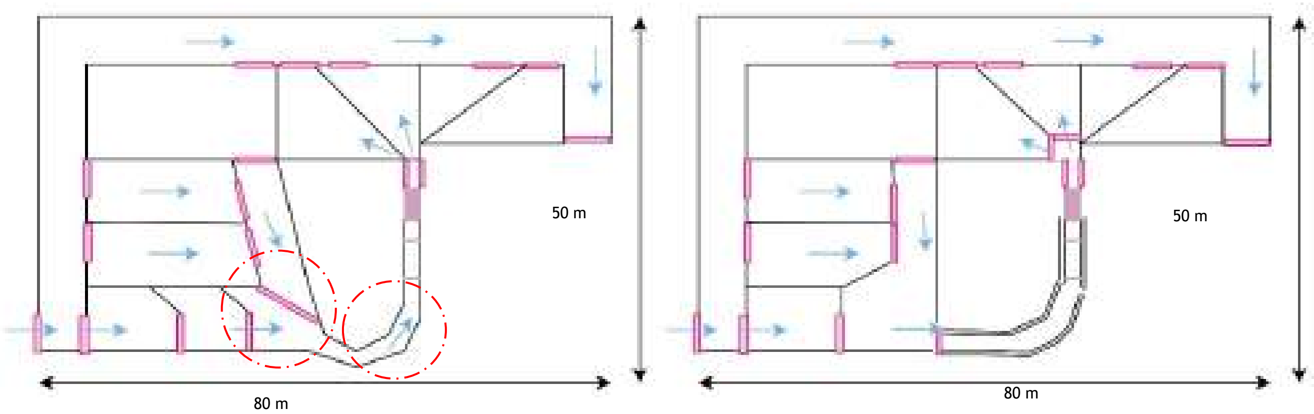

Figure 7: Farm F current vs ideal facility

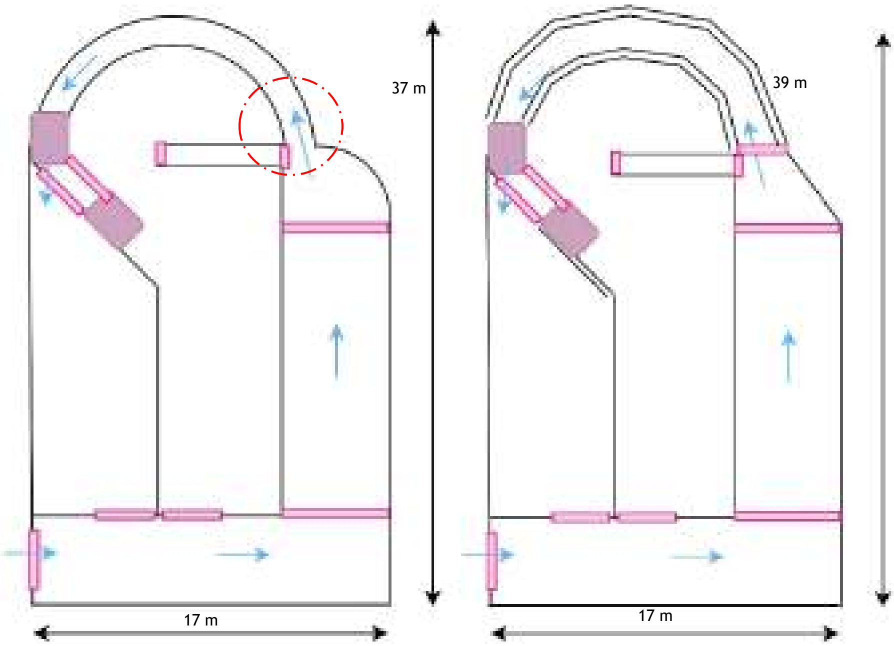

Figure 8: Farm G current vs ideal facility

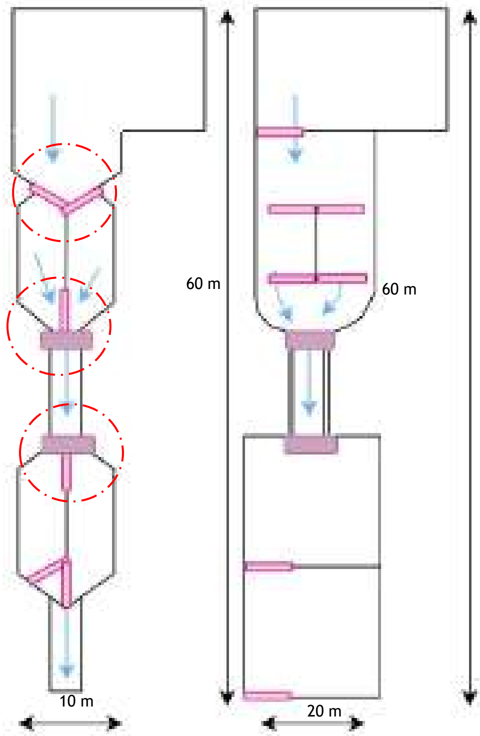

Figure 9: Farm H current vs ideal facility

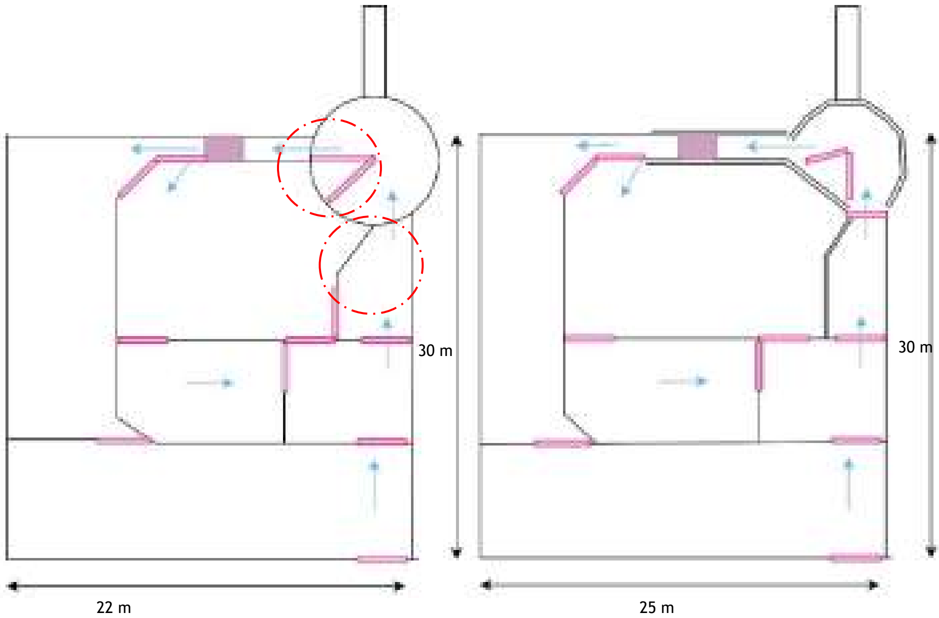

Figure 10: Farm I current vs ideal facility

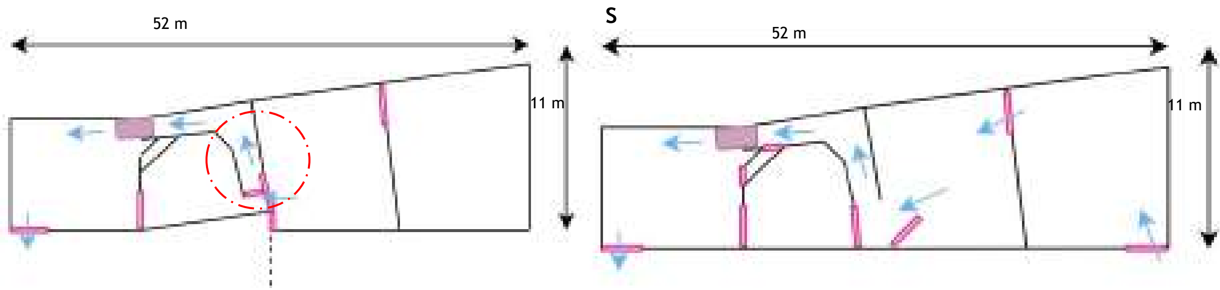

Figure 11: Farm J current vs ideal facility

The chutes were redesigned with curved sections to provide smooth and gradual turns for the cattle, following Temple Grandin's recommendations [10]. Solid sides and strategically placed gates were incorporated into the chutes, crush, and chute pen to minimise stress and promote calmness by limiting the cattle's view of other animals, the working area, and handlers. Consideration was given to different cattle breeds, adjusting the positioning of pipes and fence heights to avoid direct eye contact and to accommodate specific breed requirements. The pens were designed to allow comfortable 180-degree turns, while the single-file chute width and gate lengths were standardised for suitable cattle passage. Safety measures were implemented, including smooth surfaces, padded corners to prevent injuries, and gates equipped with tiebacks for ease of operation, ensuring both cattle and handlers' comfort. For a detailed verification against the design principles, please refer to Table 1, which serves as a comprehensive checklist.

7 VERIFICATION

The new concept designs were verified against the design requirements from both the client and the literature, ensuring their potential to improve cattle handling. Proof that the new concept design met these requirements is presented below.

7.1 Verifying Client Requirements

The list of client requirements was provided in Section 5.1. Proof of how these requirements were met in the new concept design is provided in Table 2.

Table 2: Verification of adherence to client requirements

1. Safety	The new layout puts safety first by including elements like rounded edges, non-slip flooring, and securely fastened gates to reduce the possibility of injuries while performing cattle handling procedures.
2. Efficiency	Optimising the layout and flow of the facility, reducing unnecessary movement, and minimising handling time, thereby improving overall productivity, and reducing labour requirements.
3. Animal welfare	The handling process by using gentle handling techniques, lowers stress levels by removing large stress factors and provides comfortable and low-stress environments.
4. Flexibility	It is simple to adjust and modify to accommodate various cattle sizes and breeds, various handling techniques, and potential future changes or facility expansions.
5. Durability	A long-lasting and robust facility is ensured by the new design's use of premium building materials and construction methods specifically to withstand the demanding conditions of cattle handling operations.
6. Accessibility	By incorporating wide walkways, strategically placed gates, and appropriately sized entrances to make it easier for people and equipment to move around the facility.

7.2 Verifying literature design requirements

To ensure that the new concept design adhered to the literature design requirement, the Temple Grandin checklist was used again for evaluating the new designs against each of the principles in the checklist. Refer to the right-hand column of Table 1.

8 CONCLUSIONS

In conclusion, this study has built upon previous research in the field of cattle handling facilities, specifically focusing on the application of industrial engineering and animal psychology principles to improve design concepts. Previous research has frequently overlooked methodological flaws like a lack of thorough analysis and integration of important design principles.

To address these shortcomings, this study employed a rigorous methodology that involved evaluating numerous design principles and best practice, taking into account the interaction between industrial engineering and agriculture. The aim was to provide improved concept facility designs that prioritise safety, efficiency, animal welfare, flexibility, durability, and accessibility. The results of this study demonstrated the significant impact that well-designed cattle-handling facilities can have on animal welfare, worker safety, and overall productivity. By implementing targeted design principles, such as low-stress handling, efficient movement, and effective worker positioning, notable improvements in cattle flow, can be achieved.

This work contributes to the research map in the field by emphasising the importance of integrating industrial engineering and animal psychology principles into the design process for cattle handling facilities. By addressing the weaknesses in current handling facilities and providing comprehensive evaluations and design concepts, this research enhances our understanding of how the engineering principle of facility design can positively impact the well-being of both animals and handlers.

An achievement of this study is the development of concept facility designs that align with the natural behaviours and instincts of cattle. By incorporating features such as curved chutes and solid sides, stress levels can be minimised, leading to smoother and calmer movement. The achievements of this work hold significant meaning and implications for the industry.

Well-designed cattle handling facilities can create safer and more productive environments, ultimately benefiting both animals and handlers.

Incorporating industrial engineering principles and Temple Grandin's insights into cattle handling has been crucial in opening up new opportunities for efficiency and improved procedures within cattle handling facilities. This study emphasises how different handling process optimisation can be when facility design concepts from industrial engineering are combined with the unique requirements of livestock management. By combining these disciplines, the study explains how specialised facility layouts, thoughtful equipment placement, and workflow optimisation all work together to improve the flow of cattle, lower stress levels, and increase operational productivity. This research has indicated that industrial engineering principles are the missing puzzle piece needed to elevate agricultural practices to increased production, improved flow, and facility optimisation.

The implications of the results extend to various applications within the agricultural sector. The findings provide valuable insights for farmers, facility designers, and industry professionals, highlighting the importance of considering design principles that optimise animal welfare and operational efficiency. These insights can guide the development and modification of existing facilities to promote better handling practices as most of the current handling facilities' flaws are due to inheriting facilities with old design layouts.

9 FUTURE RESEARCH

It is important to acknowledge the limitations of this study, which should direct future research efforts. The concept facility designs presented in this study serve as a starting point and require further evaluation and validation in real-world settings. Additionally, the study focused on specific design principles and may not encompass the entirety of factors influencing cattle handling facility design. Future research should explore additional design considerations and conduct comprehensive studies to assess the feasibility and impact of implementing these design concepts.

Furthermore, while this study investigated current designs and proposed improved ideal designs based on research-based requirements, the actual implementation and assessment of these designs in real-world settings remain pending. Future studies should focus on the practical implementation of the concept designs proposed in this paper, evaluating their feasibility, effectiveness, and impact on existing cattle-handling facilities. This could involve conducting pilot studies, monitoring performance, and gathering stakeholder feedback. By bridging the gap between conceptualisation and implementation, valuable insights can be gained into the practicality and benefits of these design improvements, paving the way for wider adoption and further refinement of cattle handling facilities. Additionally, it is important for future research to expand beyond the 10 case-study farms in the central Free State and include a broader investigation of farms in other parts of South Africa to gain a more comprehensive understanding of the current state of cattle-handling facilities.

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IMPLEMENTING A KAIZEN PROGRAMME TO IMPROVE PRODUCTIVITY AT A PRODUCER OF HEMP EXTRACTS IN GAUTENG

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ABSTRACT

This paper reports on the implementation of a Kaizen programme to improve productivity at a producer of premium hemp extracts. It emanated from a partnership with a government entity's productivity interventions mandated by the Department of Trade, Industry and Competition. The primary objective was to implement Kaizen to enable the organisation to improve quality, productivity, and throughput. The aim of the study was to achieve more efficient operations to improve productivity. The programme began with capacity building and the application of 5S principles, stock control, and quality improvement. Results over a six-month period showed marked improvements with, for example, the harvest rate, increasing by 37%, better management control, providing real-time data and visualisation of the company's performance, which resulted in more efficient action and decision-making. The government entity's interventions at this organisation are in its infancy and further industrial engineering interventions are planned towards improving processes and enhancing productivity.

Keywords: Kaizen, hemp, productivity, sustainability, operations.

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1 INTRODUCTION

The Department of Agriculture, Land Reform and Rural Development (DALRRD) [1] issued amendments to standing Regulations in October 2021. These amendments declared Cannabis sativa L, commonly known as 'hemp,' as an agricultural product, in terms of the Plant Improvement Act No. 53 of 1976 [2]. Since the 1990s, societies have decided that drug bans produce more problems than benefits [3]. The amendment was significant in that, subject to acquiring a Hemp permit from the DALRRD [1], producers may import, export, cultivate and sell hemp products.

Duvall [4] states that many authorities, especially in Europe, North America, and South America, have relaxed controls on cannabis by decriminalising and/or legalising some instances of production, sales, possession, and use. Africa has followed suit and its countries are also participating in this global wave of cannabis legalisation. Duvall [4] adds that the twentieth-century drug laws changed the economics of production, causing cannabis farming to become particularly attractive to resource-poor farmers. Several countries have recently legalised cannabis cultivation within specific contexts. In 2017, the South African parliament sanctioned the use of medical marijuana, to benefit ill people, while in 2018 the country's Constitutional Court decided that adults have the right to grow and use dagga privately [5] and [6].

The President of South Africa, Cyril Ramaphosa, indicated that progress has been made in the development of the hemp and cannabis industry in South Africa. "To date (2023), eighty-three cannabis licences, four manufacturing licences and thirty research permits have been issued by the South African Health Products Regulatory Authority (SAHPRA) [7] and DALRRD [1] has issued 371 hemp permits. These licences and permits have enabled significant investment, employment creation, the application of technology, intellectual property development and exports to highly competitive global markets" [2].

Company A, on which this paper is based is the leading cannabis provider in South Africa. They pride themselves on the full control over all operations and strict compliance with South African laws and regulations regarding cannabis. The company specialises in the production of premium grade cannabis plants and products. Established in 2018 with the aim of providing the best services for all clients, investors and businesses looking to take on the cannabidiol (CBD), world. The company is a leader in the industry and the first to produce high quality CBD flower, extracts, and related products in South Africa.

The primary objective was to implement Kaizen to enable the organisation to improve quality, productivity, and throughput. Due to the issues alluded to in point 2.1 below, it was important to first identify critical measures which were identified as quality and throughput. This was followed by data collection to study the trends in the cultivation of hemp. The trends indicated that quality related issues affected the throughput. The Kaizen project was then used to reduce quality issues that contributed to high mortality identified by the traceability report.

2 PROBLEMS INVESTIGATED AND THE RESEARCH OBJECTIVES

Company A was beset by inefficient operations. The general housekeeping was in disarray, leading to time wastage to access equipment. Accidents through poor housekeeping was prevalent. It faced challenges with its production and its competitiveness. They felt the need for interventions to improve processes and ensure its sustainability. Other problems were. Namely, the absence of a production performance measurement system and written procedures (Work Instructions), no effective monitoring of plant movements throughout the life cycle, batches are mixed up and others are not labelled leading to poor stock control and the language barrier. There were also issues of inconsistent pH, underwatering, and insecticides on plants. Chemicals and fertilisers would run out which affected operations. The primary objective was to implement Kaizen to enable the organisation to improve quality, productivity, and throughput.

3 LITERATURE REVIEW

3.1 Reasons for partnering with Productivity South Africa

This paper reports on the implementation of a Kaizen programme to improve productivity at a Company A. It emanated from Company A contacting Productivity South Africa (Productivity SA) for assistance with solutions which will enable the company to be productive and competitive through the empowerment of its employees. Productivity SA is established in terms of section 31 (1) of the Employment services Act, No. 4 of 2014 as a juristic person with a mandate to promote employment growth and productivity thereby contributing to South Africa's socio-economic development and competitiveness. Productivity SA is managed in accordance with the Public Finance Management Act (PFMA). The mandate of Productivity SA is to enhance the productive capacity of all South Africans, [8].

Productivity SA recommended a Kaizen programme to Company A. The aim of the programme was to bring an understanding and application of continuous improvement concepts that will enable more effective, and efficiency driven operations management activities. The implementation of improvement projects was aimed at ensuring that the organisation would be able to apply the Kaizen concepts. On completion of the program, a decision was made to focus on improvement of hemp production since it forms the core of the business and experiences challenges. The second improvement selected by the team was the 5S project in the chemical storeroom.

The Kaizen programme entailed conducting Kaizen Tools and Capacity Building Workshops and the implementation of identified projects. The Coaching and Review of the programme followed the implementation, to ensure that the interventions were sustainable. The selected Kaizen team which comprised of supervisors from vegetables and hemp and interns were trained on the concept of Kaizen covering the following.

Figure 1: Kaizen tools and implementation

3.2 Overview of Company A

Company A, as a leading provider of high-quality CBD and cannabis products to South Africa and the world, operates a fully compliant global Good Agricultural Practices (GAP) cultivation and processing facility, producing premium quality high CBD cannabis. Cannabis strains have been carefully selected and sourced for genetics with proven therapeutic benefits. Together with distillation partners, Company A produces a Full Spectrum Extract refined into a highly purified concentrate with quality verified by accredited, independent third-party laboratories. O'Driscoll 2020 [9] states that full-spectrum extracts, often called whole plant extracts, maintain the full profile of the cannabis plant.

Company A is one of the few SAHPRA permit holders, who has quickly positioned themselves as one of the leaders and the first to premium cannabis and produce quality Full Spectrum Extract and CBD products in South Africa. They are in the process of developing a fully compliant global GAP and Good Manufacturing Practices (GMPs) cultivation facility, certified to cultivate premium quality cannabis and high CBD hemp. ASC Consultants [10] states that the Global GAP is an internationally recognised certified standard that ensures Good Agricultural Practices.

Their nursery produces seedlings and clones, cultivating premier cannabis plants. The company envisages harvesting up over 50,000 cannabis plants across multiple strains annually.

Company A's processes include the following:

- ***Nursery***

  The nursery provides high-quality strains of seedlings, mothers, and clones. Company A has developed Clonater, which allows for the fast production of quality clones. Company A is also able to provide turnkey cannabis farming solutions to emerging cannabis farmers.

- ***Cultivation***

  Company A cultivates A-grade high CBD hemp in their state-of-the-art facilities. Company A's farming operations comprises hemp farms spanning eighty-one hectares across three provinces thus ensuring security of supply to their off-take clients against adverse weather conditions. Each of the farms have been equipped with state-of-the-art security systems.

- ***Drying and Processing***

  The drying and processing solutions makes use of automated environmental regulation controls to ensure the perfect environment is maintained to ensure a high-quality output. Company A is occupying both machine trimming technology as well as a dedicated hand-trimming team to provide the desired solutions that will meet any of the customers' needs.

- ***Inclusion Programme***

  The Company A Inclusion Programme will allow emerging cannabis farmers to partner with.

- ***Offtake Agreements***

  Pistilli [11] states that an offtake agreement is a binding contract between a company that produces a particular resource and a company that needs to buy that resource. Apart from cultivating hemp for their own supply chain, Company A is also able to supply offtake agreements to large clients looking to secure a crop/crops of high-quality CBD hemp. By securing an offtake from Company A, clients can guarantee their supply for the next year and get a more competitive price than market value.

- ***CBD Products***

  Company A has launched a range of high-quality CBD products under the wellness brand *alkmi*. All products produced for *alkmi* are assessed through an independent third party.

Company A is focused on providing bulk off-take agreements concentrates or flower products, and only operate within compliant legal markets with qualified suppliers and buyers. Their highly qualified and accredited team specialises in helping manufacturers and brands to procure suitable hemp derived CBD. The company has multiple permits within its stable and a healthy strategic partnership with other permit holders which affords them the platform to provide their clients with rich research and quality product to meet the ultimate needs. They collaborate closely with clients to ensure that all bulk off-take agreements are meticulously planned and managed in order develop their own supply chain to ensure continuity of supply. Grown on home soil, Company A was established in 2018 with the aim of providing the best services for all clients, investors and businesses looking to take on the CBD world. The business is based on a farm in Mogale City, Krugersdorp and currently has a staff compliment of ten and on a needs-basis employs up to one hundred casual workers.

3.3 Defining Kaizen

Kaizen is often associated with the Japanese manufacturing industry when Japanese companies were seeking to improve their production processes and quality standards. Kaizen also refers to the continuous and gradual development of increasing value, intensification, and improvement [12]. The idea behind Kaizen is to continually make small improvements in all areas of an organisation, from the production process to employee training, with the goal of achieving greater efficiency and effectiveness. Rather than trying to achieve large, sweeping changes all at once, Kaizen emphasizes the importance of making small, incremental improvements over time. These small improvements can lead to significant gains in productivity, quality, and customer satisfaction. Kaizen involves a continuous cycle of improvement that includes four steps, namely:

- ***Plan:*** Identify areas that need improvement and develop a plan to address them.
- ***Do:*** Implement the plan, making small changes to the process or system.
- ***Check:*** Measure the results of the changes and compare them to the previous performance.
- ***Act:*** If the results are positive, incorporate the changes into the process or system. If the results are not positive, repeat the cycle with a new plan.

These are referred to as the PDCA cycle. Kaizen is not just a business philosophy; it is also a way of life that can be applied to personal goals and habits. By making small, incremental improvements in their daily lives, they can achieve their goals and become more efficient and effective in everything we do. Daniel [13] adds that Kaizen speaks to the creation of continuous improvement based on the idea that small, but ongoing positive changes can realise noteworthy improvements. Kaizen is based on cooperation and commitment and stands in contrast to approaches that use radical or top-down changes to achieve transformation. A must mention is that Kaizen is core to lean manufacturing and the Toyota Way. Figure 2 shows that Kaizen includes seven steps, from identifying problems to finding solutions, testing them out, analysing the results and then doing it all again, [13]

Figure 2: Kaizen Seven Steps

3.4. Hemp cultivation

The cultivation of hemp dates to China around 2700 BC and is believed to have then expanded across Asia, making its way to Europe 2000–2200 years ago, [14]. Hemp is a variety of the Cannabis sativa plant species that is grown specifically for industrial or medicinal use. Unlike marijuana, another variety of the Cannabis plant, hemp contains very low levels of the psychoactive compound THC (tetrahydrocannabinol) and does not produce a "high" when consumed. Hemp has been used for thousands of years for a variety of purposes, including making textiles, paper, and rope. Ely and Fike [15] state that it has been used as a source for fibre, food, fuel, and building materials for millennia. Hemp seeds, for example, are rich in protein, healthy fats, and other nutrients and can be eaten raw, roasted, or turned into oil. Farmers extract valuable oils, cannabidiol (CBD), seeds, and fibers from the material when hemp plants are harvested, [16].

Hemp has gained renewed interest in recent years due to the increasing popularity of CBD (cannabidiol), a non-psychoactive compound found in hemp and marijuana that is believed to have potential health benefits. CBD is extracted from the hemp plant and used in a variety of products, including oils, tinctures, and edibles. In many countries, hemp was previously banned due to its association with marijuana, but its cultivation and use have been legalised in many places for industrial and medical purposes in recent years.

Figure 3 shows the high-level process of hemp cultivation. The process was studied to investigate critical issues in the process.

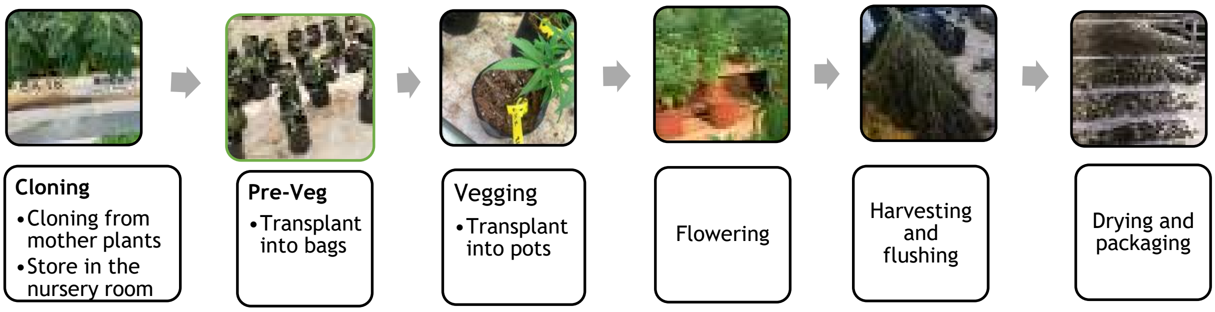

Figure 3: Hemp cultivation process

3.5 Productivity

Kenton [17] states that productivity is defined as the ratio of an extent of output to the unit of all the resources used to produce this output. Stevenson [18] states that productivity is an index that measures output (goods and services) relative to the input (labour, materials, energy, and other resources) used to produce them. It is usually expressed as the ratio of output to input. Seminal works by Slack, Chambers and Johnston [19] define productivity as the ratio of what is produced by an operation or process to what is required to produce it, that is, the output from the operation divide by the input to the operation. Jacobs and Chase [20] state that productivity measurement is fundamental to understanding operations-related performance and in its broadest sense, productivity can be defined as:

$$\text{Productivity} = \frac{\text{Output}}{\text{Input}}$$

Higher productivity means that there is better management of inputs and processes, so that outputs of better quality and lower costs are produced [21]. A productivity ratio can be computed for a single operation, a department, an organisation, or an entire country. In business organisations, productivity ratios are used for planning workforce requirements, scheduling equipment, financial analysis, and other important tasks.

3.6 The application of 5S principles

Paulise [22] states that 5S is one of the first tools that can be applied in a company that is starting down the path of a continuous improvement culture. The American Society for Quality [23] defines 5S as a lean methodology that results in a workplace that is clean, uncluttered, safe, and well organised to help reduce waste and optimise productivity. It is designed to help build a quality work environment, both physically and mentally. The 5S philosophy applies in any work area suited for visual control and lean production. The 5S condition of a work area is critical to employees and is the basis of customers' first impressions.

Table 1: The 5S's

Japanese	Translated	Principle	Definition
Seiri	Organise	Sort	Eliminate whatever is not needed by separating needed tools, parts, and instructions from unneeded materials.
Seiton	Orderliness	Set in order	Organise whatever remains by neatly arranging and identifying parts and tools for ease of use.
Seiso	Cleanliness	Shine	Clean the work area by conducting a cleanup campaign.
Seiketsu	Standardise	Standardise	Schedule regular cleaning and maintenance by conducting *seiri*, *seiton*, and *seiso* daily.
Shitsuke	Discipline	Sustain	Make 5S a way of life by forming the habit of always following the first four S's.

Company A selected Kaizen team which comprised of supervisors from vegetables and hemp and interns were trained on the concept of Kaizen to be trained by Productivity SA. The training focused on placing everything where it belongs and ensuring proper housekeeping, which would make it easier for employees to conduct their daily activities without the loss of time or the risk of injury. The Kaizen team was trained on 5S principles during the Kaizen training.

4 Research methodology

Kaizen and 5S principles were used as the research methodology to effect process improvements towards improving productivity. It describes actions and solutions implemented towards improving the efficiency in the process of producing hemp extracts. Kaizen can bring many benefits to an organisation, such as improving quality and increasing productivity and efficiency by standardising processes, eliminating waste, and optimising resources.

4.1. Data collection (Trend Analysis)

To understand the challenges outlined in point 2.1 above, it was necessary to quantify the current issues in the nursery so that improvements can be made. The team created a Traceability document to track nursery performance from the cloning stage to the packaging. Table 2 displays what the document measures and is based on information collected between 15 March to 31 March 2022. It shows the batch number, the number of clones in a batch, the number of days spent in the clonator, and the number of clones transplanted, any difference between the clones and transplants indicates quality issues and other related issues.

Table 2: Cultivation Records (Nursery)

Batch number	Mother ID	Date cloned	Amount of clones in batch	Days spent in clonator	Pathology	Mortality rate (%)	Date transplanted to pre-veg	Amount transplanted
1	CA10	15-Mar	200	17		63.5	01-Apr	127
2	CA55	15-Mar	150	16		23.33333333	31-Mar	35
3	CA85+CA68	16-Mar	200					
4	CA87	16-Mar	200	16		46.5	01-Apr	93
5	CA10+CA60	16-Mar	200					
6	CAX	17-Mar	200	15		80	01-Apr	160
7	CAX	17-Mar	200	15		52	01-Apr	104
8	SC01+SC14	17-Mar	200	19		92	05-Apr	184
9	SC	17-Mar	110	15		79.09090909	01-Apr	87
10	DM2.5	22-Mar	185	14		62.7027027	05-Apr	116
11	CA87+CA55	24-Mar	200	14		84	07-Apr	168
12	CA87+CAX	24-Mar	200					
13	SC01	25-Mar	200	17		90	11-Apr	180
14	CA10	29-Mar	200	13		69	11-Apr	138
15	CA87+CAX	30-Mar	200	12		69	11-Apr	138
16	CAJ12/X	31-Mar	200			37.5		75
Totals			3045	15,25		76,57143		1605

From Table 2, the following inferences can be made.

- From a total of 3045 clones, only 50% were transplanted between the period of 15 March and 31 March.
- The mortality rate is drawn from the difference between the cloned and transplanted plants, and it shows that 76,57% clones were lost.
- This could be due to quality issues or loss (theft).
- The table can also provide a Mother performance. Mother CA 10 on line 1 and line 14 indicate a consistent mortality rate.
- More investigation is necessary to determine the cause of mortality on Mother CA10.
- The focus of the project was on improving quality and throughput of Hemp.

5 FINDINGS AND RESULTS

Results over a six-month period showed marked improvements with, for example, the harvest rate, increasing by 37%, better management control, providing real-time data and visualisation of the company's performance, which resulted in more efficient action and decision-making. During the implementation, the following challenges were encountered which impacted on the progress.

- Some of the Kaizen team members had resigned from Company A.
- Due to Covid-19, the new tools introduced could not be used accurately, and coaching by the Kaizen champion was not possible.
- Kaizen activities implemented are being incorporated to the Tillo Application to be used to monitor and control production. This delayed the impact realisation as employees first needed to manual record information and be provided with training on the use of the tools.

- In terms of 5S, various improvement areas were identified, however it was put on hold due to management plans to renovate the plant and allocate designated areas accordingly in line with GAP compliance.

5.1 Quality issues and improvements

The pictures below illustrate common defects that results to reduced throughput.

Figure 4: Quality issues

Based on the information collected using the traceability document and the observations made by the Kaizen team, it was decided to focus on improving the quality issues which would improve throughput. The starting point was to conduct a root cause analysis of the defects/high mortality rate, followed by developing solutions to reduce defects/mortality and finally develop performance measures to monitor and control defect rate. The American Society for Quality [23] defines a root cause as a factor that caused a nonconformance and should be permanently eliminated through process improvement.

To determine the root causes of the defect rate, a fishbone diagram was used to explore various possible causes. These causes may come from either Man, Method, Machine, Measurements, Material, and Environment. Table 3 below shows possible causes of high mortality rate according to each category, these were obtained through brainstorming session with the Kaizen team.

Table 3: Mortality rate possible causes

MAN	MATERIAL	MACHINE	METHOD	MEASUREMENT	Environment
Shortage of resources (not keeping up with feeding times)	Mother plant could be defective	Load shedding and machine failure of environmental equipment	Underwatering	Incorrect mixing of fertiliser	Pests

Lack of training (employees not able to follow instructions)			Lack of documented work instruction	Nursery Room temperature	Heat stress
Late ordering of chemicals (delayed feeding)			Incorrect mixing and feeding	Unstable PH	Rainfall/Power failure

5.2 Corrective Actions

From the observations pertaining to the causes of the identified defects, feasible solutions and remedial actions for each cause were put together.

Table 4: Corrective actions

	Main causes	Corrective actions
MANPOWER	Resources are sometimes taken away from their core jobs in the nursery to assist in other areas. This takes time away from feeding the clones. Barriers of communication between the supervisor and team members, not being able to follow instructions.	Create visual instructions (inclusive of pictures). Create checklist with timelines on when plant feeding, and watering should occur. In-house refresher training by the quality personnel.
MATERIAL	Clones are taken from mothers, and if the mother is defective the entire batch could be discarded. Shortage of fertiliser. Poor/late ordering of fertiliser which are sometimes only ordered when its run out. This delays the feeding.	Create visuals of healthy and unhealthy mothers, including necessary requirements such as the PH levels that a mother should have before being cloned. Create a system to monitor stock and improve communication.
METHOD	Lack of a visual method of grooming the plants from nursery to harvesting. No standard operating procedures. Lack of consistency in monitoring batch numbers. Sometimes batches are mixed up. Tracking of quality issues then becomes a problem. Employees forgetting to update batch numbers.	Create standard operating procedures/ work instructions for the grooming of plants. Create a check sheet to monitor plant PH and other necessary quality issues (pesticides) and water level.
MEASUREMENT	Incorrect mixing of chemicals. Underwatering impact on the PH levels of the plants. This affects the quality of hemp produced.	Create standard operating procedures/ work instructions for mixing chemicals and watering. Create a check sheet to monitor plant PH and other necessary quality issues (pesticides) and water level.
MOTHER NATURE	Plants perish due to heat stress. Plant diseases such as spider mites, caterpillar, and grasshoppers. Rainfall and power cuts.	Pest control. Heat control.

5.3. Actions implemented

Table 5 shows the following five actions which were implemented.

Table 5: Actions implemented

KPA	Indicators	MONTH: Baseline	Week 1	Week 2	Week 3	Week 4
Production	% Yield/batch					
	Turnaround time per cycle					
Quality	Mortality Rate %					
	Pathology (Disease) %					
Cost	Cost of errors (mortality) - lost plants					

Table 6: Key performance indicators

Number	Description of action	Impact	Responsible person
1.	Work Instructions with visual pictures (for cloning and fertigation).		Supervisor
2	Check sheets and task sheets- used for every feed. Important checkpoints were PH level and diseases.	Reduce underwatering.	Supervisor
3	To reduce heat stress. Pots and pipes were painted with white paint. More fans were added.	Reduce heat stress. Control PH	Supervisor
4	Weekly stock taking of fertilisers and other chemicals to prevent running out of stock.	Control Pesticides	Supervisor
	To improve PH consistency, the team conducted a problem-solving exercise. Findings showed inconsistency due to contamination on the mixing jug. Solution to this was to rinse the jug before every mix.	Better control of Hemp	Supervisor
5	Visual Management system for tracing plant movement, pathology, yield, and cycle time.		Supervisor

5.4 Recommended Key Performance Measures (Nursery)

A Key Performance Indicator (KPI) is a measurable value that demonstrates how effectively a company is achieving key business objectives. Organisations use KPIs at multiple levels to evaluate their success at reaching set targets. High-level KPIs may focus on the overall performance of the business, while low-level KPIs may focus on processes in departments such as sales, marketing, HR, and others. The Kaizen project at Company A was focused on ensuring maximum output through reduction of quality issues that cause high mortality rate, longer turnaround time and poor-quality hemp (weight). Table 6 shows the KPIs for production, quality and cost are recommended for hemp production.

5.5 5S Implementation

The Kaizen team started with implementing 5S in the chemical and the tools store. The pictures below show the start of the implementation of 5S in the storeroom. Note that this was the starting point towards the broad vision as management plans to renovate the stores in line with GAP compliance. The renovations are focused on separating chemicals from water to prevent contamination and to implement suitable control measures of chemicals and fertilisers.

Figure 5: Before and after minor progress

Figure 5 displays evidence of water spillage was observed. This can ruin powdered chemicals in the store. There is a mix of chemicals decanted from larger containers into smaller containers, however, these were not labelled, posing a serious manufacturing and health hazard. The stores were repainted, and demarcations added. Steel tables and shelves were also added.

6 CONCLUSIONS AND RECOMMENDATIONS

The following note-worthy conclusions were drawn from the Kaizen intervention.

Management had requested a programme that will inculcate a culture of continuous improvement withing the company. Kaizen was deemed necessary to build the culture of continuous improvement through the application of problem- solving methodologies. The Kaizen team was trained on Kaizen concepts which they were then required to apply by identifying problem areas and suggesting improvements. Due to the unavailability of data, the team developed a system to collect data (Traceability and predictability) which covers the process of hemp cultivation. This system will serve as a visual management tool that displays problem areas.

Upon analysing data collected, it was found that there is high mortality rate in between the process of hemp cultivation, this impacts on the throughput. The Kaizen activity was then focused on reducing the mortality rate through development of Standard Operating Procedures and check sheets. The newly developed system will be used for visualising problems and will also assist with overall management and control of the hemp cultivation process.

The Kaizen intervention by Productivity SA was deemed a success as is evidenced in Table 7 which provides the Kaizen Impact figures:

Table 7: Kaizen Impact figures

KPI	Indicators	Pre-Productivity SA intervention	Month one - post intervention	Month five - post intervention	Notes
Production	Cloning rate (number of plants propagated per month)	3045	3200	4800 ***55% increase in number of clones produced per month.***	Propagation production has increased since Productivity SA's intervention.
Production	Harvest rate (average number of plants harvested per day)	50 plants/day	68 plants/day	75 plants/day ***37% increase in number of plants harvested, cut, and trimmed per day***	Harvest efficiency and output has increased since Productivity SA's intervention.
Production	Yield per month (amount of floral mass processed per month kg/month)	110.0 kg/month	149.6 kilograms/month	180.0 kg/month **47% increase in dry floral mass yield per month**	Biomass yield has comparatively increased. This can be attributed to improving tools, process, and resources for the harvesting process.

The company is in the process of using a Tillo Application to manage the farm where performance will be loaded on the application. The Kaizen programme assisted in the identification of the necessary production information that should be collected for better management and control [24]. It is recommended that all employees be trained on the new processes, especially the check sheets that have been implemented to ensure accuracy of information to management. It is also recommended that the implemented activities are expanded to other parts of Company A.

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START-UP SUCCESS: PIECING TOGETHER THE PRODUCTION PLANNING PUZZLE

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ABSTRACT

During their critical growth phase start-up organizations often face challenges in achieving their production targets. This is due to frequent interruptions in production flow. This article addresses this issue by presenting a conceptual framework of considerations for use when designing production plans that contribute to proper resource allocation during this crucial period. A rapid literature review was conducted to investigate existing strategies and key factors for scaling a start-up organisation's production. The findings of the literature review have been combined into a framework for developing effective growth production plans for start-up organizations. By considering these factors, start-up production organisations can accelerate their progress towards their goals.

Keywords: production planning, resource allocation, start-ups

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1 INTRODUCTION

All organisations, small or large, have to start somewhere. At one point in time any organization was a so-called "start-up organization". According to Shane and Venkataraman (Shane & Venkataraman, 2000), ("s)tart-ups are newly formed organizations that are trying to achieve market-oriented objectives under conditions of extreme uncertainty." During these uncertainties, a production plan is critical for the up-scaling endeavours of the production start-up organization attempting to reach its targets. Different components have been identified that are required in production plans, although not all production plans contain all of these components. Examples of these are 1) a bill of materials, 2) facility layout and 3) labour and assembly schedule. In the context of a production start-up organization that is in its very beginning stages, these production plans must be meticulously crafted to meet the organization's requirements, starting from ground zero. Also, when a start-up organization decides to enter the upscaling phase, its current resources have to be considered in addition to the goal they would like to reach. Problems that are common to most start-up organizations are:

- Cashflow is limited - creating a pressing need to allocate and spend funds effectively in order to grow the organization and ensure that it becomes a significant contributor to its market.
- Standardising quality, followed by the implementation of quality control practices that allow for continuous improvement, while balancing production costs with quality considerations.
- Managing market uncertainty because the start-up organization is not established or yet well-known.
- Developing policies to confront unexpected challenges like equipment failures, supply chain delays or unforeseen demand fluctuations, and the need to build an organizational culture.

According to [1], entrepreneurs experience more extreme emotions than the general population, and their study explores and highlights the role of emotional regulation in a new venture's success. Some of the negative emotions that [1] mentions, are "high levels of information overload, uncertainty, time pressure, fatigue, and strong emotions, both negative and positive." Cognitive reappraisal ("changing the way we see things") is a focal point in their study, as it is one of the "most well-established and researched types of emotion regulation". The role of information overload and uncertainty is significant due to the fact that there is such a plethora of factors to consider when building a new organisation. All of these factors lie before decision makers like scattered puzzle pieces. While the end vision is crystal clear, decision makers have no idea where the puzzle pieces fit, or even which pieces should be used.

The aim of this study is to develop a framework to be used by start-up organizations to develop a production plan during their critical growth phase, where proper resource allocation is key. A Rapid literature Review (RR) was used to investigate the factors to consider. The framework developed will fuse different considerations during the critical growth phase into a logical and easily visualised format, thereby mitigating the problem of information overload and uncertainty. To this extent it offers an approach that is step -wise, over-arching and foundational, thereby giving the leadership figures at new organisations a clear structure to follow. The framework will help decision makers to identify, and make sense of, the pieces that are necessary to build the puzzle.

To achieve this aim, a rapid literature review was conducted to identify the considerations (Section 2). Section 3 presents the findings from the RR. Section 4 presents the combined design. The conclusions drawn from the study and the proposed future research are presented in Section 5 and 6, respectively.

2 RESEARCH METHODOLOGY

According to (Speckemeier, Niemann, Wasem, Buchberger, & Neusser, 2022) "(a) rapid review (RR) is a form of knowledge synthesis that accelerates the process of conducting a traditional systematic review through streamlining or omitting a variety of methods to produce evidence in a resource-efficient manner". The aim of this rapid review is to investigate the considerations when developing production plans for start-up organizations during their critical growth phase, where proper resource allocation is key.

Table 1: Research protocol followed in the RR

Purpose of the study	To investigate and develop a list of considerations for developing a strategy for designing production plans for start-up organizations during their critical growth phase, where proper resource allocation is key.
Keywords	"production startup" AND "growth strategy"
Search databases	• Emerald Insight • Web of Science • IEEE Explore • Scopus • EBSCOHOST
Inclusion criteria	• Production plan - literature • Entrepreneurship - literature as well as startup literature • Literature about non - digital production processes.
Exclusion criteria	• Technology-focused or quality control-focused literature • Literature pertaining to chemistry, biology, materials, energy, politics or economics. • Literature focused on geography, environment and sustainability. • Literature pertaining to financing, modelling, sales or marketing. • Literature that only mentions the keywords but does not consider further growth strategies. • Literature that discusses aspects of entrepreneurship and startup organizations, other than growth strategies for startup organizations. • Industry-specific literature. • Non-English literature.
Quality assessment criteria	• Studies should be published in English. • Repeatable and reputable scientific research methods should have been followed.

The literature search was conducted between May and June 2023.

The RR steps listed below have been used in this study (Speckemeier, Niemann, Wasem, Buchberger, & Neusser, 2022).

1. Develop a research purpose/objective.
2. Develop a research protocol.
3. Establish relevance criteria.
4. Search and retrieve the literature.
5. Selection of studies: screen for relevance criteria.
6. Quality assessment of relevant studies.
7. Data extraction.
8. Analysis and synthesis of findings.
9. Reporting.

2.1 Step 1: Develop a research purpose/objective.

The aim of this study was to investigate the considerations to be taken into account when developing a production plan for start-up organizations during their critical growth phase, where proper resource allocation is key.

2.2 Step 2: Develop a research protocol.

The research protocol that was developed during this RR is illustrated in Table 1.

Step 3: Establish relevance criteria

The inclusion and exclusion criteria were established and used to determine which articles were relevant to the current study (Table 1). The exclusion criteria were drawn up as the review was conducted, and categories of topics were identified that yielded results to the search, but did not contribute to achieving the purpose of the study, and literature that mentioned the keywords, but explored tangential or industry-specific topics instead. Non - English literature also had to be excluded due to the language barrier presenting an obstacle in comprehension of the literature in that category. The inclusion criteria were identified as the categories of topics of which the literature must be a part in order to be capable of rendering useful and relevant information.

3 FINDINGS FROM RAPID REVIEWS

The databases were searched according to the protocol that had been outlined previously and relevant literature was identified and retrieved. Section 3.1. shows how the screening process was conducted from the literature that had been identified initially. Section 3.2 shows which literature was rejected and which of the accepted studies overlapped in different databases, while section 3.3 gives more detail regarding the quality assessment criteria and section 3.4 presents a summary of the findings from the rapid literature review.

3.1 Step 4: Search and retrieve the literature

Step 4 of the protocol was to search and retrieve the literature. A total of 535 studies were found (refer to Table 2). The first phase of the study selection (Identification) shows the studies that were found in each of the listed databases prior to the commencement of screening. This phase corresponds with Step 4 of a RR, as given in (Speckemeier, Niemann, Wasem, Buchberger, & Neusser, 2022). The second phase of study selection involved screening the literature for relevant criteria, corresponding with step 5 in (Speckemeier, Niemann, Wasem, Buchberger, & Neusser, 2022). The eligibility phase overlaps with step 5 in (Speckemeier, Niemann, Wasem, Buchberger, & Neusser, 2022), but is shown distinctly in the table to indicate that the identified studies are eligible and do not contain duplicate information.

Table 2 gives an overview of the phases described above.

Table 2: Process of selecting the studies used in this RR

Phase of study selection	Studies found in each database
Identification	• Emerald Insight: 230 • Web of Science: 96 • IEEE Explore: 3 • Scopus: 200 • EBSCOHOST: 6 Total studies found: 535
Screening	• Emerald Insight: 2 • Web of Science: 3 • Scopus: 1 Total studies found:3, as all of them overlap between different databases to an extent. For more details, refer to Figure 1.
Eligibility	After eliminating duplicates, the total studies remained 3.
Quality	Total studies to be used: 3

3.2 Step 5: Selection of studies

After applying the inclusion and exclusion criteria to ensure relevance, only three titles have been selected as relevant. Table 3 gives a break-down of how the search results were filtered, and how the rejection criteria were applied. The first two reasons for rejecting papers were inaccessibility from within the database, and papers that were duplicates. Rejection reason numbers 3 – 5 and 8 - 17 in Table 3 state in summary that they focus on topics other than start - ups. Reason number 6 discusses entrepreneurship and start-up related topics but does not dive into growth strategies for production startup organisations, while reason 7 only mentions the keywords as a means of describing the organisation discussed in the papers involved, without engaging in further discussion regarding growth strategies.

In the right-hand column, the total number of articles that were rejected for each of the reasons given in the left-hand column, is given. The last three rows of the table calculate the total articles rejected per database, the number of articles that were found in each database and the number of articles that were accepted for this study. This is the result of subtracting the number of articles that were rejected from the number of articles that were found.

Table 3: Break- down of rejection quantities and rejection reasons for each database that was searched

Number of papers rejected							
Database		IEEE Explore	EBSCOHOST	Web of Science	Scopus	Emerald Insight	
Nr.	Rejection reason						Total
1	Not accessible		2				2
2	Duplicates				1		1
3	Technology- focused	2		1	2	15	20
4	Quality control- focused	1					1
5	Geography- focused		1				1
6	Start- ups, but not in- depth about growth strategies		1	1	1	178	181
7	Keywords only describe organisations		2				2
8	Chemistry- focused			35	10		45
9	Economy- focused			5	2	4	11
10	Biology- focused			45	7		52
11	Environment and sustainability- focused			2	1	4	7
12	Energy- focused			1	1		2
13	Materials- focused			1	1		2
14	Financing- focused			1	2	10	13
15	Modelling- focused			1	1	4	6
16	Sales or marketing- focused				1	11	12
17	Politics- focused					2	2
	Total rejected per database	3	6	93	30	228	360
	Total articles found	3	6	96	31	230	366
	Total articles included	0	0	3	1	2	6

Of the articles found, Fine, Padurean and Naumov (Fine, Padurean, & Naumov., 2022) was found in Web of Science as well as Scopus, while McDonald, Shalloo, Pierce and Horan (McDonald, Shalloo, Pierce, & Horan, 2013) and Solaimani, van Eck, Kievit and Koelemeijer (Solaimani, Eck, Kievit, & Koelemeijer, 2022) were found in both Web of Science and Emerald Insights, as shown in Figure 1. Therefore, only 3 articles were accepted in this RR.

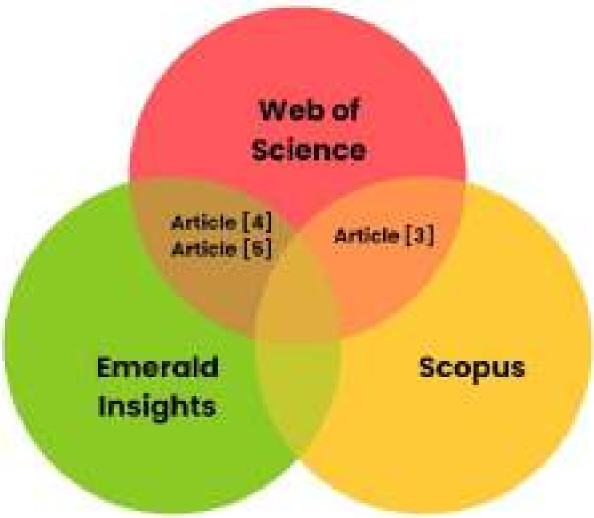

Figure 1: Venn diagram of studies overlapping in different databases

3.3 Quality assessment

The full text of each of the 3 selected studies was read to assess the quality of these texts. The quality phase corresponds with step 6 of (Speckemeier, Niemann, Wasem, Buchberger, & Neusser, 2022) and the studies conducted in the remaining papers have followed reputable and repeatable scientific methods. This step is of critical importance and ensures that only literature of acceptable quality, and therefore validity, is selected for inclusion.

3.4 Summary of findings

Table 4 gives a summary of the data that has been extracted from the abovementioned literature studies.

Based on the findings from the RR, the following are factors to be considered when designing a production plan for a start-up organization. The details of each factor are discussed as part of the concept design (Section 4).

- Risk (McDonald, Shalloo, Pierce, & Horan, 2013)
- Profitability (McDonald, Shalloo, Pierce, & Horan, 2013)
- Cashflow (McDonald, Shalloo, Pierce, & Horan, 2013)
- Practicality (Solaimani, Eck, Kievit, & Koelemeijer, 2022)
- Processification (Fine, Padurean, & Naumov., 2022)
- Professionalisation (Fine, Padurean, & Naumov., 2022)
- Culturalisation (Fine, Padurean, & Naumov., 2022)
- Automation (Fine, Padurean, & Naumov., 2022)
- Segmentation (Fine, Padurean, & Naumov., 2022)
- Platformisation (Fine, Padurean, & Naumov., 2022)
- Collaborations (Fine, Padurean, & Naumov., 2022)
- Capitalisation (Fine, Padurean, & Naumov., 2022)
- Replication (Fine, Padurean, & Naumov., 2022)
- Evaluation criteria (Fine, Padurean, & Naumov., 2022)

4 CONCEPT DESIGN

The factors discussed in Section 3 have been combined into a pillar diagram (Figure 2). This diagram gives a structured overview of the order in which the factors should be considered. The pillar diagram consists of three levels: the roof, pillars and foundation. As in a house, each of these levels has an important and unique role and the factors have been structured into these 3 levels that correspond in function with the analogy of the house. The reasoning followed in grouping each factor in the associated level of the house is explained under its associated sub-heading in this section. The over-arching factors, which represent the roof of the house, have been indicated using an alphabetic numbering system to show their sequence, and to act as a reminder that these should be constantly considered with each decision, during an iterative process. This should be done in the same manner that the weight distribution of a roof should be considered when attempting changes to the pillars or foundation of a house in order to prevent the roof from collapsing. The pillar and foundational factors have been sequenced with Arabic numbers, indicating the order in which they should be considered. The foundational factors are sequenced first as they form the basic building blocks of the organisation, and everything else is dependent on them. If the foundation fails, the entire house will fall. Each of the pillars represent a different production plan element. Additional pillars could be added, or the current pillars could be replaced by others, but this literature review has focused on the 3 pillars that are shown here.

Table 4: Summary of the data extracted from the selected literature

Title	Authors	Year	Summary	Ref
Evaluating expansion strategies for startup European Union dairy farm businesses	R. McDonald, L. Shalloo, K. M. Pierce, and B. Horan	2013	The paper considers risk, profitability and cash-flow projections of different expansion strategies.	(McDonald, Shalloo, Pierce, & Horan, 2013)
Operations for entrepreneurs: Can Operations Management make a difference in entrepreneurial theory and practice?	C.H. Fine, L. Padurean and S. Naumov	2022	The paper posits that “operations tools can make a significant difference in the scaling stage” and a catalogue of 10 tools was developed for entrepreneurial scaling. These 10 tools are explained below: **Processification**: Well-defined processes have the advantages of enabling efficiency and repeatability, while allowing delegation and decentralisation. **Professionalization:** as the organization grows, more professionals with specialist-knowledge are appointed. **Culturalization:** “Building and maintaining a culture that supports the organization’s goals is critical to efficient scaling.” This process requires constant communication of the culture - with cultural reinforcements taking place during rapid scaling to mitigate the challenges presented by the number of new employees and partners. **Automation** **Segmentation:** exploring how to drive growth into adjacent or different market segments. **Platformization:** “utilizing a platform to exploit cross economies of scale from multiple customer segments or constituent groups” **Collaborations** **Capitalization** and the “dilemma of needing to give up significant control” in order to gain additional capital.	(Fine, Padurean, & Naumov., 2022)

Title	Authors	Year	Summary	Ref
			Replication of the process in different locations and settings, with or without modifications. Replication efforts' capabilities and outcomes must be documented and trained. **Evaluation:** making use of Key Performance Indicators with caution, to prevent stifling the organization's innovative spirit.	
An exploration of the applicability of Lean Startup in small non-digital firms: an effectuation perspective	S. Solaimani, T. van Eck, H. Kievit and K. Koelemeijer	2021	This paper confirms that non-digital entrepreneurs use effectual logic when applying the lean start-up approach and provide a "view on how different effectuation principles are at play". It proposes that lean start-up practices should be "reconsidered in light of physical constraints and possibilities, but also, what skills and competencies need to be developed to employ LS in the most effective ways". It further shows that contextualising the lean start-up approach to a non-digital environment "calls for a particular set of skills and competencies, including applying mixed-methods cross-validation, affinity and passion for craftsmanship and aesthetics, inferring from limited, qualitative, and often skewed, data, establishing an empathetic collaborative relationship with customers and suppliers, and leveraging prior market knowledge and experience." Contextualising the Lean Startup approach with effectuation logic, while considering the physical constraints and possibilities, as well as the skills and competencies needed. The Lean Startup approach involves "accelerating product development and launch while maximising efficient use of available resources". Effectuation, on the other hand, involves beginning with what you have, focusing on the acceptable cost, placing emphasis on "strategic alliances and pre-commitments", leveraging environmental contingencies and attempting to control an unpredictable future.	(Solaimani, Eck, Kievit, & Koelemeijer, 2022)

The factors that have been placed in the pillars differ between pillars, as some factors will only have an impact on some, but not all, of the pillars. The reasoning of the factor-allocation under specific pillars, has been explained in section 4.2.

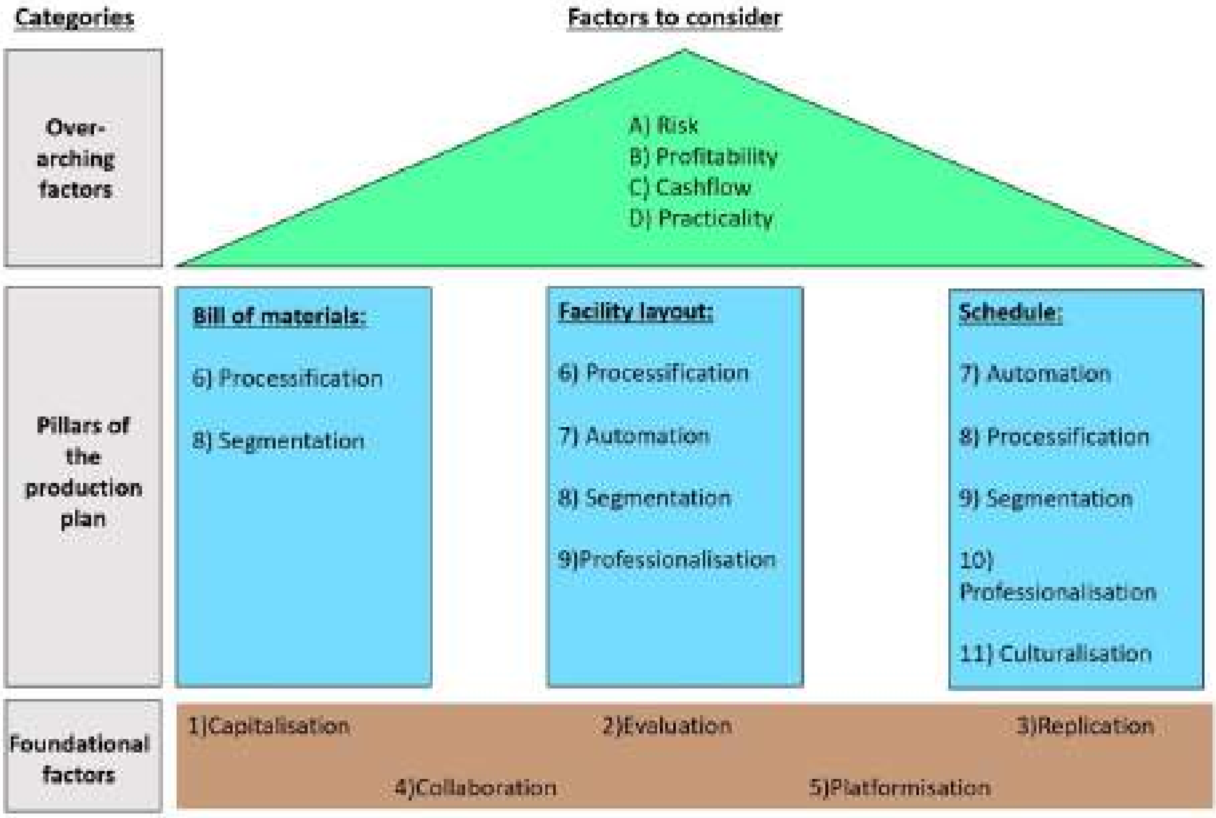

Figure 2: The house of considerations when designing a production plan to build your organization

4.1 Foundational factors

Starting at the bottom-left corner of Figure 2, the foundational factors should be considered first as they describe the decision-making process, role-players, and the objective(s) of the production plan.

4.1.1 Capitalisation

As the investment structure changes, the decision-makers might change as well. This factor, as well as the relationships between investors and the founder(s), will play an important part in determining how funds for the organization's growth will be obtained as well as the costs associated with obtaining funds. Examples of costs associated with obtaining additional funding include interest on loans and the fees associated with legally obtaining a different ownership structure (sole proprietorship/partnership/private company/public company). While this factor does not have a direct influence on the production plan, it influences the potential profitability of each alternative growth strategy that is considered.

4.1.2 Evaluation criteria

The evaluation criteria, requirements, and key performance indicators will influence every aspect of the production plan since the requirements and criteria are the foundation upon which the production plan is built, and the key performance indicators and criteria are used to evaluate, improve and update the production plan in an iterative process over time.

4.1.3 Replication

The organization's vision will impact whether or not replication will be necessary. For example, whether the organization desires to open more factories in different locations around the country or around the globe, as well as all of the legal implications associated with such a decision. If an organization desires to grow to the extent that replication becomes necessary, the production plan should be designed with future replicability in mind, thereby saving the time of drawing up a new production plan for each replication that takes place.

4.1.4 Collaborations

Collaborating with other manufacturers or suppliers will have an impact on the production scheduling if it involves sending the work-in-progress goods to the collaborative partner at any stage of the process, or cutting down steps in the production process because the collaborative partner now supplies the organization with better-prepared raw material, such that the production organization no longer has to perform the preparation steps. This, in turn, will influence the facility and bill of materials, depending on the relationship between those steps in the production process (impacting the flow within the facility), and the material requirements involved in production.

4.1.5 Platformisation

Utilising platforms, or increasing platform use, could have a big impact on sales. Therefore, it could have an impact on the magnitude of the growth that the production plan aims to achieve, thereby affecting all three parts of the production plan.

4.2 Pillars of the production plan

In the middle of the framework (Figure 2), the pillars represent the different elements of the production plan and the factors that should be considered during the design process of each of these parts.

4.2.1 Processification

Defining and stabilising the production processes, as well as the quality standards of the product, is essential before any production plans for growth can be designed. This impacts the bill of materials since it impacts the quality standards agreed upon with suppliers, and the scheduling of activities within the assembly process and, correspondingly, the facility layout to ensure a good work-flow within the facility.

4.2.2 Automation

Automation is often a necessary consideration where upscaling and growth is concerned as automated procedures provide a more consistent level of quality, with less variation, and often at a higher production rate than manually completing the same procedures can provide. Productivity must be weighed against cashflow and financial risks, while considering legislation. The scheduling in the production plan will be most significantly affected by automation decisions, and the facility layout will also change with regard to these decisions, depending on the spatial requirements, noise levels and safety regulations associated with these decisions.

4.2.3 Segmentation

When adjacent or different market segments are explored as potential growth opportunities, the bill of materials, facility layout and schedule may all be impacted, depending on what additional products will be manufactured, and how much their production processes differ from the production processes currently in use.

4.2.4 Professionalization

During growth more specialist appointments are common, and this greatly impacts scheduling decisions as work will be distributed to the person who has the most expertise and/or experience in the relevant field to ensure that their talent is maximally utilised. It will also, to a lesser extent, influence the facility layout if it has an impact of the workflow-facility relationship.

4.2.5 Culturalisation

Building organizational culture is an important consideration when making hiring decisions, and therefore it impacts training and scheduling. The pace at which new employees are introduced to the organization must be properly managed to ensure that the organizational culture remains aligned to the founders' and stakeholders' vision, and to ensure a productive and positive working environment for employees.

4.3 Roof of over-arching factors

Lastly at the top, the roof represents the over-arching factors. These should be kept in mind all the time and will have an overarching effect on the design of the entire production plan. When making any decision the influence of the over-arching factors must be considered. An analogy can be drawn from this as the effect that a pillar's adjustment would have on the stability of the roof.

4.3.1 Risk

This factor considers the changes made to the organization's overall risk profile that occur with each decision in the production plan. Resource risks influence both the bill of materials as well as the scheduling agility required. An example of a resource risk is the risk of a particular brand of machine breaking down and causing production delays. Operational risks influence scheduling and facility layout considerations. An example of an operational risk is the risk of employee injury. Supply chain risks have an impact on the bill of materials and alternative supplier options, as well as on scheduling decisions. Legal and compliance risks, as well as talent risks when appointing new staff, influence scheduling. Reputational risks influence decisions with regard to quality compromises.

4.3.2 Profitability

Financial returns should be an important consideration. One of the tools that is useful in measuring the financial returns is Return on Investment (ROI). Projections and scenario analyses for different growth strategies that are practical for the specific context of the organization involved, that consider the profitability over time for a set investigation period, would also prove to be helpful in the process of determining the most profitable growth strategy that will be used in the production plan. Additionally, asset growth or decline should be factored into these calculations where applicable.

4.3.3 Cashflow

Business growth usually requires significant additional investment, causing an outflow of funds into assets. It is important that the cashflow of the organization must be sufficient to balance these investments and prevent the organization's solvency and liquidity from being negatively influenced by these growth decisions. Failing to consider this factor could lead to bankruptcy. Therefore, cashflow is a critical consideration.

4.3.4 Practicality

Consolidating the Lean Start-up approach with the physical and practical constraints that the organization faces will influence all aspects of the production plan. Efficient fund allocation is important for a start-up's success as well as the success of any growth strategy and the Lean Start-up approach ensures that this aspect is considered. However, the physical and practical constraints of the organization must be weighed against the Lean Start-up Approach in order to determine, as far as possible, what the organization can achieve within the Lean framework. Physical and practical constraints include aspects like legislation, facility and storage constraints, and the employee productivity that can be reasonably expected.

5 CONCLUSION

From the literature obtained in the Rapid Review, it is observed that there are various factors that should be considered during the design of a production plan for a start-up organization. These factors are dispersed throughout different articles, like scattered puzzle pieces, and there is no combined list of considerations. The aim of this study was to develop a framework to be used by start-up organizations to develop a production plan during their critical growth phase where proper resource allocation is key. An RR was used to identify the factors to consider. The resulting framework can be likened to the outer frame of a puzzle, which is often built first, and then the puzzle can be built further because there is now a clear view of things that have to be kept in mind.

From the factors that were identified and gathered, a novel conceptual framework has been developed, producing a combined list of considerations, as well as the sequence in which they should be considered and visualised (Figure 2). This list unifies the research on the topic, giving an overview. This research therefore offers a combined set of considerations, reducing the time and effort required for start-ups to develop their scaleup production plans, and facilitating their success in a competitive market.

6 FUTURE RESEARCH

A limitation of this Rapid Review is that it has been conducted in a hurry and it is possible that an oversight could have occurred. Another limitation is the fact that this review has only been done on five databases. Future research could increase the databases so that more literature is covered. The keywords that were used in this review could be improved to include more studies and different variants of the keywords could be considered. Both of these improvements could result in an expansion of the list of considerations. Additionally, a production plan consisting of different, or more elements, than a bill of materials, facility layout and schedule may be required, and additional pillars can be added to Figure 2 for a more comprehensive view of different variations and elements of production plans. It should also be noted that the framework that has been presented in this paper is a concept design that has not yet been tested. Future research should involve testing and refining the concept design as necessary.

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EXPLORING TECHNOLOGIES AND MANAGEMENT STRATEGIES THAT CAN LEAD TO SUSTAINABLE WATER USE IN SOUTH AFRICA'S AGRICULTURAL SECTOR

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ABSTRACT

The water and agricultural sector have multiple synergies. In a water constrained society, appropriate choice and use of irrigation technology is vital. The research presented investigates various irrigation technologies and supplemental agricultural strategies to derive a decision-making framework that can be used by stakeholders to achieve long-term water sustainability. Irrigation technology is broadly classified into sprinkler and micro irrigation which has many sub-categories. Examples of management strategies include deficit irrigation and rainwater harvesting. It is proposed that once the appropriate irrigation technology is chosen and implemented with supplemental management strategies, the objective of sustainable water use is achievable. Findings show that most stakeholders/farmers interested in commercial grain crops favoured center pivot irrigation technology whereas more emergent farmers/researchers favoured more progressive irrigation technologies such as drip irrigation. Irrespective of the choice, regular reassessment of the technology is necessary to prevent low water use efficiency. Furthermore, although a generic framework/guideline was developed to choose a suitable irrigation technology, it must be expanded to consider geo-specific factors and limitations as experienced by the individuals and organisations within the agricultural sector.

Keywords: Sprinkler irrigation, Micro irrigation, Water Use Efficiency (WUE)

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1 INTRODUCTION

There is a water scarcity crisis affecting South Africa and Southern Africa as a whole which will inevitably affect the agricultural sector [1]. Historically there have been interventions efforts such as grey water recycling, installation of water efficient fixtures, conservation programmes and public awareness campaigns [2], [17]. However, the agricultural sector requires a more multifaceted approach to achieve water sustainability. It will involve selecting the right irrigation technology, the use of supplemental management techniques and finally the correct implementation of policy interventions [3], [4].

Traditionally, surface irrigation was used which involved using gravity and furrows to distribute water to the agricultural pasture. This is still used in some parts of the world, but it is highly inefficient as only 65 % is used by the crop [3]. By implementing irrigation technology such as drip or sprinkler irrigation systems, unnecessary water losses could be prevented, and more water could be theoretically used by the crop thereby increasing the water use efficiency of the crop(s). It has been stated [3], that if there are insufficient management interventions then sustainable water use will not be achieved. Examples of these interventions include irrigation scheduling (which involves how much water to apply and when to apply water to the crop(s)), soil management to address porosity and water retention properties of the soil and other knowledge-based interventions such as the use of drought resistant seeds and rainwater harvesting.

Rasul [5] states that policies implemented by government organisations should consider the interdependence of water and energy on the agricultural system. If policies from one sector are made without considering the dependencies on other sectors, then the overarching goals such as water sustainability, food security and energy conservation will not be fully realised.

The research presented aims to develop an irrigation framework/guideline that incorporates various factors such as crop type, topography, capital investment, to name a few, to assess which type of irrigation technology is suitable for the stakeholder's needs. This would be a first step to achieve sustainable water usage in the agricultural sector. However, it is imperative that a holistic strategy be employed which additionally involves incorporating supplemental management techniques and targeted policy interventions.

The primary objective of the study is to investigate the various irrigation technologies available, including how and why these technologies are chosen based on the agricultural context as well as investigating the supplementary agricultural practices to derive a decision-making framework/guideline to be used by stakeholders to achieve long-term water sustainability. Furthermore, the research will also determine the irrigation technologies and practices that have succeeded or failed to be adopted in the South African context. It is believed that the findings of the study will contribute towards the water resource management in the agricultural sector and industrial management practices across both sectors.

The research questions addressed are:

i. Is there a suitable irrigation decision-making framework/guideline to assess what type of irrigation technology is suitable for the stakeholder's specific needs?
ii. How does the appropriate choice of irrigation technology lead to sustainable water use?
iii. What management techniques can easily be adopted in South Africa to achieve sustainable water usage?
iv. What current technologies and practices are used by farmers/agricultural stakeholders and why have certain technologies and practices failed to be adopted in South Africa?

2 REVIEW OF IRRIGATION TECHNOLOGIES

There are many types of irrigation systems which can be broadly classified into surface irrigation, sprinkler irrigation and micro irrigation. Hi-tech irrigation systems lead to an increase in water use efficiency (WUE) and is further evidence to support that by improving the efficiency of existing irrigation system the water supply for available use can be improved by 10 % to 15 % [6],[7]. Since surface irrigation involves minimal technological interventions, only sprinkler and microirrigation technologies will be considered for the irrigation framework.

2.1 Sprinkler Irrigation

Sprinkler irrigation is designed to mimic rainfall and can be used to irrigate a variety of crops. Generally, the system works by pumping water through pipes or hoses to rotating nozzles or sprayers on fixed or moving laterals [8]. The sprinkler irrigation systems can be broadly classified into continuous move and set systems. Continuous systems are more common and operate by sprinklers attached to moving laterals, an example of this being the Center-Pivot Systems. The set systems have fixed laterals and sprinklers to irrigate the field without having to move the equipment. The set systems are more suited for orchards and perennials and are not preferred for grain crops.

Mane and Ayare in [9], further classify sprinkler irrigation systems according to the sprinkler heads and nozzles, portability, precipitation rates and principle of operation. These aspects can differ in sprinkler irrigation systems; however, they all operate by forcing pressurised water through a nozzle to create a wetted diameter. When discussing sprinkler heads and nozzles configurations, the most common are rotary sprinklers, impact sprinklers and gear driven sprinklers. Rotary sprinklers, according to [8], operate by discharging a jet of water that breaks up into droplets which mimic rainfall, and, in some instances, a dual nozzle configuration can be used to create an outer and inner wetted diameter. Impact sprinklers involve a different sprinkler head and nozzle configuration, whereby the force of the jet of water emitted, forces the sprinkler arm to rotate. Lastly, in gear-driven sprinklers the pressurised water entering the sprinkler will move a small water turbine which operates in reducing gears to provide a slow continuous rotation of water.

Another sub-category in sprinkler irrigation is the portability of the system. From the information stated in [9], a portable, semi-portable, semi-permanent or permanent system is dependent on the pump, mainline and lateral piping systems and their respective portability. Therefore, a portable system refers to the ability to move the pump and the mainline and lateral piping from one location to another with relative ease. A semi-portable system refers to a pumping system that is fixed to the water source(s) but the mainline and laterals can be extended to a significant distance from the pump. A semi-permanent system, on the other hand, usually has a singular fixed water source, pumping system and mainline piping and is restricted to light-weight laterals and sprinkler heads. And finally, a permanent system has a permanent pump, mainline and lateral system.

Precipitation rates, which is another sub-category consideration, is dependent on the type of crop and depth of root zone. So, depending on the crop a low volume, medium volume or high-volume sprinkler system could be used. There are many advantages to using sprinkler irrigation systems. For example, they tend to have high irrigation efficiencies, saving water in the long run. These systems are also not as dependent on soil infiltration rates and can be used on a variety of soil profiles. Another significant advantage is that this robust system can support crop growth from germination to harvesting with minimal reliance on labour except for maintenance which can be scheduled [10].

Gilley [10] highlights some disadvantages with the system, for example, it requires a continuous supply of water from a water source limiting the geographic locations. Municipal supplies can be used; however, it would greatly increase operational costs. In addition, there is water loss that can occur due to evaporation and wind drift. Finally, sprinkler irrigation systems still require expert management and maintenance to maximise the efficiency of the system.

2.2 Micro irrigation

Micro irrigation (MI) involves the frequent application, of water applied at a low volume dosage on or below the soil surface as drops, tiny streams, or miniature sprays. This method of irrigation prevents ponding as it is applied directly to the root zone of the plant by capillary action and gravity [11]. Micro irrigation is broadly classified into (i) Drip irrigation and (ii) Micro spray irrigation [8].

Drip irrigation (DI) is a system whereby water is supplied to the crops through an emitter opening in plastic tubing or piping. The water is applied at a slow rate to targeted points in the crop i.e., the root zone. The spacing of the emitters will depend on the crop spacing, rooting pattern and soil characteristics [8]. DI usually has tubing that is on the surface and parallel to the row of crops, however, variations of this system can include the tubing to be suspended from trellising in crops that require trellising such as vineyards or it can be placed a few centimetres below the soil, under a plastic mulch, in horticultural crops. The latter is known as subsurface drip irrigation (SDI) and its advantages include less water wastage due to surface evaporation and suppression of weed growth [12]. However, drawbacks to SDI include plugged emitter holes which require additional maintenance, the implementation of specialised tillage methods and using the correct equipment to ensure that roots do not plug emitter holes.

According to the information seen in [11], drip irrigation has become more prevalent in recent years because of the availability of plastic material for tubing, improvements in manufacturing and in emitter designs. The system has also been proven to conserve water and can be used in water scarce areas with compromised water quality. Drip irrigation systems can also be utilised for targeted fertilisation of the crops at the root zone – known as fertigation – which eliminates unnecessary run-off and contamination of surface or underground water sources. It is important to note, however, despite these advantages, without effective management the system will not perform optimally as it should.

Micro spray irrigation involves applying water by a small spray, jet or mist over the soil surface [11]. These systems tend to operate at lower pressures than sprinkler heads and can wet diameters between 2 m – 6 m, covering a larger rooting area, as with tree crops, which is impractical with drip irrigation [8].

Micro spray and drip irrigation involves some or all the below listed components [11]:

- Control head which includes a: pumping station, control and monitoring devices, fertilizer and chemical injectors and a filtration system.
- Mainlines, submains and manifolds
- Emitters
- Flushing system

As seen in Figure 1 below, the control head includes a variety of sub-systems. The pump is required to pressurise the irrigated water, the valves regulate flow and pressure to the mainlines, submains and manifolds and the filters are needed to ensure that the water does not contain particles that could block emitter holes [8].

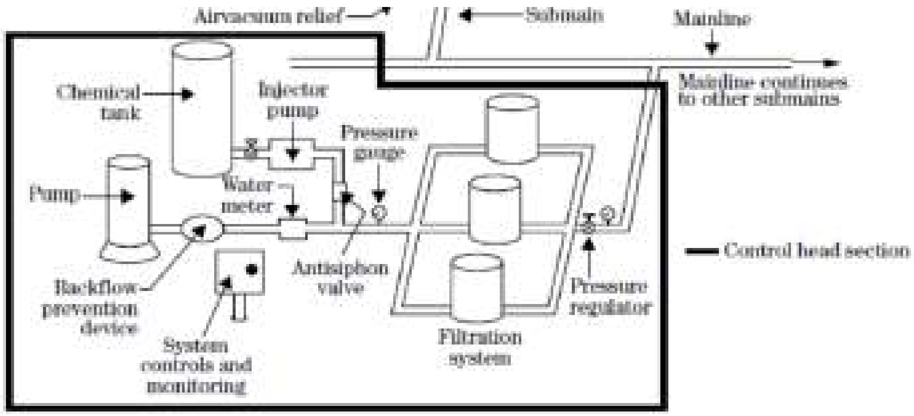

Figure 1: Typical Micro irrigation layout. Source Lamm F.R & Kansas State University in [11]

It is explained in [11] that the function of the mains, submains and manifolds is to deliver pressurised water to laterals and emitters. The manifold (header) connects the mainline to the laterals. The emitters function as small throttles and are responsible for discharging water at a constant rate. The type of emitter chosen as well as their relative placement is an important consideration when designing MI system. It is dependent on the factors such as crop type, type of soil and complementary farming practices [8], [11].

A flushing system, included in advanced micro irrigation systems will involve pressure gauges, pressure relief valves, and flush valves. The function of this system is to remove the build-up of particles and organic matter in the system to prevent blockages of emitters [11]. According to the information presented in [8], some of the advantages of MI is the potential reduction of water usage because water is applied to the root zone and is commonly used for trees, vineyards, and shallow rooted crops. Fertiliser and pesticide application is targeted reducing leaching into ground water sources. The direct application of water also contributes to less weed growth and plant disease cultivated by high moisture environments. MI is also adaptive to different types of topography and the system can use treated effluent or slightly saline water without the risk of contamination of surface and ground water sources. Although there are many benefits to MI, some disadvantages highlighted in [8] include the fact that germination is not always successful, that emitters can be frequently blocked and that the system requires more regular maintenance that SI systems.

2.3 Factors that affect the selection of irrigation system

Table 1 below shows all the factors that can affect the selection of the irrigation system – which involve the broad categories of sprinkler irrigation and micro irrigation technologies. The theoretical framework was derived from various papers namely: [8], [10], [11], [13]. This is a generic guideline/framework that can be expanded or adapted to different situations.

Table 1: Factors determining the type of irrigation system

Factors	Sprinkler Irrigation	Micro irrigation
Water cost	Medium [8], in some cases treated effluent can be used reducing freshwater requirements as well as cost[13].	High. Higher quality water is often desirable which tends to be more expensive as the water must go through a filtration process [8].
Water availability	Regular water supply is necessary; these systems can effectively use small, continuous streams of water (e.g., springs and wells)[10].	Continuous water supply. Even though water is applied to a smaller section, it is essential to have a continuous water supply to ensure

Factors	Sprinkler Irrigation	Micro irrigation
		that crop does not go into shock causing irreversible damage[8].
Water saving	Better than surface irrigation (can irrigate 1.5 × more land with similar quantity of water) since water can be applied uniformly penetrating to root zone without excess run-off[9].	Micro irrigation potentially reduces water usage as water is applied to the root zone which is particularly beneficial for tree crops and shallow rooted crops[8].
Water stress sensitivity	Moderate[8].	High[8].
Water cleanliness	Minimal[8], filtration only required when water is corrosive to pipes and has lots of debris[10].	Clean water[8]. Water requires primary and secondary filtration to ensure emitter holes don't get blocked[11].
Soil infiltration	Medium to High[8].	Any soil[8].
Surface topography	Uniform to somewhat irregular[8], can be used on varying topography[10].	Micro irrigation can occur in any type of topography. Pressure compensating emitters are necessary in sloping fields[11].
Crop type	Can be used for a variety of crops, such as low growing[8], and even tall dense crops[13].	Particularly used for trees, vineyards, and shallow rooted crops[8].
Crop value	Moderate[8].	High[8].
Cost of labour	Varies with system[8]. Mechanised sprinkler systems don't require a lot of labour, period-move sprinklers require minimal or periodic labour[10].	The cost of labour is reduced because the system can be fully automated[8]
Cost of energy	Low[8], especially if appropriate type of sprinklers are chosen[10].	Moderate[8].
Capital availability	Medium to High[8]	Initial costs are usually high but can be paid off in 2 – 3 years[11].
Technological availability	Medium to High[8].	High[8].
Skills	Appropriate management and skills are required for scheduling, management and maintenance and knowledge about what specific system is needed for specific farming requirements[13].	Meticulous maintenance by skilled personnel who can interpret data given by the system and take appropriate actions[11].

2.4 Management Interventions

Management interventions can be used to supplement the irrigation technology to achieve a holistic approach to sustainable water management in the agricultural sector. The management interventions discussed in literature include irrigation scheduling, deficit irrigation, the use of treated effluent or desalinated water and finally climate smart agricultural technologies and practices.

According to [3] irrigation scheduling refers to the quantity of water used and the timing of irrigation. This requires expertise on the soil characteristics such as the soil water content and soil water potential (the retention of water in the soil) to determine the frequency of irrigation. The speed at which the water enters the soil, known as the infiltration rate, to determine how quickly the water will enter the root zone is also a parameter considered in irrigation scheduling. Crop stress parameters are also a factor of consideration in irrigation scheduling which involves knowledge on the point of saturation. This is ideally considered in conjunction with the soil characteristic factors, mentioned above, and can be used to determine if the crop(s) are under water stress or are over-watered. Finally, the climatic impact and water balance can be used to determine the evapotranspiration rate of crops which will help agricultural stakeholders determine the ideal time to irrigate crops when water loss due to evaporation will be minimal.

Deficit irrigation is the technique used to expose the crop to calculated amounts of water stress to increase WUE and to avoid irrigation past the saturation point of the soil. The research in [14] experimented with deficit irrigation on olive tree fruit yields. The results demonstrated that even though there was a 10.97 % reduction it yields, there was also a 25.69 % reduction in water. The water savings were significant and somewhat mitigated the small yield loss experienced.

The use of Treated Effluent (TE) or Desalinated Water (DW) can be considered especially during periods of intense drought. However, the use of TE is often associated with a high salt content leading to soil degradation and additionally has a higher microbial content which could affect the crop through Persistent Organic Pollutants (POPs) [15],[16]. DW is a viable alternative to freshwater sources, but the huge initial investment is often a deterrent in most countries. The results in [15] report higher seasonal yields using DW and similar yields to freshwater sources with a 30 % reduction in water which makes this a good option if capital investment is available.

Climate Smart Agricultural technologies and practices such as using drought resistant seeds, rainwater harvesting, agroforestry, conservation agriculture and drought early warning detection decision tools can be used to improve water consumption and efficiency [4]. Except for drought resistant seeds and drought early warning decision tools, most of the interventions are management intensive and do not offer immediate return on investments but can easily be adapted and implemented for any agricultural practice.

All the above forementioned interventions can be implemented with the correct policies. It is stated that the policies implemented by government organisations need to consider the interconnectedness of water in both energy and food [5]. This lack of coherence in policy sectors dealing with food, energy and water result in a policy or policies promoting one sector at the detriment of the other sectors.

3 CONCEPTUAL FRAMEWORK

As seen from the literature, there are various factors that can affect the choice of irrigation system. Once a suitable irrigation system has been chosen, supplemental management techniques will need to be applied to achieve both agricultural performance and sustainable water use in the sector. Figure 2 below, graphically shows the conceptual framework developed for this study.

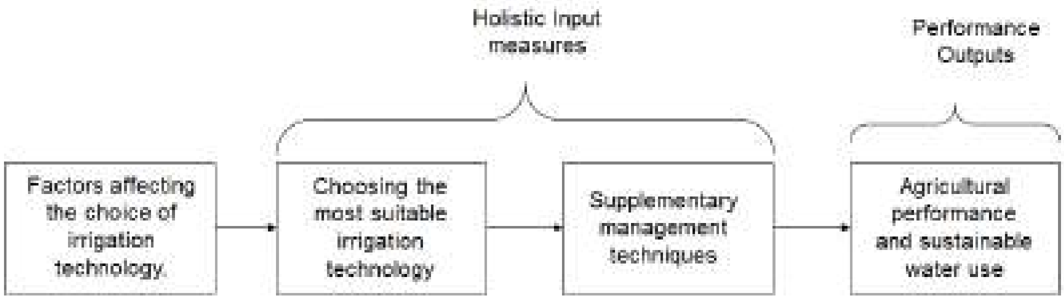

Figure 2: Conceptual Framework

The factors in Table 1 are the most common factors involved in irrigation system selection as explored by literature which leads to the first proposition (Proposition P–1) that the factors listed in Table 1 can be used as a framework/guideline for stakeholders to choose the most suitable irrigation technology.

Another proposition identified is that a specific irrigation system can be chosen after the stakeholder has made a choice between sprinkler irrigation and micro irrigation – the two broad categories of irrigation systems which are informed by the framework (Proposition P–2).

Finally, it is proposed (Proposition P–3) that if the correct supplementary management techniques are used in tandem with the correct irrigation technology informed by the framework/guideline, it will lead to more sustainable water use.

4 RESEARCH DESIGN AND METHODOLOGY

4.1 Research Design and Methodology

The research followed an inductive, qualitative approach whereby primary data on irrigation technologies and farming practices was gathered from a structured interview with a diversity of stakeholders from the agricultural sector. The information was subsequently collated and grouped according to the patterns and themes that emerged following a thematic analysis approach. From the onset, it should be noted that an inductive research approach is observational and exploratory and therefore, the results that emerge may not exactly correlate with the framework adapted from literature. Therefore, the framework should be adapted and adjusted for future research to create a robust, geo-specific irrigation framework.

4.2 Data Collection and Sample Population

The structured interview – as seen in Appendix A – included detailed questions, some of which were open-ended because most agricultural practices and irrigation systems are based on specific factors and/or preferences.

Purposive, non-probability sampling was used to gather participants for the study. The target participants involved agricultural stakeholders that used irrigation technologies or had a vested interest in them. The initial participants were gathered through personal connections and subsequent participants were through referrals (snowball sampling).

Ten participants were interviewed and included emergent farmers, commercial farmers, researchers in the agricultural sector, irrigation technology specialist and agricultural investors/entrepreneurs. According to [18], a sample size of 6 – 12 is used when there is limited accessibility to the research population which is the case in the agricultural sector do to the fact that stakeholders exist throughout the geo-landscape of South Africa and that specialists in this field are not as common.

4.3 Justification

The justification of the structured interview is based on the authenticity that the collected can be supported by literature. Structured interviews are plausible in allying the concerns and interests of the stakeholders. The interviews also provide criticality in eliciting similar observational patterns by independent researchers, under similar circumstances.

4.4 Ethical Considerations

To ensure participant engagement, it was important to guarantee anonymity – only details that the participant was willing to disclose was included in the results. Furthermore, the option to decline to answer a question was given if the participant felt it was not directly applicable or if they did not wish to disclose that information. All interviews were conducted via Zoom/telephone and consent was granted prior to the interviews. By ensuring the above forementioned protocol was adhered to, the results gathered were in line with the necessary ethical considerations.

4.5 Limitations

The agricultural sector is a niche field and therefore, the sample size of participants is small. Future research will have to be done to corroborate the results generated from the research.

5 RESULTS

The main data gathering tool used was structured interviews. Covid-19 limited in-person interviews hence the interviews were conducted online or telephonically. The number of participants, although diverse, is limited and future work will be necessary to corroborate the results of this study.

5.1 Overview of Interviewees

The interviewees were anonymous and were assigned numbers 1 – 10. The overview of the participants is as follows and were informed by questions 1 & 2 in Appendix A:

Table 2: Interviewees Description

Interviewee	Description
1	Commercial farmer with an interest in soybeans, maize, and wheat
2	Researcher/Agricultural advisor with an interest in drought resistant crops.
3	Emergent farmer with an interest in vegetable crops such as spinach, kale, spring onions, cabbage etc.
4	Commercial farmer with an interest in maize and potatoes
5	Commercial farmer with an interest in soybeans, maize, and sugar beans
6	Innovator/Researcher with an interest in medicinal crops, indigenous crops, and tea.
7	Entrepreneur/Agricultural investor with an interest in tomatoes, herbs, spinach, and chillies.
8	Technological commercialization expert in the agricultural industry with an interest in grains (sorghum, maize), vegetables, fruit and nut trees.
9	Irrigation specialist and lecturer on Agri-water management with an interest in maize crops.
10	Researcher with an interest in cereal crops.

5.2 Results from Structured Interviews

The sections explored by the structured interviews are categorised as irrigation, water and supplemental agricultural management, maintenance and lastly comments and suggestions from participants.

5.2.1 Irrigation

The results covered in this section are in response to questions 3 – 4 in Appendix A. The following notes and assumptions were made for this section of the results:

i. The approximate start-up costs and monthly costs are educated guesses from the interviewees and have been converted to R/100 hectares for ease of comparison.
ii. Where a n/a is listed, it refers to information that the interviewee could not supply or felt was irrelevant to comment on.
iii. The monthly costs for the system refer to only the labour, maintenance, and energy consumption costs for the irrigation system and may not necessarily include the whole farming operation. Where stipulated by the farmer, the water license (which is an annual cost) was calculated as a monthly cost.
iv. For all the farmers listed in the study, the majority of the monthly costs were attributed to energy used to pump water for irrigation. Therefore, it can be assumed that the monthly costs are also the cost associated with the water source.
v. It should be noted that the irrigation system mentioned by Interviewees 2, 6, 8 – 10 (the researchers, innovators, and technology expert(s)) refers to the irrigation system preferred because of positive research outcomes linked with that irrigation system.

Table 3 shows the accounting of irrigated land amongst the participants where applicable. From this we can observe that despite being a water scarce country, there is still a heavy reliance on rainfall. Only 13.32% of the combined total agricultural land is irrigated and irrigation technologies are relied on during the winter months where rainfall is scarce or absent.

Table 3: Accounting of Irrigated Land

Interviewees	Irrigated land (ha)	Non-irrigated land (ha)	Total Land (ha)
1	120	730	850
2	n/a	n/a	n/a
3	2	0	2
4	300	2200	2500
5	20	580	600
6	n/a	n/a	n/a
7	1	0	1
8	150	350	500
9	n/a	n/a	n/a
10	n/a	n/a	n/a

As per the propositions in section 3, Table 1 can be used as a framework to determine which broad category of irrigation technology should be used – namely micro irrigation or sprinkler irrigation. However, these propositions are not set as the research follows and inductive approach patterns emerge and can be observed from the primary data collected which may or may not adhere to the propositions derived from the literature. Table 4 below shows the types of irrigation systems and associated parameters from data provided by the interviewees.

Table 4: Types of Irrigation Systems and Associated Parameters

Interviewees	Type of Irrigation System	Approximate start-up costs (R/100ha)	Approximate monthly costs (R/100ha)	Years in use of technology
1	Center Pivot	1,800,000	43,541 – 49375	23
2	Drip Irrigation & In-field irrigation	n/a	n/a	n/a
3	Drip Irrigation	750,000	125,000 – 200,000	1
4	Center Pivot	3,200,000	100,000	16
5	Center Pivot	1,000,000	50,000 – 60,000	31
6	Drip irrigation and hydroponics	n/a	n/a	n/a
7	Micro sprinklers	600,000	150,000 – 300,000	3
8	Center pivot primarily and drip irrigation secondary	200,000 – 1,500,000	n/a	n/a
9	Center Pivot	800,000	17,000	n/a
10	Center Pivot	n/a	n/a	n/a

It can be observed from Table 4, that, although the start-up costs for sprinkler irrigation systems (center pivot) are higher than micro irrigation systems (drip irrigation), the monthly costs are less because the former is less manual intensive. According to the participants, the monthly costs were attributed to the energy required to pump water to the irrigation systems. This cost was lower for center pivot irrigation technology, except for interviewee 4, due to the use of twelve center pivots used in the farming operation. The framework/guideline in Table 1, was used in some form by the experienced commercial farmers when the technology was first acquired, however, a reassessment should be done to determine if the current technology is suitable and if an upgrade or a hybrid irrigation system could be incorporated.

The center pivot systems are favoured by commercial farmers and stakeholders interested in commercial crops such as grain and cereal crops. This is due to large surface area coverage, high water use efficiency (WUE) when scaling and the system is less labour intensive. The fact that these systems are often inherited and easy to use once installed are barriers to adopting or incorporating different types of irrigation technologies.

5.2.2 Water and Supplemental Agricultural Management

The results covered in this section are in response to questions 5,6 and 8 in Appendix A. The following notes and assumptions were made for this section of the results:

i. The water consumption per harvest cycle are estimates given where applicable to the Interviewee. If water consumption could not be estimated, due to not being directly applicable to the Interviewee, it was stated as non-applicable (n/a).
ii. The water consumption was often given as volume per hour or per day. To give a volumetric result that was comparable between relevant interviewees, it was assumed that the irrigation occurred 16 hours/day, 5 days/week for 12 – 18 hours per week (during the winter months) per 100 hectares of irrigated land.
iii. It should be noted that the water sources and supplemental management techniques mentioned by the non-farming interviewees are based on their experience whether direct or indirectly or because of their research focus.

Most interviewees described having an unreliable water source due to water stress from drought cycles and water scarcity in winter months. The only exception was Interviewee 3, whose water source is reliable due to the small scale of the operation. However, it is most likely that if the agricultural operation were to be scaled the water source would be strained.

Table 5 shows the management strategies used by participants and approximate water usage per harvest cycle where applicable.

Table 5: Management Strategies and Approximate Water Use

Interviewees	Management strategies to protect yield and manage water sustainably	Approximate water use per harvest cycle (m^3/100 ha)
1	Pump water to holding dam when available, monitor water level of holding dam, irrigate at night because less evaporation (irrigation scheduling).	160,000 – 240,000
2	Precision farming, calculating the minimum amount of water necessary to ensure desired yield with minimum loss of crop integrity (Deficit irrigation is a subcategory of precision farming)	60,000 – 90,000
3	Irrigation scheduling and crop rotation	48,000 – 72,000
4	Nighttime irrigation (irrigation scheduling) and deficit irrigation.	360,000 – 540,000
5	Manage pumping of water (ensure no over pumping, a form of irrigation scheduling) and water balance.	100,000
6	Plant the right crops (i.e.) drought resistant. Explore alternative technologies, off grid solutions (solar for pumping) and the creation of a localized industrial ecosystem.	n/a
7	Rainwater harvesting	n/a
8	Rainwater harvesting, conversion to DI where possible and technology to retrieve ground water.	n/a
9	Conservation agriculture, zero tillage and “plastic” mulching	n/a
10	Dam levels can be monitored, and water consumption can be varied accordingly.	n/a

Table 5 shows that irrigation scheduling and monitoring of the dam levels are significant in managing water. Rainwater harvesting allows for bulk storage of water which can be later pumped according to the irrigation schedule. Conservation agriculture which includes crop rotation, organic farming, and plastic mulching are used to improve soil quality, water retention and the prevention of weeds. Systemic management techniques such as planting drought resistant crops was also mentioned. Finally, management techniques that involve new technologies such as solar pumps and technologies that allow retrieval into deep underground sources were mentioned by participants.

Table 5 further shows that for every 100 ha of irrigated land, drip irrigation uses less water than center pivot systems. This is an important consideration, especially since the commercial farmers (interviewees 1, 4 and 5), who exclusively use center pivot irrigation systems, stated that they did not believe it was possible to use less water to achieve the same yield outputs

5.2.3 Maintenance

The results covered are in response to question 7 in Appendix A. The following notes and assumptions were made for this section of the results: Physical maintenance of irrigation equipment is not applicable (n/a) for non-farming Interviewees. However, if they had a comment regarding maintenance either from their research outcomes or as part of their experience with the industry it was noted.

The interviewees unanimously stated scheduled maintenance was important to ensure that no water was lost through leakages and/or breakdowns. This section explored the frequency of maintenance, common maintenance issues experienced by the interviewees and its relation to water management. The most common maintenance issues described by the interviewees, involve the mechanical aspects of the irrigation system such as the pumps, the bearings, nozzles, and piping which are all susceptible to wear and tear. Regular maintenance will prevent unnecessary water loss and ensure there is no decrease in WUE. Finally, since maintenance is such an important aspect of irrigation systems, it would be prudent to adapt the irrigation framework/guideline, to include the aspect of maintenance.

5.2.4 Observations from participant feedback

The results covered are in response to questions 9 and 10 in Appendix A. Supplementary management techniques are also inclusive of policy interventions which are discussed in this section. This section is strictly a reporting of the participants views on policy interventions.

According to interviewees 1, 4 and 5 (all commercial farmers) water licenses, for example, are required by government for commercial farmers to manage water consumption. This license is often difficult to obtain, subject to corruption and not universally enforced according to the participants. These observations are mentioned in [19].

Another issue amongst the participants are the operational costs associated with irrigation systems [20], which results in a heavy reliance on rainfall even amongst commercial farmers who tend to only use irrigation systems in naturally dry seasons or during drought cycles. Policies like electricity subsidies was a policy suggestion given by some of the participants such as interviewee 3 & 4 (an emergent and commercial farmer respectively) and could be an important consideration for this crucial economic sector. [21] highlights a similar observation where subsidies can be beneficial.

Furthermore, lack of government incentives, lack of knowledge of available grants and initiatives promoting different types of irrigation technologies and farming types are the shortfalls of government in incentivizing farmers and agricultural stakeholders to adopt newer, water saving irrigation technologies as expressed by interviewee 2, 3 and 7 (An agricultural researcher, emergent farm and agricultural entrepreneur and investor respectively). These views are also clarified in [22].

Although existing policies are well articulated and sound in theory, they are often misunderstood, ignored by emerging farmers, and are not universally enforced according to interviewees 9 and 10 (irrigation specialist and researcher respectively). Therefore, according to interviewees 6 and 8 (Innovator and technological commercialisation expert respectively) a concerted effort must be made to ensure the knowledge of policies is available, and assistance given at a grass-roots level to implement these policies to assist in achieving the goal of sustainable water use in the agricultural sector, a view that is shared by [22].

6 CONCLUSIONS AND RECOMMENDATIONS

This research focused on the exploration of irrigation technologies and management strategies that could lead to sustainable water use in South Africa's water sector. It is proposed that by selecting the right technology for the agricultural specifications required and/or upgrading existing technology to more efficient technologies such as drip irrigation, unnecessary water loss can be avoided and a higher WUE can be achieved. The right irrigation would have to be complemental by supplemental agricultural techniques and appropriate policy interventions to achieve the full potential of sustainable water use.

The primary data gathering tool was a structured interview. Purposive non-probability sampling was used as only agricultural stakeholders that use irrigation technology or have a vested interest in irrigation technologies were targeted. Due to the inaccessibility of the research population group, a sample size of ten participants was used which although limiting was mitigated by the diversity of agricultural stakeholders represented which included: emergent and commercial farmers, researchers, irrigation technology experts and an agricultural investor/entrepreneur. It is recommended, that future research with a larger sample size would be necessary to corroborate the results of this study.

The first research question that was answered in section 5.2.1 was: What current technologies and practices are used by farmers and agricultural stakeholders and why have certain technologies and practices failed to be adopted in South Africa? The research showed that center pivot irrigation systems are primarily used by commercial farmers and agricultural stakeholders interested in high-value grain or cereal crops. These systems are favoured because of the ease of use, large surface area coverage and the minimal amount of labour required for maintenance. With respect to the commercial farmers these systems are also inherited and the up-front capital costs and additional maintenance requirements of upgrading the system or converting to another system are huge barriers to new technology adoption. The other participants which included researchers and emergent farmers preferred drip irrigation due to the high WUE because of root-targeted irrigation.

Proposition 1, in the conceptual framework, states that the factors in Table 1 can be used as a guideline to choose the broad category of irrigation system – sprinkler irrigation or micro irrigation – and Proposition 2 states that once that broad category is chosen a specific irrigation system within that category can be chosen. Although Table 1 was not used by the participants in the study, a tacit framework or guideline was used to establish the type of irrigation system such as the type of crops (grain, cereal, or vegetable crops), the capital investment and surface area coverage and maintenance requirements based on their individual experiences and knowledge.

The second research question that was answered in section 5.2.2 of the was: What management techniques can easily be adopted in South Africa to achieve sustainable water usage? The supplementary management techniques employed or recommended by the participants included: Irrigation scheduling and monitoring of dam levels, rainwater harvesting, the use of conservation agriculture such as crop rotation, zero or minimal tillage to retain soil integrity and plastic mulching to prevent the growth of weeds, and growing drought resistant crops. Additionally, the use of new technologies such as, solar energy for pumping, technology to retrieve deep ground water and the conversion to DI systems where possible, were recommended.

The use of irrigation scheduling, rainwater harvesting, and conservation agriculture can easily be implemented to any agricultural practice. However, the use of drought resistant crops and the use of modern technologies would require significant buy-in from the agricultural stakeholders as it would require a focus shift and more intensive implementation capital. Although, the management techniques implemented are essential and necessary, it cannot completely offset the potential water loss because of irrigation technology that has not been accurately assessed and subsequently upgraded or replaced – as supported by Proposition 3 of the conceptual framework.

Maintenance was also discussed in section 5.2.3. The interviewees were in unanimous agreement that scheduled maintenance was essential to ensure unnecessary breakdowns or water losses. The main maintenance issues involved the mechanical aspects of the irrigation system such as pumps, bearings, nozzles, and piping which are subject to wear and tear. Regular maintenance will ensure there is no water loss and subsequent decrease in water use efficiency. Comments and suggestions highlighted by participants were discussed in section 5.2.4. Since supplementary management techniques are also inclusive of policy interventions it was necessary to find out from participants what policies are in place and what gaps exist. Most participants said that legislations such as water use licenses are a legal requirement, especially for commercial farmers, but are difficult to obtain and often subject to corruption. Gaps in legislations, according to participants, include no subsidies for electricity which is necessary for the pumping of water in irrigation systems and lack of incentives or funding to adopt newer, possibly more water efficient, irrigation technologies.

A few recommendations can be made from the primary data gathered:

A reassessment of the current irrigation technology used by commercial farmers is necessary to determine if an upgrade to newer similar technology is required or a migration to a different type of irrigation technology is necessary. If the equipment is not reassessed and an action is not taken, then the supplementary management techniques and regular maintenance will not fully mitigate the ineffective water use in the irrigation system.

Emergent farmers often lack the initial capital investment to buy the appropriate irrigation technology for their specific needs. This leads to the use of irrigation systems which are inefficient at saving water such as impact sprinklers. Government grants and incentives should be given to these farmers to ensure the adoption of more water efficient irrigation systems. Since water scarcity is prevalent, a robust system of agricultural supplemental management techniques should be used in conjunction with the appropriate irrigation system for sustainable water management to be fully realised. Maintenance is such an important aspect of sustainable water usage, and it would be prudent to adapt the irrigation framework/guideline to include this factor. A system needs to be developed with multiple layers of accountability and transparency before more policies or suggestions (e.g., grants) are implemented.

With respect to the research, a limitation was the small sample size which was somewhat mitigated by diversity of agricultural stakeholders involved. Future research should be done with larger sample sized to corroborate the results of this research. Furthermore, specific research can be made to quantifying the costs of the irrigation technologies to inform government policies and grants which could assist in the adoption of more water saving technologies.

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8 APPENDIX

Appendix A: Structured Interview

1. What is your role in the agricultural sector (i.e., farmer, researcher, member of agricultural organisation)?
2. What type of crop(s) are you interested and/or invested in and what are the motivations for your choice of crop(s)?
3. What is the size of the land that the crops are grown in?
4. What irrigation system is used to water the crops?
   - 4.1. Why was this irrigation system chosen?
   - 4.2. How many years has this irrigation system been in use?
   - 4.3. What is the approximate start-up cost of this irrigation system?
   - 4.4. What are the approximate monthly costs of the system (i.e., labour, maintenance and energy?)
   - 4.5. If given funding, would you continue using this irrigation system or would you convert to another irrigation system? If you would change irrigation systems, can you motivate why?
5. What water source is used (i.e., river, dam, municipal or a combination)?
   - 5.1. Is the water source reliable throughout the year or does it undergo periods of water stress/scarcity?
   - 5.2. If the water source goes through periods of scarcity, what management techniques are employed in order to protect crop yields?

5.3. Is there a cost associated with using this water source (i.e., municipal water costs, pumping systems, filtration systems?)

6. How important is sustainable water management in your role in the agricultural sector?
   6.1. Approximately how much water is used to irrigate the crops in one harvest cycle (from planting, germinating to harvesting)?
   6.2. Do you think that less water can be used to irrigate the crops, if so, why hasn't the water usage been lowered?
   6.3. Are there any specific water management strategies or techniques used in order to use water more sustainably?
7. How important is scheduled maintenance in your operation?
   7.1. How many days are allocated to maintenance?
   7.2. What are the common maintenance issues (i.e., leaks, breakdowns etc.)?
   7.3. How many of these maintenance issues are related to water?
8. Are the following management strategies/techniques used in your operation?
   - Irrigation Scheduling
   - Deficit Irrigation
   - The use of desalinated water or treated effluent
   - Climate-smart agriculture technological innovations (CSATIs) such as rainwater harvesting, genetically modified seeds, agroforestry, conservation agriculture and the use of systems to detect periods of drought.

   8.1. If your operation uses none of the above listed, can you elaborate on what management strategies/techniques, you do use for your operation?
9. In your opinion, are there any regional or governmental policies which may promote or hinder the sustainable use of water in the agricultural sector?
10. Are there any final comments/suggestions you would like to contribute towards the topic of sustainable water use in the agricultural sector?

ADOPTION READINESS OF TECHNOLOGY USED FOR MAINTENANCE MANAGEMENT DURING THE 4TH INDUSTRIAL REVOLUTION IN A PETROCHEMICAL INDUSTRY

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ABSTRACT

The desire to increase reliability and productivity has driven organisations to adopt newer technologies that promise predictable operations. This need has led to organisations adopting these technologies rapidly. Information technology has for years been identified as an enabler of higher competitiveness. The perceived opportunity has driven this rapid technology adoption, including associated workflows and processes. Technology readiness is one avenue that organisations consider as a guide in adopting new technologies. Methodologies to determine technology adoption readiness measure the index based on the users perceived befits. The outcome of this research paper will be utilized to consider an early model that can be utilized to develop a sustainable technology adoption approach that will consider both internal and external aspects affecting the readiness for adoption, especially in petrochemical maintenance management.

Keywords: Technology Adoption, 4th Industrial Revolution, Adoption Readiness, Maintenance Management

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1 INTRODUCTION

Stakeholders recognize the need to improve equipment reliability to increase productivity and plant uptime [14]. Several innovative solutions have been proposed and introduced to the market and promised to increase the plant uptime by providing predictable and reliable operations. Sustainable asset management is one of the key factors that drives a successful organisation in such an environment [6].

The introduction of the 4th industrial revolution (4IR) has brought another dimension to these developments by bringing intelligence systems supporting these innovative solutions to the fore. The desire of companies to increase their reliability has driven the need to adopt these systems, promising to close the gap at a rapid pace [6].

The 4IR introduction has forced organisations to move from traditional maintenance strategies to predictive maintenance and, recently, prescriptive maintenance management. As much as organisations have employed robust maintenance strategies to try and extend the asset lifecycle, the evolution of technology has created a complex environment to adopt holistic maintenance strategies [6]. This holistic maintenance strategy includes prescriptive maintenance, predictive maintenance, production and supply chain optimization, and performance monitoring, to mention a few [6]. The 4IR allows industries to collect and analyse large amounts of data and predict an expected outcome. This data can be used to predict failures before they occur, thus allowing companies to plan the repairs [6]. This prediction methodology is defined as predictive maintenance and depends on data collection.

The advantages brought to the fore by adopting information technology have proven beneficial to companies and have played a central role in enabling petrochemical organisations to be competitive during this challenging economic climate. The lean operating margins for petrochemical industries can benefit from the advantages of the 4IR. However, leaving the 4IR to its own device is dangerous. The 4IR must be managed closely to achieve Sustainable Technology Adoption Readiness.

There is a conflicting view on whether introducing some of these technologies will increase economic activities and thus increase job opportunities [32]. The result from the previous evolution suggests otherwise [14]. The introduction of the 4IR will, however, improve the standard of living. There is also a view that it will also reduce the overall cost of living due to the reduction of the cost of goods and services, thus making life easier for most people [32]. This drastic and tremendous change in the socio-economic situation will benefit society. The shortage of core critical skills challenges maintenance management in the petrochemical industry, and the introduction of this revolution will present these industries with certain challenges in this regard [8].

The advantages above will benefit a petrochemical organisation if the entities are ready to adopt the 4IR technology enablers [28]. The exact opposite is possible if these new technologies hit these organisations and there is no readiness to adopt them. Radical adoption can often lead to incorrect technology being adopted if the business is unprepared. In a petrochemical space with little room for error, such mistakes could be costly and have dire consequences for the facilities [24].

Despite the advantage of globalization in enabling different countries and communities to be interconnected, emerging economies still need help to break forth and exploit these opportunities [14]. Adopting the correct technology is easily achievable for economies and industries at the right readiness level. If the economy is amiss, there is a high probability that the wrong technologies may be adopted. In the case of adoption, some of the benefits of such technologies may be overlooked, and technologies need to be more utilized [12].

Several technology adoption frameworks have been utilized to assist companies in adopting newer technology [23]. There needs to be more focus on the readiness for adopting new technologies in the petrochemical industries in emerging economies [24]. It is important to note that adoption readiness is not only an element of internal adoption but also issues outside the organisation if not addressed, might compromise technology adoption readiness [23].

This paper addresses Technology Adoption Readiness in the 4IR in Petrochemical Maintenance Management by reviewing existing Technology Adoption Readiness through a literature review.

2 LITERATURE REVIEW

2.1 Petrochemical

Oil and gas energy has played a significant role in developing and growing economies of oil-producing and oil-importing countries and has remained relevant to humankind's activities [9]. In the petrochemical industry, chemical products such as petrol, diesel, and jet fuel are produced through crude distillation [24]. Other products, such as plastic, polymer, medical device fertilizers, etc., are produced as by-products of the primary production process [21]. These final products are derived from crude oil, natural gas, or natural gas liquids [21]. The industry is segregated into Upstream, Midstream, and Downstream [26], as described in figure 1.

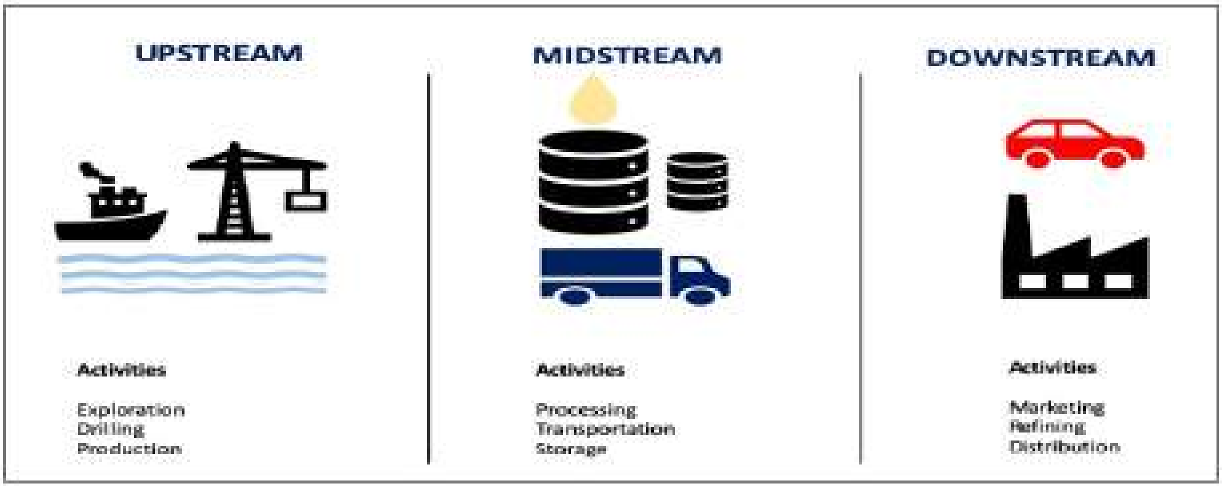

Figure 1: Petrochemical Value chain [26]

The discovery of oil and gas brought about staggering advancements to industrial growth worldwide and has helped ease transportation at both international and local levels [9]. Oil and gas energies have made life easy for humankind in cooking, heating, provision of electricity, local mobility and many more [24]. Thus, petroleum and its related products as energy sources are still being replaced in the contemporary world [9].

As much as petrochemicals have played a significant role in developing and growing economies, they remain a challenge to sustainable environmental management [21]. They are comparatively more polluters than other industries, as petrochemical generates significant air emissions, wastewater, noise pollution, and hazardous waste [21]. Petrochemical facilities are also listed as major hazard installations as they store and process a large amount of flammable and toxic gases [21]. They are high-risk plants with potential explosion, poisoning, and fire risks.

There is a concerted effort in the industry to increase the safety and security of petrochemical plants by developing and understanding the risk associated with these plants [21].

A stable plant also minimizes the number of environmental incidents. There is increased pressure from some activists to shut down petrochemical plants due to pollution. Every incident directly causes an impact on the emission and release of hazardous substances, thus compromising the environment [9].

There is a direct correlation between a reliable plant and a reduced number of safety-related incidents. Therefore, a reliable and stable plant will reduce the risk of exposure to these undesired events [16].

2.2 Maintenance Management

The nature of how equipment is designed and operated will always be liable to wear and tear [16]. The past few years have seen organisations increase their dependency on technologies for productivity [15] and necessitate a need to maintain equipment [16].

Maintenance is keeping equipment in or restoring it to the serviceable condition [16], defined as a collection of actions executed on an asset to restore it to a specific condition [15]. It includes service, test, inspection, adjustment, alignment, removal, replacement, reinstallation, troubleshooting, calibration, condition determination, repair, modification, overhaul, rebuilding and [11]. Maintenance Management involves planning, leading, staffing, organizing and controlling maintenance resources to adjust, repair, replace and modify technical systems. Maintenance is vital for the sustainable performance of any industrial operation [16]. Maintenance management maximises resources such as people, skills, tools, and money [16]. Different maintenance approaches are sometimes referred to as strategies or philosophies [15]. These strategies have evolved from reactive to predictive or precision maintenance and from being seen as a necessary evil into a strategic focus [10].

In the early stages of maintenance, breakdown maintenance, commonly known as reactive or corrective maintenance, was the more popular approach to maintenance management [16]. This reactive maintenance management approach started to hurt that organisation as there was an increase in the volume of goods produced and the complexity of the systems and processes in use [11]. These challenges saw the birth of the preventative maintenance approach [11].

Reliability-Centred Maintenance (RCM) was first introduced in the late 1950s in the airline industry [11]. RCM approach is an optimum mix of different maintenance practices (reactive, time or interval-based, condition base and proactive) [11]. This approach integrates the strategies mentioned above to maximise the different advantages that each maintenance approach possesses and minimise the total life cycle cost by maximising equipment reliability [11]. The RCM approach's goal is to improve an organisation's productivity [11].

In the petrochemical industry, this improvement has reduced the number of safety and plant incidents. Chemicals used in these plants are corrosive, and some have auto ignition if exposed to air. Ensuring that the integrity of this equipment is understood and maintained is critical. Adopting a Risk Based Inspection has been critical in improving the reliability of these facilities and thus ensuring that maintenance turnaround and inspections are taken at the right time.

Over and above this, some of these facilities have existed for a prolonged time. There is a mixture of old and new technology with limited smart technologies installed. Condition-based maintenance is thus a challenge in some of these facilities as minimal instrumentation is installed to enable maintenance management to extract data for analysis and predict the performance of some of these machines in operation.

2.3 Industry 4.0

The term Industrial Revolution was made popular by Arnold Toynbee in the late 18th century to define Britain’s economic growth [16]. The noun “industry” is defined as the production of services or goods through commercial and technological organisational advancement [30]. On the other hand, industrialism is the development of scientific technology and knowledge leading to the development of industries on a wide scale [23].

The industrial revolution is brought about by a sudden and violent change that launched the industrial society by transforming society beyond what the previous revolutions were able to achieve [28]. The industrial revolution directly impacted technological, socioeconomic, and cultural features [14]. In simple terms, this phenomenon can be explained as the move from doing work at home by hand to more work being done in industries through machines [28]. All industrial revolutions challenge the applicable skills and competence deemed relevant in the previous revolution [18].

Before the Industrial Revolution, humans depended on their hands and livestock for survival [18]. Any industrial revolution is driven mainly by the needs of human beings [23]. The 4IR is centralised around big data, artificial intelligence (AI), robotics and the Internet of Things (IoT). The 4IR is a system that integrates machines and humans with information and objects to enable complex system management [27]. Core instruments comprise the IoT, AI, cyber-physical devices, 3D printing, blockchain, big data, cloud computing, nanomaterials, and synthetic biology [20]. It is not an abstract concept but an actual technology that intends to improve a factory [27]. The projected benefits of the 4IR are, amongst others, a shift in trade and an increase in volume production, and trade is largely digital [27]. Employee's skill sets also need to be evaluated to establish themselves in this competitive era of the 4IR [18]. In a study conducted by the World Economic Forum, complex problem-solving is the key competence [18].

2.4 Readiness Framework

Readiness is defined as the ability to capitalize on future productivity opportunities, mitigate risk and challenges, and be resilient and agile in responding to unknown future shocks [32]. This is a measure and capability of any organisation to be prepared to manage and deal with any uncertainties presented by the future. In relation to technology adoption, it measures how ready the organisation is for the uncertainties introduced by adopting technology [8].

2.4.1 Fit - viability

This model discussed here has two components to determine the readiness for adoption. The first component assesses Fit for purpose. The second component focuses on the viability of the technology under scrutiny [29]. Viability determines the likely payoff if the investment is made in the proposed technology. Fit and viability need to be assessed jointly in collaboration. They both need to achieve a high level of success before a new technology can be adopted. The model provided in Figure 2 is referred to as the Fit and Viability model [32].

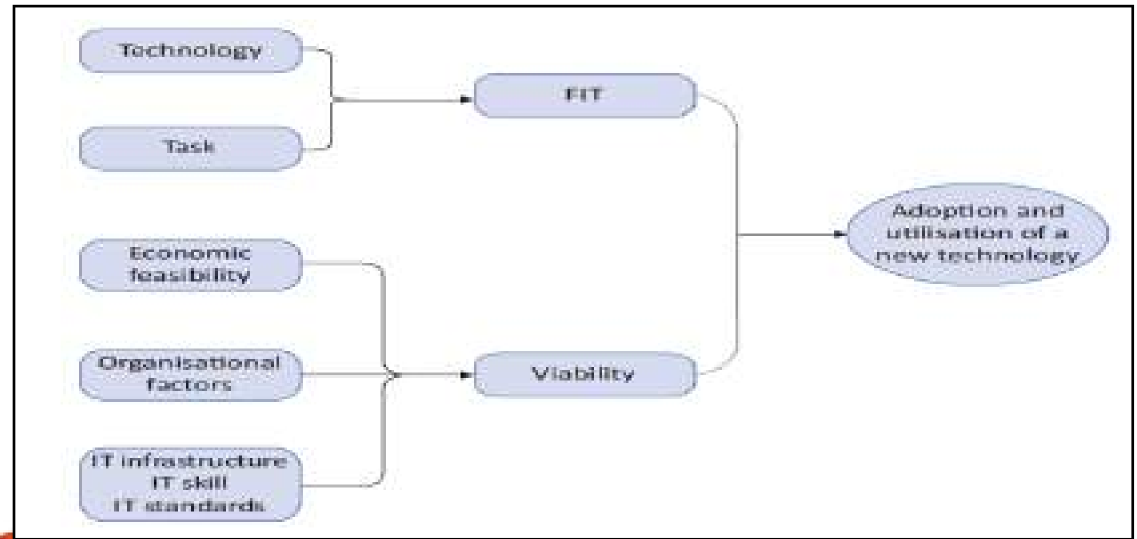

Figure 2: Fit and Viability Model [32]

2.4.2 Task - Technology Fit

Task–Technology Fit (TTF) is a model that focuses on whether the technology provides adequate functions to enhance the performance of the target task. This model is an improvement from the Fit-viability model. Two components form part of this model. The first is the Task technology fit dimension and the second is the viability dimension, slightly advanced from the viability dimension discussed in the Fit -viability model [29].

As depicted in figure 3 below the Task technology fit dimension is further broken down into three components: Task, Technology, and Fit. The assessment of task fitness focuses on the requirement of the organisation [29]. Technology, on the other hand, focuses on the attributes of the technology available. Lastly, Fit is used to understand the extent to which the new technology meets the task requirement of the organisation [32].

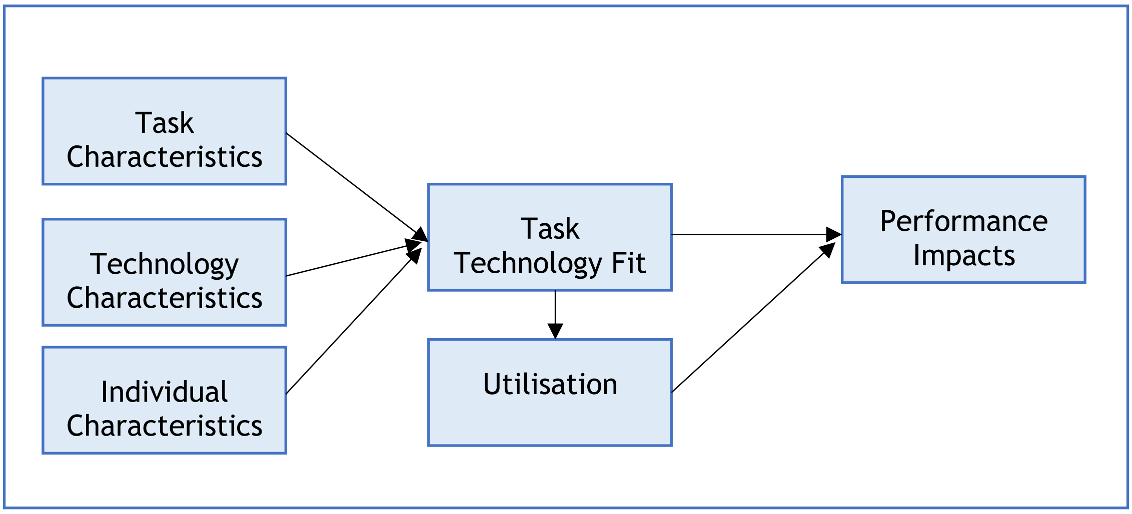

Figure 3: Task – Technology Fit [32]

3 TECHNOLOGY ADOPTION CASE STUDIES

A few articles were selected as case studies on technology adoption to establish if there is a pattern or a trend from previous Technology Adoption Readiness cases in petrochemical industries with a particular focus on maintenance management.

3.1 Technology Adoption

Technology remains a concept of innovation until it is accepted and applied by individuals, organisations, or a group of people and becomes a behaviour [27]. Technology adoption demands active engagement from affected parties and must not be treated as a passive solitary activity. It is not a straightforward but rather complex process [16]. New technologies that organisations should adopt in the maintenance management space are usually offered by third-party service providers [23]. Technologies introduced as part of the 4IR are being introduced faster than can be anticipated by adopters in the maintenance space [1]. Research suggests that there needs to be more interest in adopting and the actual rate of adoption [1]. The technology introduction must meet the adopter's expectation to ensure the ultimate use of the technology. The use will be challenging if not well received equally [1].

Adoption cannot happen without the acceptance of the technology. Acceptance usually happens at an individual level, while adoption is a decision that is normally taken at an institutional or individual level [8]. The decision to accept or adopt is thus influenced by social and behavioural factors, which is the main reason for adoption and acceptance failures [8].

3.2 Psychological Factors influencing technology adoption: A case study from the oil and gas [33]

The success of technology adoption is in the hands of key decision makers in any company. There is reluctance in the adoption of new technology in the upstream and gas industry. The reluctance is primarily caused by the innovativeness of leaders who are critical decision makers in these petrochemical industries. Evidence suggests that leaders in this space are risk averse due to the scepticism around the perceived radicalness of these new technologies being introduced. The increase in the number of cyber security incidents is also viewed as a factor that has led to the fear of adoption in the maintenance space in the petrochemical industries.

The reluctance to adopt technology has significant cost implications for organisations, including loss of competitive advantage and potential revenue. The knowledge and experience of staff with digital technologies are equally important. The research also highlighted the importance of strategically investing in the right technologies aligned with the business model. There should be adequate investment in infrastructure development, training, and appointing employees with relevant training because of the complexity of the technology in the market. Investments should not be made haphazardly without understanding the risk involved in the proposed technology, what benefits this technology will provide, and what support systems are required to render the technology successful, including support systems such as cyber security. Lastly, the Government needs to formulate policies that will support the deployment of such a technology.

3.3 Production capacity and energy optimization of complex petrochemical industries using novel extreme learning machines integrating affinity propagation [36].

There is a radical change driver toward the reduction of energy usage and Carbon Dioxide footprint. The findings of this article indicate that the attitude of the technology adopter has a significant role in guiding, influencing, directing, shaping and predicting the actual behaviour. The attitude contributors are innovation and optimism. As much as an attitude can be high, it was also noted that different levels of economic development counter the importance of attitude in technology adoption. The articles also cite higher anxiety toward technology adoption in the maintenance management space in the petrochemical industries due to a need for security, dependence on expectations, and a great need for the application of information.

There is an urgent need to improve the skill base of organisations in machine learning. The lack of necessary skills to adopt remains one of the most significant barriers as it not only affects the company's readiness and effective use of these new technologies, but it also is a threat to existing employees as they fear losing their jobs and thus are resistant to the adoption of these new technologies.

There is considerable pushback from general citizens to adopt some of these technologies. Cybersecurity and changes are also not comfortable. Developing countries also need more infrastructure to migrate to these newer technologies seamlessly. Exacerbated by the current economic climate organisations need more capital to invest in these required infrastructures.

In addition to the challenges posed above, there is also slow movement from the government's point of view in introducing new legislation to support these new technologies. Cybersecurity issues are equally an issue that organisations must drive, but equally so the Government can introduce legislation to protect consumers and suppliers.

3.4 A Feasible Framework for Maintenance Digitalisation [35]

There is an opportunity for maintenance management to take advantage of the opportunities brought about by the 4IR. The radical growth of digital technologies has presented the industry with a reduction in technology adoption expenses. The global transformation related to the 4IR is due to a significant global transformation. Manufacturing industrial machines are becoming more intelligent and in line with these developments, there are global regulations that have created a demand for more secure, reliable and safe systems. There is however a lag in the adoption of maintenance related technologies, maintenance operations are still performed manually due this lag in maintenance digitalisation. Minimal research has been done to eradicate the challenges brought about by this delay in adoption. The current estimation is that 45% of the time of maintenance resources is spent in the manual capturing of data.

The lack of necessary skills to adopt remains one of the most significant barriers as it not only affects the company's readiness and effective use of these new technologies in the maintenance space, but it also is a threat to existing employees as they fear losing their jobs and thus are resistant to the adoption of these new technologies.

There is a large pushback from general maintenance personnel to adopt some of these technologies. Organisations also need more infrastructure to migrate to these newer technologies seamlessly. Exacerbated by the current economic climate organisations need more capital to invest in these required infrastructures.

In addition to the challenges posed above, there is also slow movement from the government's point of view in introducing new legislation to support these new technologies.

3.5 Adoption patterns and performance implications of Smart Maintenance [34]

There is no denial of the criticality of maintenance in the manufacturing process, irrespective of the size or shape. The introduction of digitalisation has increased the attention given to maintenance management. Unfortunately, the amount of research in the space of maintenance digitisation has been limited to exploratory studies and there is no empirical value proposition of maintenance management digitalisation. There is enough evidence to suggest that manufacturing facilities with a high level of maintenance digitalisation adoption have higher level of performance.

The articles focused on issues that are challenges to technology adoption readiness. There is an urgent need to improve the skill base of organisations in emerging economies. The lack of necessary skills to adopt remains one of the most significant barriers as it not only affects the company's readiness and effective use of these new technologies, but it also is a threat to existing employees as they fear losing their jobs and thus are resistant to the adoption of these new technologies.

There is a large pushback from general citizens to adopt some of these technologies. Cybersecurity and changes are also not comfortable. Organisations also need more infrastructure to migrate to these newer technologies seamlessly.

3.6 A framework to test South Africa's readiness for the 4IR [32]

The South African Economy is faced with a challenge of high unemployment. Introducing new technology has the prospects of creating job opportunities, and curbing this challenge is well exploited. South African technology adopters can exploit this opportunity by upskilling and/or retraining human skills to ensure the retention of skills and new employees' employment in the South African's market. Adopters urgently need to proactively retrain and upskill to prepare for the radical shift that is fast approaching. Organisations in the country that don't have the right skills associated with new technologies are not technically ready to adopt.

Coupled with the problem of unemployment, South Africa needs help to recover from the impact of COVID-19 on economic activities. South Africa was no exception to what most emerging economies went through an economic recession, and organisations in those countries felt the impact. Companies in emerging economies thus find themselves in a space where they need more capital to invest in new technologies.

4 METHODOLOGY

The study intends to contribute to the body of knowledge by providing conceptual insight into technology adoption readiness in the 4IR in maintenance management in the petrochemical industry. The research essentially follows an exploratory research (desktop research/ literature review) approach to establish readiness for technology adoption in the 4IR maintenance management for petrochemical industries through a literature review. Technology adoption literature in the maintenance and petrochemical space was utilised to derive a conclusion on the factors affecting the readiness of technology adoption in the petrochemical space in maintenance management. A Fit and Viability model, in conjunction with a literature survey and case studies, was utilised to determine the requirement for readiness and the findings will need to be tailor-made for the petrochemical industries in adopting technology. An approach adopted to reach the end goal includes:

- An initial literature review has been conducted on 4IR, maintenance management, the petrochemical industry and current readiness frameworks, focusing on technology adoption readiness. See section 2.
- Key issues have been extracted from the literature review in section 2, case studies in section 3 and is the basis for determining readiness. See the results discussed in section 5
- The research outcome for this paper is then a draft conceptual insight, presented and discussed in section 5, towards readiness for adopting maintenance management technology in the 4IR.

The outcome of this research paper will be utilised to consider an early conceptual model that can be utilised to develop a sustainable technology adoption approach to consider both internal and external aspects affecting the readiness for adoption, especially in petrochemical maintenance management.

5 CONCEPTUAL INSIGHT INTO TECHNOLOGY ADOPTION READINESS IN THE 4IR IN MAINTENANCE MANAGEMENT IN THE PETROCHEMICAL INDUSTRY

The findings of this study are based on the literature review conducted in section 3. Below in Table 1 is a summary of the findings with additional information, including the additional articles utilised to draw some conclusions on factors necessary for technology adoption readiness. The significance of the study was based on the total number of articles that supported the view over the number of total articles consulted.

Table 1: Summary of Literature Survey Findings

	Findings	Significance	Sources
Cyber Security	Lack of security systems to ensure the protection of users. There is a need to ensure robust security to protect humans, data, and the environment.	9/9	[36], [31], [35], [7], [13], [5], [33], [17], [32]

	Training in cybersecurity understanding		
ICT Infrastructure	Upgrade of existing hardware Consideration to be given to the integration of existing hardware with the new hardware	6/9	[32],[34], [35], [33], [13], [17]
Human Capital	Reskilling and upskilling of resources to align with new technologies Hiring of resources with the required expertise	7/9	[36],[32], [34], [35], [33], [13], [7]
Users Enablement	Developing software and hardware that is compatible with new technologies Development of the infrastructure for internet service Adequate investment in infrastructure development Stability of the internet services	6/9	[32],[35], [33], [13], [5], [7]
Economic Feasibility	There is a need to reskill and retrain Lack of knowledge and experience of staff motivate staff members to use new technologies Attitude of the adopter	8/9	[36],[32], [35], [33], [13], [5], [7], [17]
Technology Knowledge	Importance of strategically investing in the right technologies Relevant skills needed for the adoption	8/9	[32],[36], [35], [33], [13], [5], [17]
Government Support	Promulgation of necessary policies and legislation Support from the Government to ensure feasible adoption Understanding of development in the market to influence and ensure correct investments	8/9	[32],[34], [35], [33], [13], [5], [7], [32]

Information consolidated from the study conducted indicates that there is a need to have the right skill internally and externally to the Petrochemical industries and integration of these skills and knowledge bases will be critical in ensuring speedy adoption and correct adoption of technologies. Maintenance Management resources in the Petrochemical industries need to be empowered to understand cyber threats and thus ensure that they can curb the prospect of any attack and proactively put the necessary control measures in place. Understanding the ICT technologies is equally important as it will help with quick adoption and correct adoption. There needs to be an understanding of these technologies beyond the adoption phase, even during the operation phase.

There is no need to employ new employees, but the currently employed staff can be upskilled or reskilled to be on par with the new technology. Incorrect data diagnostics can lead to the wrong maintenance regime adopted, even wrong items being maintained, or the right equipment not being maintained. Hence, skilling the internal resources and support services must be balanced.

There is a need from both technology suppliers and Petrochemical industries to ensure that their infrastructure is developed for easy integration with new and proposed technology to be adopted. A better understanding of the technologies to be adopted will help minimize the developmental infrastructure capital required, as the best technology will be deployed without additional continual support from the service providers. The cost constraint can restrain any prospects of adoption, hence, there is a need for both external and internal resources to work jointly in the optimization of the capital investment required.

The benefit realised by Petrochemical industries should they adopt some of these proposed technologies are going to be of benefit to the Government as well as it will assist with curbing the challenges of unemployment. It will thus be beneficial for the Government and Petrochemical industries to work hand in glove in attracting necessary investment, and in particular, the Government has a role to play in marking the country a fruitful ground for investments. This can be achieved through policy shifts and amendment or promulgation of legislation.

The lack of relevant internal and external cybersecurity policies for the Petrochemical industries will render the joint focus exercise irrelevant. There is a need for the Petrochemical industries to put in place the necessary training to ensure a clear understanding of cybercrime and attack. Lastly, what is the role of an employee to ensure that over and security mechanisms are put in place by the company? How can an employee mitigate the threat posed to the organisation by cybersecurity?

6 CONCLUSION

The work presented as part of this paper is only preliminary and exploratory work on factors to be determined by petrochemical organisations to establish their readiness to adopt new technologies. This research intended to formulate a preliminary conceptual framework.

It is important to note that as much as there is a need for further work, several issues addressed as part of this study cannot be ignored and need to be considered, as presented in this preliminary study. Adopting technology in the petrochemical space requires proper understanding, as there is minimal room for error due to system failures. It is, therefore, critical that a proper framework is used to adopt these technologies and ensure that correct technologies are adopted. Coupled with this are the lean operating margins in this space making it extremely important that there is a small room for spending money on the wrong technology that cannot have a direct return on investments.

The outcome of this research paper will be utilized to consider an early model that can be utilised to develop a sustainable technology adoption approach entailing both Internal and external aspects affecting the readiness for adoption, especially in petrochemical maintenance management.

The work presented is not complete; additional work, including refined model development, interviews and surveys with industry experts, can ensure that all or more aspects linked with technology adoption in the 4IR within the petrochemical industries are captured.

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COMPLETING THE PUZZLE: ACCURATE RECORD-KEEPING FOR INFORMED GRAZING MANAGEMENT DECISIONS

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ABSTRACT

Pasture management is an important aspect of every livestock farm. The quality of pasture directly influences the condition of the livestock grazing on it. For a farmer to make an informed decision on where to move his livestock, he needs data on the grazing patterns of his animals. The problem is that farmers do not keep records of where their animals have been grazing, making future decisions difficult. The aim of this study is to design a grazing management record-keeping system that processes real-time data on grazing patterns in livestock and assists farmers to make informed pasture management decisions. A tracking collar is used to track the grazing patterns. This system helps farmers identify the most suitable area on their farms for livestock to graze, allowing their animals to be in the best possible condition.

Keywords: Pasture, Livestock, Grazing, Management, Data, Record-keeping

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1. INTRODUCTION

Cattle farming in grass-based systems, also known as grass-fed or pasture-based farming, is a sustainable and environmentally friendly approach to cattle farming. In this system, cattle consume a diet composed primarily of natural grasses and forages, as opposed to being confined in feedlots and fed a grain-based diet. Grass-based systems prioritise the natural behaviour and physiological needs of cattle, aiming to provide a more natural and humane environment for them [6]. Grass-based systems are the most common approach to cattle farming in South Africa.

In grass-based systems the key focus is on utilising the natural forage resources available in the pasture. Pastures must be managed carefully to ensure a continuous supply of nutritious grasses and forages throughout the year [6]. By developing and following effective pasture management strategies, farmers can improve the quality and quantity of the pasture on their farms. The condition of a farmer's livestock is directly linked to the quality of the pasture they are grazing [6]. Therefore, by managing and improving the pasture on the farm, a farmer is also improving the condition of the animals. The result of animals being in a better condition is better breeding results and better growing performances in calves, making the farm more profitable [1]

The use of precision technologies in grass-based livestock systems has increased animal welfare and health, improved the quality of meat and milk, and decreased the impact on the environment [2]. Precision technologies can facilitate improved decision-making that maximises the value in grass-based systems [2]. In the long term, precision technologies can also be used to determine the effects of animals on different grassland areas. However, these technologies are not widely available and used by livestock farmers.

A number of different pasture management strategies exist and are implemented on South African farms. These strategies include rotational grazing, continuous grazing, strip grazing and spell grazing [3]. Each of these strategies has its own advantages and disadvantages. Farmers implement the strategy that fits their farms and infrastructure best.

Regardless of the chosen strategy, a successful system will have the following attributes:

- Effective management of pasture utilisation that considers carrying capacity and the allocation of rest periods [3];
- Reduction of irregular grazing patterns that tend to be counterproductive or harmful [3]; and
- Balances stocking rates with the dietary requirements of animals [3].

Furthermore, strategic grazing strategies can significantly contribute to disaster management and the effective management of invasive plant species [3].

The general farmer does not have good record-keeping data (other than memory) of where the animals have grazed previously. Often animals are just moved to the closest field that looks like it has sufficient pasture. Within this field the chosen grazing strategy is implemented until the available pasture is depleted.

In summary, the problem is that farmers have limited historical data available to support them in making informed decisions regarding future grazing management.

For these reasons the aim of this study is to develop the concept design of a grazing management record-keeping system. This system will assist farmers in making informed pasture management decisions, leading to more profitable farms.

A case study farm was used to conceptualise the study and test the technology. The case study farm is located on the banks of the Vaal River near Potchefstroom. Farm activities focus mainly on cattle farming in a well-established strip-grazing system. This is done by providing the animals with a small piece of pasture, only enough to last for a short period, and then moving the fence forward and providing a new piece of pasture. This system improves pasture quality and increases the number of animals that can be kept on a particular piece of pasture. It is important to note that the animals have sufficient feed at all times, are never starved, and have sufficient space to move.

2. METHODOLOGY

The V-model method, an extension of the Waterfall model, is a specialised tool to develop software programmes [3]. This model improves the efficiency and effectiveness of the development process [3]. The model below is an adapted V – Model that incorporates coding and continuous verification throughout the process. This paper will focus only on the research, customer requirements, design requirements, and the conceptual design. The remaining steps of the model will be addressed in future research.

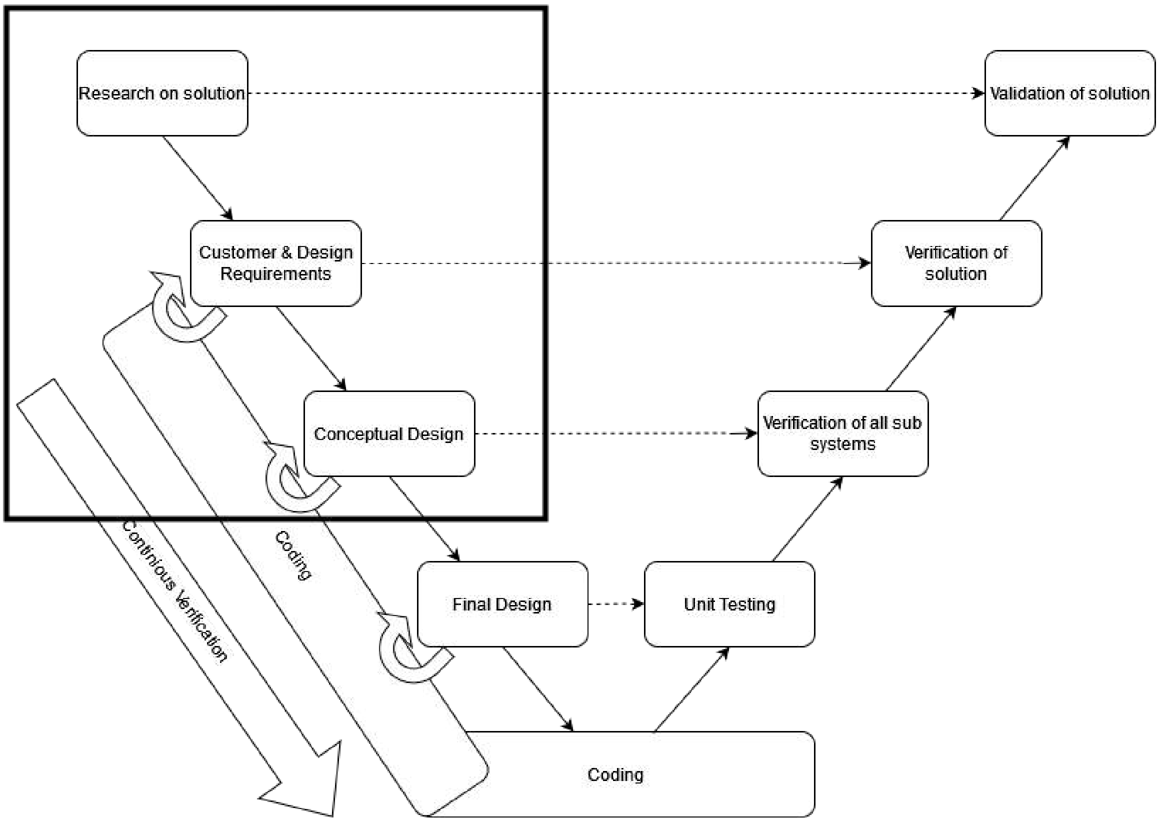

Figure 1: V-model method

a. Research

The first step in solving the problem is to conduct research on the problem, as well as the possible solutions to the problem. A narrative literature review was conducted making use of Gemba walks (a lean manufacturing term for, “going to the place of work, to see for oneself”), industry visits, and informal discussions to investigate the problem and identify possible solutions and the design requirements.

b. Customer and Design Requirements

A list of design requirements was established based on customer, literature and software design requirements.

c. Conceptual Design

The conceptual design was done based on the design requirements in the previous step, and the findings from the literature review. The conceptual design went through a continuous verification process to ensure it adhered to design requirements and achieved the aim of this project.

d. Coding

Coding of certain aspects of the solution started after the design requirements had been set. There were repeated references to the design requirements to code aspects of the solution.

e. Continuous Verification

Throughout the coding process continual reference was made to the design requirements in order to verify that the solution conformed to the requirements.

3. LITERATURE REVIEW

The aim of the narrative literature review was to determine the design requirements to which the grazing management record-keeping system needed to conform, as well as the essential variables needed to develop the record-keeping system.

The literature gave insights on precision livestock farming (PLF) technologies [4], and factors to consider when making decisions regarding grazing management [1]. In addition, methods on how to record these factors, both with and without PLF technologies, were also identified.

Important factors to take into account when keeping a record of grazing patterns are the grazing time of the herd on a specific piece of pasture, the structure of the herd during the grazing time, and lastly the quality of the pasture at the time the herd was grazing on it [2] [5], the details of which are discussed below.

a. Grazing time

The grazing time can be described as the number of days the animals grazed on a specific piece of pasture [1]. This factor can be broken down further into 1) the location of the animals and 2) the available fields where the animals could graze. The location of the herd can be recorded using precision livestock farming technologies such as GPS trackers, anti-theft collars and GPS tracking ear tags [2] [4]. Farmers can also manually keep a record of where their animals are grazing.

b. Available fields

A farmer needs to know where he can move his animals, where his animals grazed, and where they are grazing currently [1]. The fields that are available for grazing can be stored on any mapping app such as Google Maps.

c. Herd structure

A calf of 50kg eats less food than a 400kg cow [6]. Therefore, to accurately record the herd, the structure of the herd, such as weight, age, sex, lactating module, and reproduction status needs to be considered [5]. The herd structure recording also includes animal identification which can be done by using ear tags or branding cattle. PLF technologies such as microchips and RFID tags can also be used for animal identification and herd structure recording [4].

d. Pasture quality

Pasture amount and quality depend on a large variety of factors such as seasons, rainfall, growth time and previous grazing strategies [1] [7]. Pasture amount and quality can be measured with several PLF technologies. This includes satellite imagery, drone footage, rising plate meters, sample analysis, spectral analysis, and normalised difference vegetation index (NDVI) values [2] [8]. All these sensors rate the pasture on a vegetation index [4]. This data can then be recorded on cloud storage or other manual systems such as spreadsheets and computer-based programmes. However, very few of these grass measuring sensors are commercially available.

Further research produced a method that provides the same vegetation index by scoring the vegetation based on visual factors. Pasture specialists commonly use this scoring index to determine the carrying capacity of fields in the sense of hectares per large livestock unit as explained in section 3.5 below [9]. The index takes five factors into account, namely 1) basal cover, 2) botanical composition, 3) insect and rodent damage, 4) ground surface condition and 5) growth strength. These factors are assigned a score out of 100.

1. Basal cover includes the overall cover of the field. How much of the field is covered in a pasture, and how much pasture there is on the field. The better the coverage of the field, the higher the score assigned to it.
2. Botanical composition is the composition of different types of plant species. Some plants are eaten more by animals because they are tastier. If the composition of plants contains more tastier plants, the assigned score is higher.
3. Insect and rodent damage can be seen on plant bases and roots. If there is no damage visible, the factor is scored 100.
4. Ground surface condition considers the overall surface of the field. This includes all types of erosion and bare spots in the field. The assigned score drops down as the surface condition deteriorates.
5. The growth strength of the field can be seen in the plant bases. A high score is assigned if the grass base is very dense, and the grass is growing strongly. The opposite happens if the grass base is sparse with few stems.

These values are then put in an equation to calculate the overall vegetation index. The equation considers all variables mentioned previously and can be seen below.

$$Vegetation\ Index = (BaCo * 0.3) + (BoCo * 0.3) + (BaCo * BoCo * 0.002) + (GS * 0.05) + (GSC * 0.1) + (IRD * 0.05)$$

Where:

VI = Vegetation index

BaCo = Basal cover

BoCo = Botanical composition

GS = Growth strength

GSC = Ground surface condition

IRD = Insect and rodent damage

e. Animal Carrying Capacity

To sustainably farm with livestock farmers need to continuously balance stocking rate (amount of animals) with available pasture, all this while considering environmental factors and an uncertain future [10]. Animal carrying capacity, or stocking rate is defined as the maximum number of animals that a certain area of land can sustainably support during a defined grazing time [11]. Carrying capacity is usually measured in livestock units per hectare per year [11]. A livestock unit (LU) is determined by the use of specific coefficients established for each species of livestock on the basis of their nutritional requirements [11]. In terms of cattle, an animal of 450kg is considered to be one livestock unit [12]. Therefore, carrying capacity of livestock units per hectare per year can be calculated to kilogram per hectare per day, which states the area of pasture necessary to sustain a kilogram of animal for a day.

Animal carrying capacity can be determined by the pasture quality (section e above), accurate grazing records [13] or other measurement tools and techniques [14]. By knowing the carrying capacity of his fields, a farmer can accurately predict the number of grazing days available on that specific field.

Animal carrying capacity differs from season to season, landscapes, type of plants and nutrient contents of the vegetation. The farmer therefore needs to continuously monitor these factors [11].

The equation below calculates the carrying capacity of an area of pasture based on the historic recorded data:

$$Animal\ Carrying\ Capacity = \frac{TW}{A}/GT$$

Where:

TW = Total Herd Weight

A = Grazing Area

GT = Grazing Time

f. Literature Review Conclusion

The aim of the literature review was to determine the design requirements with which the grazing management record-keeping system must conform.

The narrative literature review has explored various studies and sources to determine the essential design requirements for the grazing management record-keeping system. Through an analysis of existing literature, key factors and technologies have been identified that must be considered in the design process. By exploring these findings, a set of design requirements has been established, providing a foundation for developing a grazing management record-keeping system.

4. DESIGN REQUIREMENTS OF A GRAZING MANAGEMENT RECORD KEEPING SYSTEM

a. Client Requirements

i. Informal discussions

By engaging in informal discussions with the client, a number of design requirements were identified:

1. The solution needs to be easy to use and access since administrative tasks should not remove the farmer from his value-adding (farming) duties;
2. The solution must require minimum maintenance;
3. The solution must be integrable for other uses in the future, such as more precise animal identification and keeping track of multiple herds;
4. The client should be able to change data that was recorded incorrectly manually;
5. The system must integrate with his existing precision livestock farming technologies;

ii. Data Flow Analysis

A case study farm was visited to get a better understanding of how farmers make grazing management decisions. The process was documented, and a data flow analysis was conducted to get a visual flow of the information needed for the farmer to make informed grazing management decisions. Figure 2 indicates what information is needed for a farmer to make an informed decision, as shown in the far-right green block of the data flow analysis.

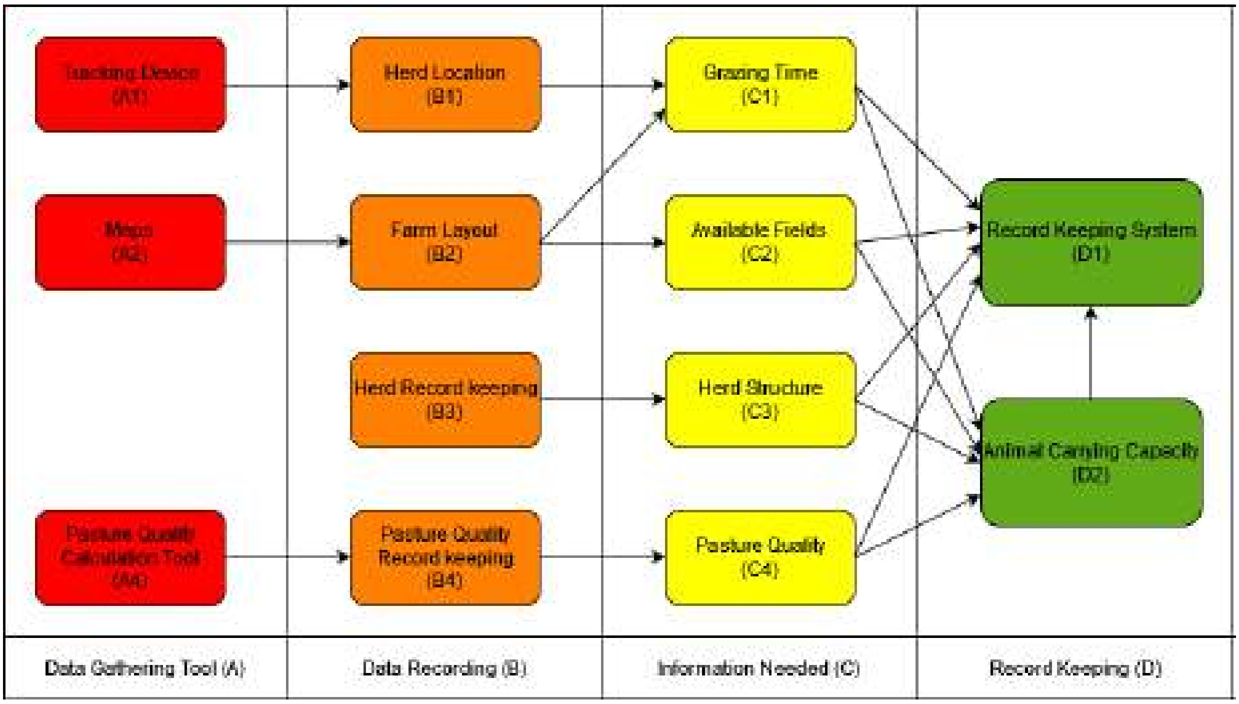

Figure 2: Data Flow Analysis

In order to calculate grazing time (C1), a farmer needs the layout of his farm (B2), and he needs to record the location of his herd (B1). He can gather the location data by using a tracking device (A1).

Secondly, a farmer needs to know the available fields on his farm (C2). In order to know this, he needs to have a complete and accurate layout of his farm (B2). He can gather this data by using third-party apps such as Google Maps (A2).

Thirdly, a farmer needs to know the structure of his herd (C3). Therefore, he needs a way to accurately record the structure and size of his herd that considers all relevant factors (B3).

Lastly, the farmer must know the pasture quality index (C4). He needs a way to record this data over time (B4). He can collect this data by using pasture evaluation technologies or tools (A4).

The data flow analysis thus provided the basic structure for determining the design requirements for the grazing management record-keeping system.

b. Literature Design Requirements

Based on the findings in the literature review and the data flow analysis in Figure 2, the following design requirements were set.

1. The solution must be able to accurately calculate the grazing time in each field based on the location data gathered and the layout of the farm.

2. The solution must be able to record the real time location of the animals accurately.
3. The solution must be able to record the farm, and all fields available for grazing.
4. The solution must be able to record the size of the herd, as well as the total weight of all animals based on their age.
5. The solution must be able to record and calculate the overall pasture quality index of each field.
6. The solution must be able to accurately calculate the animal carrying capacity in each field based on the data gathered.

c. Software Design Requirements

Based on the above design requirements, software requirements were identified to ensure the solution is effective.

1. User Interface: The solution needs to have an easily navigable user interface that is easy to use and understand.
2. Data Management: The solution needs to capture, store, and retrieve data effectively. It must have robust validation to ensure accuracy.
3. Scalability: The solution must be able to handle large volumes of data without compromising the integrity and performance of the system.

5. CONCEPTUAL DESIGN OF A GRAZING MANAGEMENT RECORD KEEPING SYSTEM

Based on the previous design requirements, each aspect of the record-keeping system was designed. The structure of the record keeping system is based on Figure 2, and it will be referenced as such throughout this section.

a. Data Recording (B)

The record keeping-system needs to record the data specified in Figure 2, namely herd location (B1), farm layout (B2), herd structure records (B3), and pasture quality (B4). These factors are recorded by the technologies or strategies mentioned in column A, data gathering tools.

i. Herd Location (B1)

The system tracks and records the real-time location of the herd. The design requirements state that the solution should use the customer’s existing precision livestock farming technologies. An animal location and theft prevention GPS collar (A1) was already in use on the farm. The collar provides the farmer with a GPS coordinate every 2 hours.

The solution uses this device to track and record the location of the animals. The collar has a battery lifespan of 18 months and therefore needs minimal maintenance. The GPS coordinates are uploaded to a website where it is accessible by the owner of the collar. The data can also be extracted in a file for other applications.

ii. Farm layout (B2)

The layout and the sizes of the fields were recorded by the farmer and the researcher on Google Maps (A2). The fields were divided into areas that were usually grazed together or along fences and roads. This data is accessible from the computer-based programme.

iii. Herd structure record keeping (B3)

A computer-based program was developed enabling a farmer to enter the number of animals of a certain age and weight to keep track of the size and structure of the herd. The record-keeping system considers weight and age, and automatically calculates the total weight of the herd.

iv. Pasture quality record keeping (B4)

There are several PLF technologies available that can calculate the quality of pasture. However, these technologies are not commercially available. Therefore, a decision was taken to make use of the pasture quality index system (A3) that takes the following factors into account: 1) Basal cover, 2) species composition, 3) ground surface condition, 4) growth strength and 5) insect and rodent damage. These factors are then visually scored. These scores are recorded in the same computer-based programme as the herd size and structure.

b. Information Needed (C)

After recording the raw data are processed to make it useful for making decisions. The information that the farmer needs can be seen in the yellow blocks in Figure 2 and includes grazing time (C1), available fields (C2), herd structure (C3), and pasture quality (C4).

i. Grazing Time (C1) and Available Fields (C2)

The data gathered from the GPS tracker can be downloaded from a website. The data is then entered into the computer-based programme. The programme determines in which field the animals were grazing at the time the coordinates were sent. This data is plotted on a map in order to show where the animals were grazing. From this map, the farmer can see which fields he still has available for grazing (C2). The program also uses this data to calculate and store the grazing time (C1) in each field.

ii. Herd Structure (C3)

The recorded data on herd size and structure are calculated to an overall weight. The size and structure of the herd are recorded for each coordinate point at the specified time (C3), and for the grazing periods in each field.

iii. Pasture Quality (C4)

The pasture quality index (C4) is calculated by taking the values assigned to each visual factor and inputting it in the equation. The pasture quality index value is then recorded and used to make more accurate decisions.

c. Record Keeping

i. Record Keeping System (D1)

The gathered data on grazing time, available fields, herd structure and pasture quality are accurately recorded in a database. The database is accessible from the platform and can be manually edited in order to ensure accurate data.

ii. Animal Carrying Capacity (D2)

Animal carrying capacity, which is defined as the maximum number of animals that a certain area of land can sustainably support during a defined grazing time [11]. As found in the literature review above, carrying capacity of livestock units per hectare per year can be calculated to kilogram per hectare per day, which states the area of pasture necessary to sustain a kilogram of animal for a day.

To calculate the carrying capacity, the herd structure (kg) is divided by the area of pasture that they have grazed, and divided by the number of days they grazed in that area (grazing time). This value is then stored together with the data from the grazing session in the record keeping system.

d. User interface

The user interface for the solution consists of tabs that have a clear description of their function, as seen in Figure 3. A user can enter each type of data recording section by clicking on the corresponding tab. Data can also be updated by clicking on the corresponding tabs and following the instructions. Safety measures are implemented to ensure users do not contaminate or duplicate data.

Figure 3: Grazing Tracker user interface

The information will assist the client to make decisions on how long he should allow his animals to graze a field. It will also assist with herd management – will he have enough pasture for his animals? or, does he need to sell some of them?

6. VERIFICATION

To achieve the aim of the research, it was necessary to verify that the conceptual design met the design requirements (set in section 4) and that the problem (in section 1) was addressed.

a. Verification of Conceptual Design

The client, literature design and software design requirements (from section 4) are listed in Tables 1-3. Verification that the conceptual design adheres to these requirements is provided in each table.

Table 1: Client Requirements Verification

Customer Design Requirement	Verification
1. The solution needs to be easy to use and access since administrative tasks should not remove the farmer from his value-adding (farming) duties.	The user interface consists of several easily navigable tabs. Each tab has a clear description of its function. The system will be accessible on the client's computer.
2. The solution must require minimum maintenance.	The system requires little to no maintenance. The battery power of the GPS collar is 18 months. The data only needs to be updated when the structure of the herd changes.

3. The solution must be integrateable for other uses in the future, such as more precise animal identification and keeping track of multiple herds.	The system can integrate more herds in the future by simply adding another GPS collar. Animal identification software can easily be added as the database already exists.
4. The customer needs to be able to change incorrectly recorded data.	The customer can access the recorded data and make changes where necessary.
5. The system must integrate with the customer's existing precision livestock farming technologies.	The solution uses the theft prevention collar that is already used on the farm (A1).

Table2: Literature Design Requirements Verification

Literature Design Requirement	Verification
1. The solution must be able to calculate the grazing time in each field accurately.	The herd location data and the fields recorded in Google Maps are used to calculate the grazing time (C1) of the animals in each field.
2. The solution must be able to accurately record the real time location of the animals.	The solution makes use of a theft prevention and GPS tracking device that provides a GPS coordinate every 2 hours. This data is stored on a website, and in a database (B1).
3. The solution must be able to record the farm layout, and all fields available for grazing.	All fields are created and stored (B2) in the Google Maps app, which can be accessed from the user interface (C2).
4. The solution must be able to record the size of the herd and the total weight of all animals based on their age.	The solution has a herd structure record keeping section where the number of animals is entered by their age and weight. The system stores this data in a database (C3).
5. The solution must be able to record and calculate the overall pasture quality index of each field.	The solution uses a visual method to calculate the pasture quality index (C4). The index is stored in a database.
6. The solution must be able to accurately calculate the animal carrying capacity of each field based on the data gathered.	The solution calculates the carrying capacity of each field from the recorded data and updates it continuously as new data are recorded.

Table 1: Software Design Requirements Verification

Software Design Requirement	Verification
1. User Interface: The solution needs to have an easily navigable user interface that is easy to use and understand.	The user interface consists of several easily navigable tabs. Each tab has a clear description of its function.
2. Data Management: The solution needs to capture, store and retrieve	The solution validates all data that is entered into the system. Duplicate and

data effectively. It must have robust validation to ensure accuracy.	outlier data are removed to ensure accuracy. Data are stored and referenced in a database.
3. Scalability: The solution must be able to handle large volumes of data without compromising the integrity and performance of the system.	The solution can handle large volumes of data, as only small pieces of data are processed at a time, not all the data at once.

By referring to Tables 1, 2 and 3, it can be verified that the conceptual design meets all client, literature, and software design requirements.

7. CONCLUSION

By keeping accurate grazing records, farmers can make informed grazing management decisions which will help them to make their farms more profitable.

This research has provided farmers with a foundation for an accurate grazing management record-keeping system. The system allows farmers to keep a record of all relevant grazing management factors that will influence their decisions.

The information will assist farmers to make decisions on how long they should allow their animals to graze in a field. Farmers will also be able to manage their herds better. By analysing historical data, they can determine whether or not they will have sufficient pasture for their animals. They will also be able to identify how their practices have changed the quality of their pasture over time.

All of these factors will help farmers make better decisions in terms of grazing management. This will result in their animals being in better condition and making their farm more profitable.

The system will form the base for livestock farmers to start incorporating and utilising available precision farming technologies. It can be seen as the missing puzzle piece that connects livestock farmers to precision technologies that will help them increase the profitability of their farm.

8. LIMITATIONS AND FUTURE RESEARCH

Any data recording system is only as accurate as the data provided to the system. It is important to note that the farmer needs to keep the data in the system up to date in order to ensure accurate record-keeping. The herd structure and size must be updated regularly, as well as the pasture quality, which needs to be updated for every season.

A Limitation of the study is that the system has only been tested on the one case study farm. Future research should extend the application to other similar farms in order to further test the validity of the system.

The current system is designed only for one herd and was tested only on cattle. Future research should extend the application to a data-gathering system suitable for all types of livestock farms. It must also be extended to cater for multiple herds.

Currently, the system only operates from a personal computer. Future research should focus on adapting the system to a quick-asses app that can be used on a cell phone.

Future research could focus on using precision livestock farming technologies to improve the accuracy of the data recorded in the system.

The main function of the current data recording system is to capture accurate real-time data to support the farmer in making grazing management decisions. For future research, this data recording system should also include a discussion support functionality that will provide various “what-if”-calculations, predictions, and calculated suggestions.

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PREDICTIVE PROCESS CONTROL FRAMEWORK FOR ONLINE QUALITY CONTROL IN A HOT ROLLING MILL

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ABSTRACT

Recent data science advances in statistical classification techniques, and in particular, machine learning techniques, have resulted in more efficient and robust ways of continuously monitoring and managing processes to achieve continuous quality improvement. With increased automation and process data outputs in industrial processes, traditional univariate Statistical Process Control (SPC) is proving impractical in some aspects and slowly loosing overall relevance. The main aim of this study is to develop a predictive process control framework for online quality control. This predictive process control framework employs data science approaches through machine learning techniques. The results of the study revealed a marginal 17 percent improvement in predictive process control defect rate compared to univariate SPC defect rate. Factors found to have a positive impact on the success and sustainability of predictive process control were compliance to predictive model prescriptions, data science knowledge, senior management commitment and Extract, Transform and Load (ETL) approach.

Keywords: Predictive Process Control, Quality Control, Online Quality Control, Rolling Mill Quality, Machine Learning, Data Science

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1 INTRODUCTION

In the last 100 years, manufacturing has gone through four major industrial revolutions [1]. In the first revolution, there was significant shift to mechanization and transition of harvesting water as the source of power to more reliance on steam energy. In the second revolution, there was a transition to mass production and harvesting of electricity as a source of energy. In the third revolution, automation through the use of computers and robotics gained significant prominence. The reality for most manufacturers in the third revolution has been that customer quality expectations advanced while majority struggled with decades-old technological approaches, generating inaccurate, dated, and disconnected analytics from siloed systems [2]. For decades, univariate statistical process control (SPC) has been the most widely used online quality control approach to address customer quality expectations in the third industrial revolution. SPC has been credited with assisting organisations to improve their quality, with the benefits of improvement having an overall impact on waste reduction and yield improvement [4]. However, criticisms of SPC as an effective quality control approach have grown steadily, with Bhote [5] arguing that Japan, the primary proponent of SPC, abandoned SPC in the 1970s due to its ineffectiveness. Furthermore, Gunter [6] argues that modern manufacturing and service processes have transcended the relevance and usefulness of SPC, with Woodall [7] emphasizing the need to move away from SPC to newer approaches that include multivariate methods.

In the fourth industrial revolution, manufacturers are expected to be able to generate meaningful analytics that support process improvement required to meet increasing customer expectations. It was anticipated that by the end of 2021, at least 20 percent of the largest manufacturers would rely on embedded intelligence built on cognitive data applications (like machine learning and artificial intelligence) and internet of things [3]. Recent advances in statistical classification techniques, and in particular, machine learning techniques, have resulted in more efficient and robust ways of continuously monitoring and managing processes to achieve continuous quality improvement. According to Singh [8], multivariate methods are relevant in the fourth revolution of big data because they provide alternatives that incorporate the interdependence and volume of process characteristics that were previously restricted. Multivariate analysis has recently migrated to the machine learning and artificial intelligence space, where it can be used to predict future performance [8]. Multivariate process control using machine learning techniques is a new field of study with very limited framework reference available. With SPC becoming less relevant and data science (through machine learning and artificial intelligence) gaining relevance [10], the purpose of this study was to develop a predictive process control framework based on multivariate approach for online quality control that will be used as a viable alternative to an increasingly irrelevant SPC approach. The effectiveness of the predictive process control framework was evaluated as part of this study through a single case study experiment at a hot rolling plant known as Company X.

1.1 Research Questions

The central research question of this study is “How can advances in data science, especially machine learning techniques, be structured into a predictive process control framework that is a viable alternative for univariate SPC?” The sub questions are:

1. How can a machine learning or artificial intelligence model be deployed to enable predictive process control framework for online quality control in a rolling mill?
2. What is the effect of predictive process control on the defect rate of a rolling mill?
3. Which aspects of predictive process control are applicable at different levels of a rolling mill?
4. Which factors greatly influence the outcome of the predictive process control deployment in a rolling mill?

1.2 Hypotheses

The following hypotheses were tested (where the defect rates of predictive process control and univariate SPC were tested):

H_0: There is no significant difference in the defect rate of traditional univariate SPC and predictive process control when defect rates of the two approaches are compared.

H_a: There is significant difference in the defect rate of traditional univariate SPC and predictive process control when defect rates of the two approaches are compared.

2 ONLINE QUALITY CONTROL

Quality control is a process that a company uses to ensure that product quality is maintained or improved [11]. Online quality control, on the other hand, focuses on the monitoring and surveillance of a process to detect anomalies, analyse and eliminate the causes of variation. In this study, the proxy metric for online quality control is defect rate. Three of the most common quality control techniques used in industry are [5]:

- SPC: This method involves the use of statistical techniques to control a process or production method.
- Taguchi method: This is an engineering approach that emphasises the role of research and development in reducing defects and failures during manufacturing.
- Failure testing: This method involves testing a product until it fails to expose the weaknesses of the product.

SPC is the most widely used method for online quality control in the industry [12] and forms the foundational construct for predictive process control and this study.

2.1 Univariate Statistical Process Control

SPC is a quality control method that uses statistical methods to monitor and control process variation in quality with the aim of ensuring that processes are efficient and operate effectively. It was developed in 1924 by physicist, Walter Shewhart while working for Bell Telephone Laboratories [19]. Traditional quality control methodologies tend to focus primarily on product quality control which emphasizes defect detection through inspection while SPC is process oriented [11]. Understanding and controlling variation is central to understanding SPC. Variation can be understood as the spread between parameter numbers in a data set and the most common measure of variation is standard deviation [13]. Shewhart recognized that variation is unavoidable in processes and that every process has inherent variation due to what he identified as chance causes (also known as common causes) and assignable causes (also known as special causes) [14]. Control charts (especially $\overline{x}$ – R charts) are the most common SPC tools found on the manufacturing shop floor [1].

There are numerous well documented successes, controversies and challenges associated with SPC. Criticisms of SPC as an effective quality improvement approach and questions about its relevance have steadily grown since the early 1990s. According to MacGregor [9], the SPC approach to continuous quality improvement is completely inadequate for most modern processes because it assumes that all variables are independent of one another. Since the early development years of SPC, very little has changed in the way that it is applied in the industry [6]. Woodall [7] offers a more balanced view in that he notes, SPC's primary objective of understanding, modelling and reducing variability over time remains relevant and important. He further emphasizes the need to expedite the transition from classical methods to some of the newer approaches when appropriate. Montgomery [10] highlights how recently developed methodologies that include multivariate methods, variance components, change-point techniques and regression-based methods can greatly increase the usefulness of SPC in some common situations.

2.2 Predictive Process Control

Predictive process control is a term that does not have a universal definition. Micronite [16] defines predictive process control as tool-centric predictions of process patterns and low-risk assurance of compliance with a specification, while Funk [17] defines predictive process control as, a method for predicting the performance of a process outcome by separate measurements of selected fundamental properties of each input parameter of a process. In this study, predictive process control framework should be understood as the structured approach to deploying multivariate machine learning or artificial intelligence (AI) models of a process for online quality control.

Even though machine learning or AI has seen steady growth in the manufacturing industry over the last ten years, AI is not new to the industry. AI software tools such as artificial neural networks, fuzzy logic, genetic algorithms and SVMs have been widely used in various manufacturing industries in a piecemeal manner over the last three decades [15]. Here are some examples of how rolling mills have used machine learning and AI approaches:

1. An artificial neural network model was developed by Pican, Alexandre and Bresson in 1996 for the pre-setting of a steel temper rolling mill [15]. The model was built with support from Sollac (in France) and CRIN-INRIA (also from France), using 12 process parameters as input to predict roll force during temper rolling. The architecture of the neural network used to estimate the rolling force is shown in Figure 2. Model training and testing phases occurred at the CRIN-INRIA laboratory before the online implementation in the plant. Real data were used and it was obtained from the actual steel temper mill process over six months. They found that the mean model error of prediction by artificial neural network model was 13.2% against 24.7% error of prediction by theoretical mathematical models.

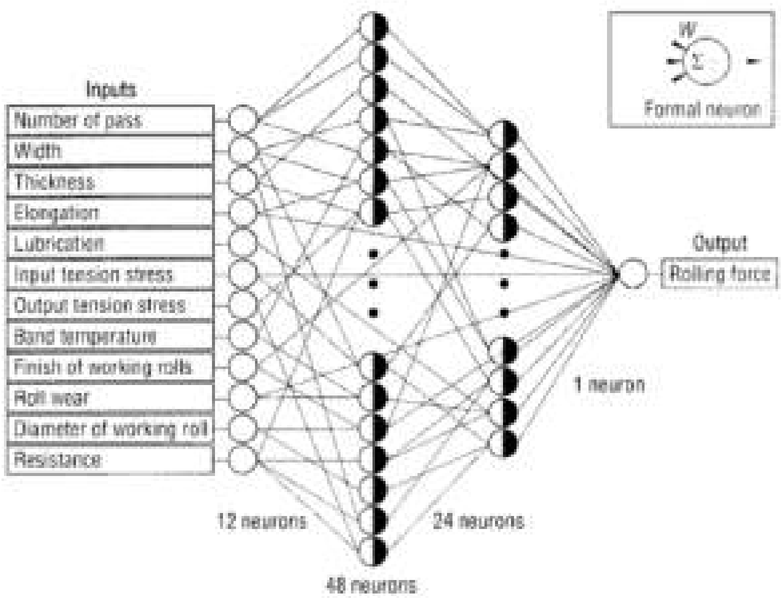

Figure 2: Artificial neural network for rolling force Source: Rath [15]

2. An artificial neural network model was developed by Cho in 1997 for the prediction of rolling load for the tandem cold mill of the Pohang Iron and Steel Company (POSCO) using a backpropagation algorithm with 4944 process data collected from the mill [15]. They found that model error was reduced by 33.88% with the application of the artificial neural network.

Alshraideh [21] published a framework for predictive control in 2020, detailing a standardised approach to adopting predictive modelling for process control. The framework is depicted in

Figure 3 and is limited to a decision tree approach to predicting quality using random forest techniques. The framework is general in the sense that it can be applied to any production process where profile data are available, and it can easily integrate process specific features based on process operator experience or commonly used transformations of observed signals as additional features.

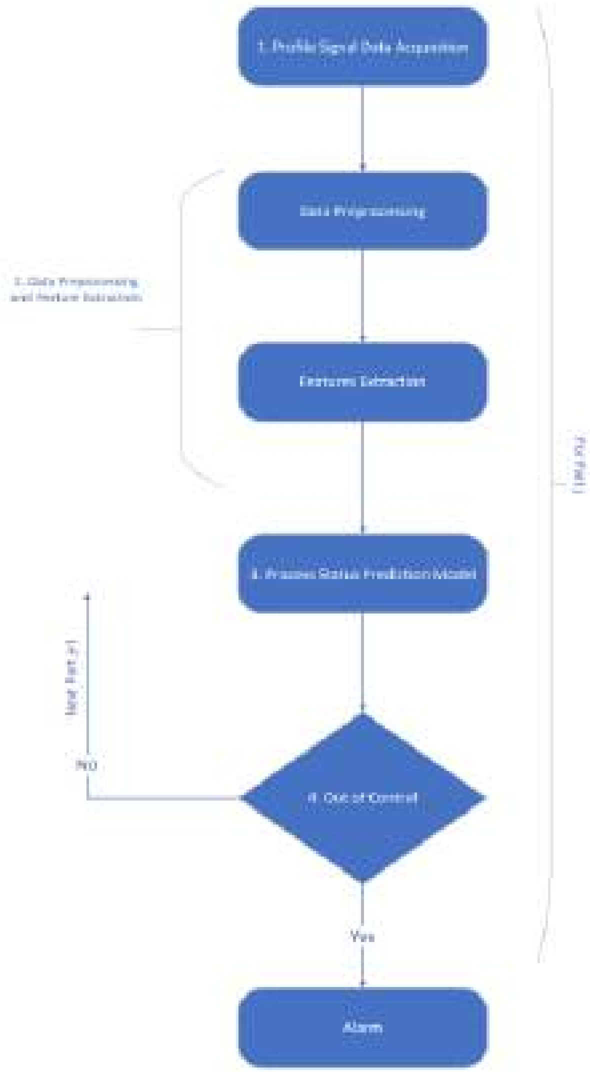

Figure 3: Framework for predictive control model **Source: Alshraideh [21]**

Alshraideh's [21] framework summarises theories for predictive control coming from the following domains:

- Data Engineering
- Computer Software (machine learning and artificial intelligence)
- Computer Hardware
- Statistics
- Maths

3 ROLLING MILL PREDICTIVE PROCESS CONTROL

Based on a review of literature on the impact of variables (both dependent and independent) of variation, SPC, data science, leadership, organisational culture, and base capabilities, it is argued that they have a positive influence on the successful deployment of predictive process control. Figure 4 depicts the rolling mill predictive process control framework (RMPPC framework), which serves as the foundation for this research and validation at Company X. The RMPCC framework is a construct of the author and consist of some elements (highlighted in figure 4.) that are standard machine learning modelling steps. This framework assumes a discreet manufacturing process with sensors or tags that measure process parameters during production. The RMPPC framework has eleven aspects (with some aspects having multiple steps).

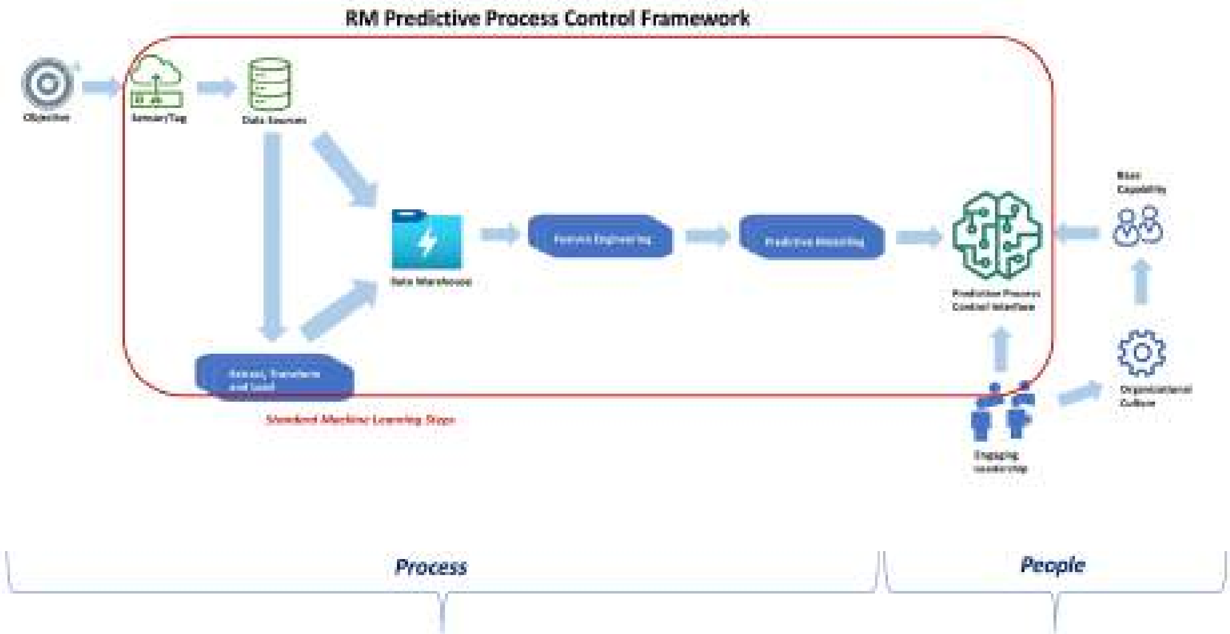

Figure 4: RMPCC Framework for Hot Rolling Mill **Source: Author's own compilation**

To assist a green-field rolling mill know how well they're implementing the RM predictive process control framework, a maturity assessment tool has been developed by the author and is presented in Figure 5. The proposed maturity model consists of eight areas of focus that were identified and standardised during the experimental deployment of RMPCC at Company X. These eight areas are assessed using a score of one to five, with one being the worst and five being best.

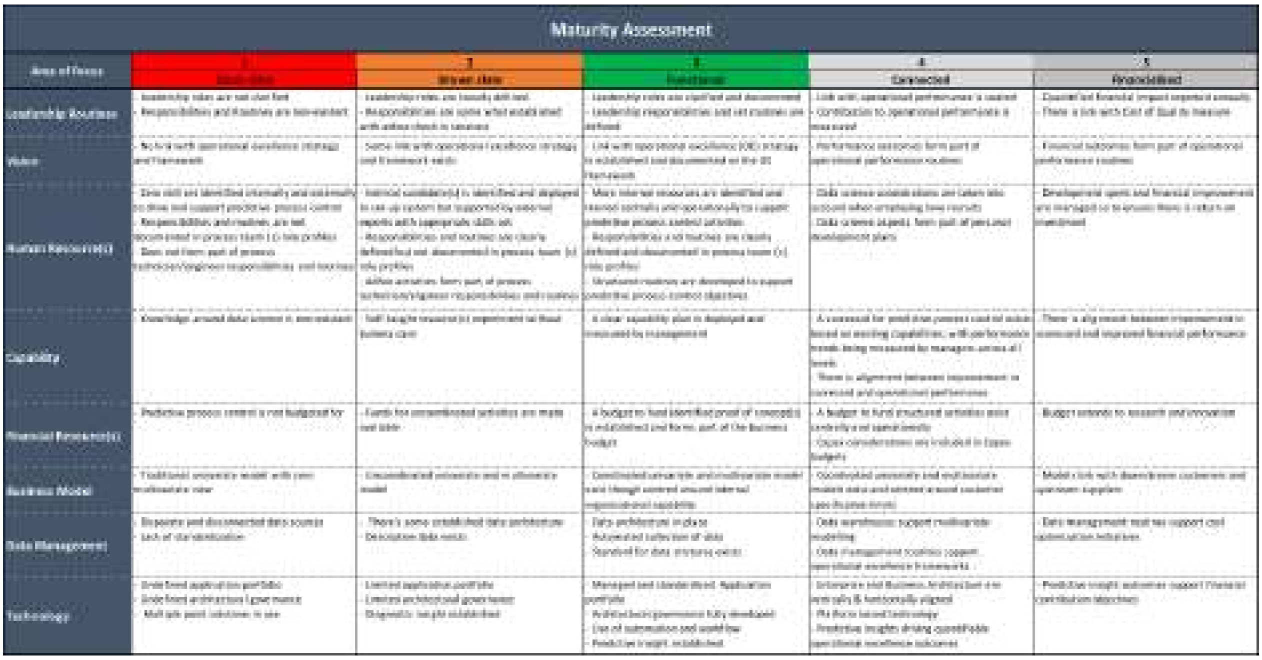

Figure 5: Maturity Assessment Model **Source: Author’s own compilation**

4 RESEARCH METHODOLOGY

Validation of the RM predictive process control framework was based on single-case study research, focusing on real-life events that demonstrated a single source of evidence at Company X. For the purposes of this study, the population is defined as an organisation (referred to as Company X). Company X denotes a single company with a single hot rolling mill. Company X is a company based in South Africa. Feature Engineering and Predictive modelling of the experiment was developed by Lombard [18] of Data Prophet. Although the population of one organisation may appear to be small, the test and control groups were large enough to test the hypotheses without jeopardizing the experiment's credibility. Quantitative sample design was used in this study, and the specific method used in order to establish sample size is called power analysis. Power analysis methods refer to a group of statistical methods used to determine the appropriate sample size for an experiment. These methods produce a power statistic, which quantifies the likelihood that the planned experiment will successfully detect a meaningful difference between the test and control populations, if one exists [18]. Random sampling is a key assumption in power analysis. The sample on which power analysis is performed is drawn through the random sampling process. The test and control groups in this study's experiment are made of the AA5182 alloy. Power analysis for the AA5182 alloy was performed using Python software, with multiple confidence intervals indicated by alpha, as shown in Table 2. Table 1 provides data that support the sample size calculation.

Table 1. Input data table for power analysis of AA5182 alloy

	Number of coils evaluated in data modelling using historical data falling within defect free zone	Number of coils evaluated in data modelling using historical data falling outside defect free zone	Total number of coils evaluated in data modelling using historical data
Count	267	2840	3107
Mean	0.288	0.54	0.53
Standard Deviation	0.45	0.5	0.5

Table 2. Power analysis table for AA5182 alloy

Statistical Power	Alpha	Experiment sample size (Number of coils)
0.8	0.01	80
0.8	0.05	27
0.8	0.1	23
0.8	0.025	35

Using the above AA5182 alloy power analysis table, to obtain a 95 percent confidence interval (alpha = 0.05) on the evaluation of test results, the number of sample metal ingots or metal IDs required for the main experiment of the study to reach a statistically significant conclusion is 27. The initial sample size of 27 ingots or coils was increased by a factor of three to get to 81 ingots or metal IDs as the final sample size to account for non-related process drifts. Feature selection was a key driver in the power analysis. The power analysis was carried out based on the significance of each feature in explaining defects in the hot rolling process. The feature importance rating is attributed to that feature, relative to all other features.

Prior to data analysis, data preparation was completed. This process entailed verifying the completeness and accuracy of collected data, as well as converting the data into a format that allows for analysis and interpretation. The Hotmill process and control engineers validated the test metal ingots or coils that were hot rolled using data science approaches for the purposes of this study. The quantitative data was analysed using Minitab (version 21.1.0) statistical software package. Hypotheses testing for this study was performed using the two-samples proportion test.

5 RESULTS

The results are divided into the five sections. Section 5.1 reported on the machine learning or artificial intelligence (AI) deployment results, Section 5.2 reported on defect rate results, Section 5.3 reported results on applicable aspects at different management levels, Section 5.4 reported on results of factors that greatly influence the outcome of predictive process control and Section 5.5 presented hypotheses testing results.

5.1 Machine learning or AI Deployment Results

Data for the experiment's predictive model was extracted from seven processes shown in Figure 6. These processes are metal melting, metal holding, metal casting, metal scalping, metal reheat (pusher furnace), metal hot roughing (HRM) and metal hot finishing (HFM). The structure of the extracted data was such that it needed to support time-series modelling. Time-series modelling is a statistical technique that deals with data that is in a series of a particular time period or intervals. The machine learning process control prediction model was developed to predict HRM and HFM processes. The other five processes provided input process data that assisted with prediction of HRM and HFM processes.

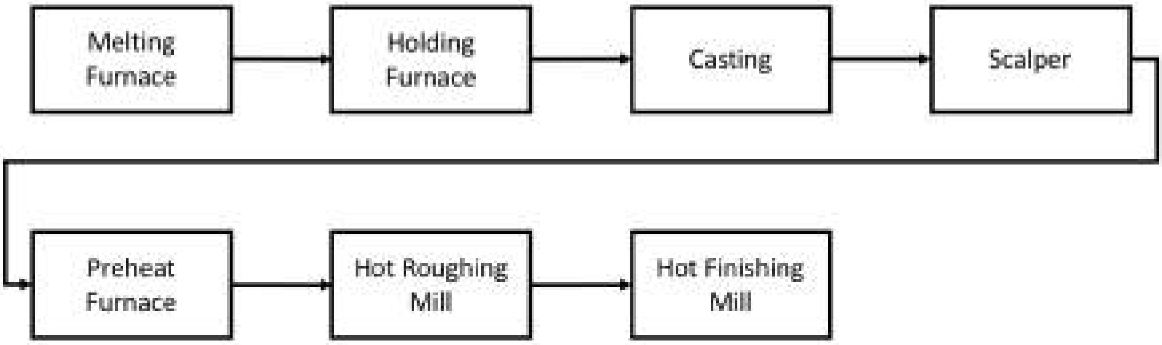

Figure 6: Data provision processes

Figure 7 depicts the ETL architecture as developed by Lombard [18]. The input data span was two years, beginning in 2020. The data was processed in daily batches. The total number of variables extracted as part of ETL for feature engineering was 3100 across all seven processes. Before being loaded into the data warehouse, the extracted data was decoded and dumped to S3 as daily parquet files. There were over 1000 files and 1TB of decoded data, each with approximately 550 unique days.

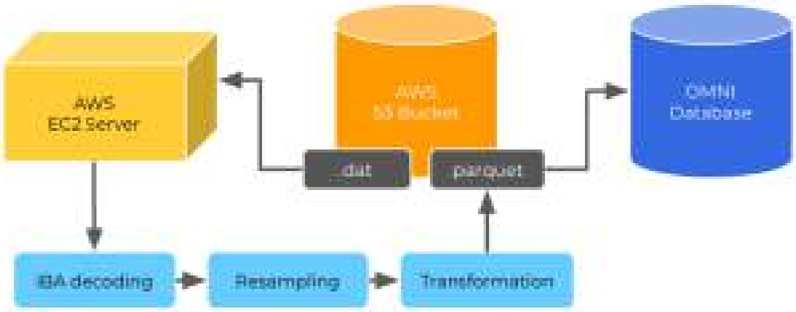

Figure 7: ETL architecture

The principal component analysis (PCA) technique was used to determine features for predictive modelling of this study's experiment. Python language was used for modelling. Variational auto encoders were also used in the feature engineering architecture (VAEs). VAEs generate a low-dimensional representation of a high-dimensional input data set. The input data classes are divided into clusters. The unified process parameters were reduced to two dimensions, providing representations of the state of the process for each metal ingot identification code (metal ID) during the relevant production window. Because of the low dimensionality, it is possible to see the state of the relevant processes during the production of each metal ID.

Derived features were created using Fast Fourier Transform (FFT) to capture the necessary fourier components for the model to approximate the input signals. For feature extraction, FFT features of each signal were extracted. This allowed for finding a compressed representation of the time series signals. For the unified view, six FFT components with the largest magnitudes were used. For both HRM and HFM, the upper and lower bound of the body and tail phase of the signals were extracted. Figure 8 depicts an FFT extracted for rolling speed at HFM. To drive the predictive model, 395 features from both HRM and HFM were identified.

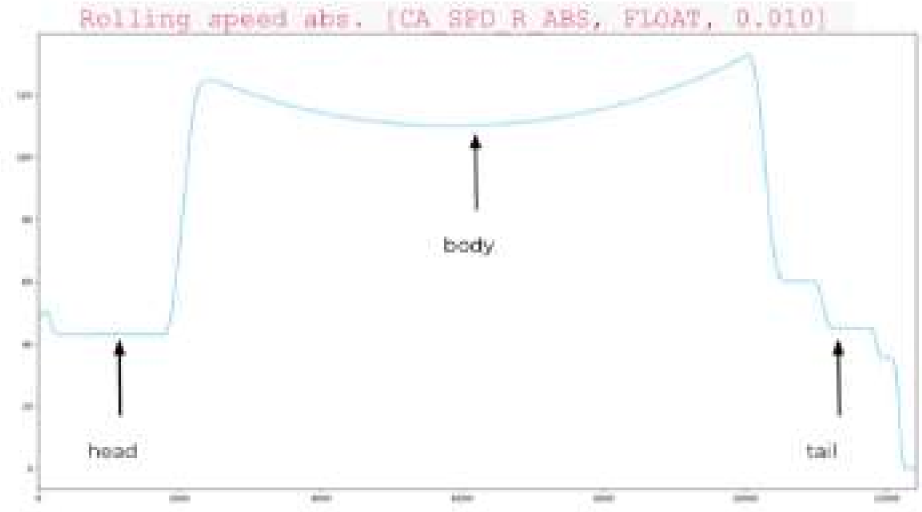

Figure 8: Rolling Speed FFT

The derived features were classified as controllable or non-controllable. Controllable features are those that the rolling mill operator can directly control. Non-controllable features are those directly controlled by the mill control system without involving the operator. Following the establishment of the initial feature list, further investigation was carried out using the random forest algorithm to refine the final list features for accurately predicting quality on both HRM and HFM. Figure 9 depicts the random forest model results for accurate quality prediction. A supervised learning approach was used to apply the random forest model. The model represents the process control problem as a binary class classification problem where the class of interest is the process status being in-control or out-of-control. For accuracy indicator, area under the curve (AUC) is used to evaluate various classifiers in the experiment. The result associated with the model's ability to accurately predict quality is an AUC of 0.84. The random forest predictive accuracy is slightly better compared to an artificial neural network model that was also used in comparison to random forest. The artificial neural network had an AUC of 0.81.

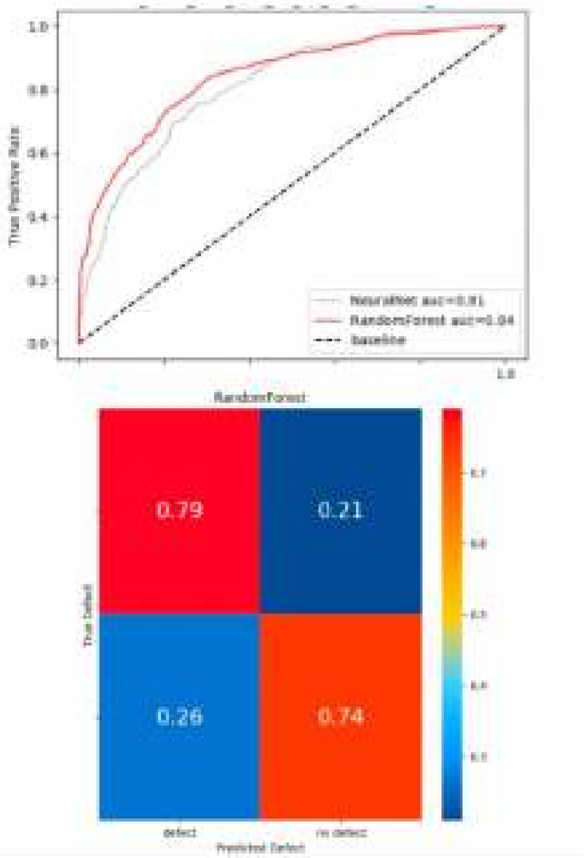

Figure 9: Random forest model for accurate quality prediction

Using the derived final list of features, a predictive machine learning model was created on Python using VAEs and the Keras algorithm to predict quality and determine prescriptions to correct process deviations. Time-series techniques were used in the modelling approach. The time-series data was stitched together into a unified view, making rolling pass performance easier to interpret. The experiment and modelling was limited to AA5182 alloy, 1620mm ingot width, 2.3mm gauge and only looking at surface defects of broken surface. The minimum metal IDs required to effectively train the model was 1000. The actual number of metal IDs used to train the model was 3107. Figure 10 presents the predictive model results in the latent space. The model results show areas of good quality and uplifted quality

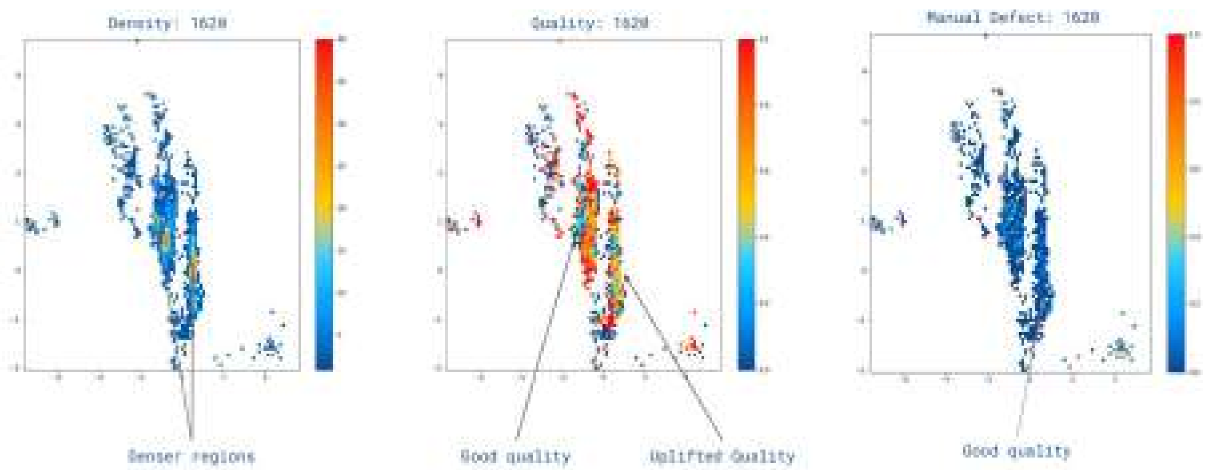

Figure 10: 1620mm ingot width areas of good quality and uplifted quality

After establishing the area of uplifted quality, it was important to establish a cluster or region of process stability that gives the best quality outcome. This entailed searching for a region in the model results' latent space with a low defect rate and relatively high density. This implies that there is a common set of process parameters for which good quality is achieved. By targeting the process parameters corresponding to this area, quality defect rate can be reduced to be lower than the global average. Process prescriptions were established for this region. Figure 11 shows the cluster of process stability that gives the best quality for 1620mm width and 2.3mm final rolled gauge. The cluster or region is depicted by a black polygon. The cluster was observed to show temporal stability with the region being visited consistently during production runs of 1620mm width metal IDs.

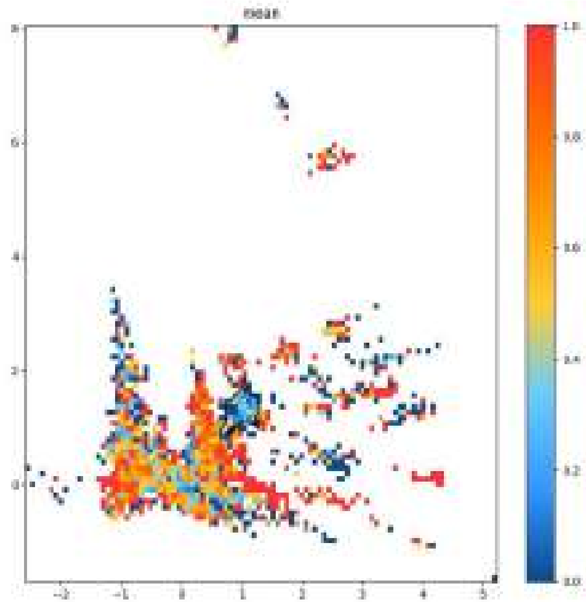

Figure 11: 1620mm ingot width cluster/region of process stability and uplifted quality

The predictive model prescriptions generated from the model were deployed for the 126 metal IDs that formed the experiment. Eleven batches of 126 metal IDs were rolled. The initial model prescriptions were generated from the predictive model and were pre-loaded for metal IDs of the first batch on the control system prior hot rolling of the batch commenced. A user interface solution was developed and designed using Lombard [18] design and architecture to provide real-time prescription ranking to HRM and HFM operators and process engineers. The user interface undertook the following steps everyone hour:

1. Pull all new raw values from data sources.
2. Upload all values into the data warehouse.
3. Build new unified view entries using the new raw values.
4. Generate ranking report on the most recent row of the unified view.
5. Serve the report to the HRM and HFM operators and process engineers.

5.2 Defect Rate Results

Using power analysis to determine the appropriate sample size for the experiment, the sample size was determined to be 81 metal IDs and 126 metals IDs were randomly experimented on. Predictive model defect rate result for surface defects of 1620mm wide ingot is 3,17 percent. The aforementioned 3,17 percent was realised against a 45 percent compliance rate to predictive model prescriptions. Compliance is the measure of proportion of controllable parameters that are within their prescribed limits. The combined (historical and during experiment) surface defect rate for univariate SPC is 3,74 percent. The historical defect rate data was collected over an 18-month period. The aforementioned equates to a 17 percent difference in defect rate between predictive process control and univariate SPC. Figure 13 depicts a box plot with a comparison of surface defect rates.

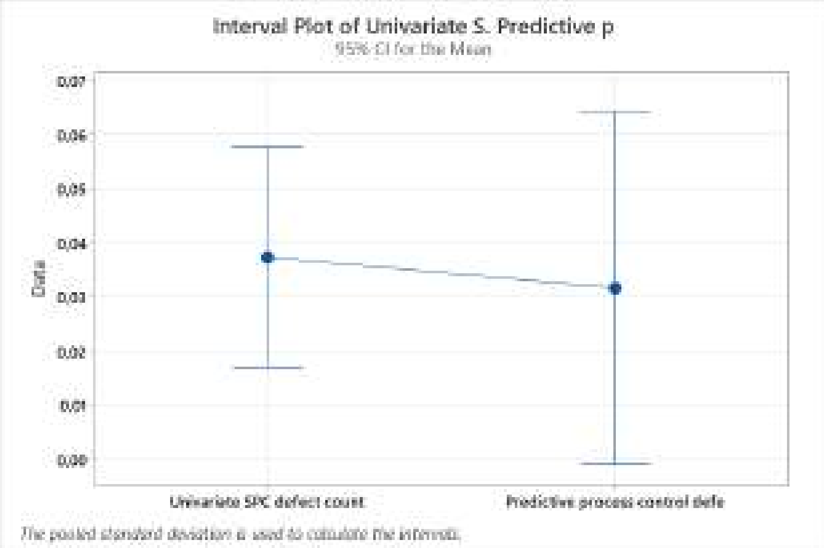

Figure 13: Surface defect rate comparison

5.3 Applicable Aspects at Different Management Levels

Prior to beginning the predictive process control experiment, roles and responsibilities were established. Each aspect of the predictive process control framework was assigned to a role. At senior management, the results show that development of the vision for predictive process control, accountability structures, continuous capability review and built, and driving accountability for predictive process control across all levels were key requirements and drivers for effective deployment of predictive process control. This finding is consistent with Antony's [12] MEST framework theories on management being essential to successful online quality control for SPC. Furthermore, the findings reveal that the technical aspects of the predictive process control framework reside at middle- and first-line management, with shop floor accountable for execution.

The aforementioned results for all rolling mill levels identify the two dimensions of the proposed predictive process control framework, namely process and people. This further validates this study's contribution in identifying organisational development and leadership gaps.

5.4 Factors that Greatly influence the outcome of predictive Process Control

As a learning outcome of the experiment of this study, the steps to successfully deploy RMPCC framework should follow the order below:

1. Run predictive process control awareness workshop with senior management.
2. Develop a vision for predictive process control at senior management.
3. Develop predictive process control project charter and get senior management signoff. Charter includes objective, metrics of success, risks and opportunities.
4. Develop change management plan.
5. Set-up effective structure to enable predictive process control.
6. Capability determination.
7. Identify resource(s) to close capability gap.
8. Run training and coaching sessions to close capability gap.
9. Data engineering (including ETL).
10. Identify and set-up data warehouse.

11. Feature engineering and signoff.
12. Predictive modelling.
13. Development of user-interface.
14. Run predictive process control.

All but one of the aforementioned steps of the deployment process (develop change management plan) required data science training to effectively execute predictive process control. Because of the training requirements, a capability assessment activity was required prior to step 1 to ensure key concepts that enable predictive process control were understood. The single most important factor influencing the outcome was predictive process control base capability. Another factor that influenced the experiment was senior and middle management buy-in to ensure effective structures were in place and that progress was tracked. The buy-in factor related to management physically participating in project activities to enable and guide the intervention.
To understand how predictive process control capability requirements can impact its success, a gap assessment was conducted prior conducting the experiment. The approach towards the gap assessment applied skills requirements comparison. The skill requirements are divided into two categories: process control and rolling knowledge. The following steps were taken in the gap assessment process:

1. Standardise Process Control knowledge requirements for univariate SPC and predictive process control. The standard is based on literature review from chapter 2 of this study.
2. Standardise rolling knowledge requirements based on aggregated hot rolling skills matrix from Company X.
3. Compare Company X hot rolling job profile competency requirements against univariate SPC and predictive process control standard knowledge requirements.

The aggregated comparison results of the baseline capability assessment show a 0 percent gap for univariate SPC and a 25.71 percent gap for predictive process control. This result supports Amruthnath's [1] contention that the most difficult challenge in deploying data science solutions in manufacturing applications is expertise in these techniques and their application in a real-world setting.

5.5 Hypotheses Testing

H_0: There is no significant difference in the defect rate of traditional univariate SPC and predictive process control when defect rates of the two approaches are compared.

H_a: There is significant difference in the defect rate of traditional univariate SPC and predictive process control when defect rates of the two approaches are compared.

The two-samples proportion test was conducted with descriptive statistics that formed the basis of the test outlined in Table 3. The normal approximation may be inaccurate for small samples. Table 4 outline test methods and level of significance that guides correlation.

Table 3: Descriptive Statistics

Descriptive Statistics			
Sample	**N**	**Event**	**Sample p**
Univariate SPC defect count	321	12	0,037383
Predictive process control defect count	126	4	0,031746

Table 4: Test for significance

Method	Z-Value	P-Value
Normal approximation	0,30	0,765
Fisher's exact		1,000

At the 5 percent level of significance, H_0 is accepted since the p-value is higher than 0.05 and therefore, the conclusion is that defect rates of univariate SPC and predictive process control are not significantly different.

6 CONCLUSION

In this study, a rolling mill predictive process control framework for online quality control was proposed and validated in a hot rolling process. The results of the study point out the following themes:

1. Data engineering is an important first step in deploying a predictive process control model. ETL was found to be the most complex step in the data engineering stage. This finding corresponds to Buvaneshwaran's [20] eight steps for developing a machine learning model. According to Buvaneshwaran [20], once a problem or objective is defined and understood, the first and foundational step in a machine learning process is data engineering.
2. Feature engineering is an important second stage in deploying a predictive process control model.
3. At a compliance rate of 45 percent, the metal surface defect rate of predictive process control is marginally better by 17 percent when compared to univariate SPC defect rate. These initial positive results are consistent with positive results reported for an artificial neural network case study by Cho at POSCO [15].
4. Key predictive process control aspects for all the roles of the rolling plant or organisation are different across the levels. Senior management has a special role in the initial stages of deploying the predictive process control framework. This role includes the responsibilities for creating the vision for predictive process control, creating an environment for the development of base capability and creating an enabling environment for the successful deployment of predictive process control. Middle- and first-line management is responsible for the technical aspects of predictive process control while the shop floor is responsible for execution and feedback loop. This finding is consistent with Antony's [12] MEST framework theories on management being essential to successful online quality control for SPC, which are summarized in chapter 2 of this study.
5. The most important factor of the proposed predictive process control framework is base capability, followed by leadership (senior and middle management) commitment. The modelling steps follow once the two aforementioned factors have been executed correctly. This result supports Amruthnath's [1] contention that the most difficult challenge in deploying data science solutions in manufacturing applications is expertise in these techniques and their application in a real-world setting.

The aforementioned results cannot be generalised for all manufacturing processes but only for metal hot rolling processes. Because the study was limited to one case, there is an opportunity to conduct further studies at other hot rolling mills. Furthermore, future research can be conducted to determine the defect rate performance of RMPCC framework at various compliance rates, replicating the same approach across multiple defect types rather than just surface defects.

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BARRIERS TO BIM IN FACILITIES MANAGEMENT AT UNIVERSITIES

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ABSTRACT

Building Information Modelling (BIM) is a valuable tool that can greatly enhance facilities management at universities with extensive asset portfolios. By utilizing BIM for service optimization, facilities management teams can effectively serve clients and optimize utilization, planning, and development. However, implementing BIM comes with its own set of barriers. This paper examines practical challenges such as installation, historical documentation, policy and standards application, the human element, and financial requirements. Within the context of facilities management, the paper discusses the practical challenges and opportunities associated with these barriers and presents potential solutions to overcome them, ultimately improving information management for the entire department.

Keywords: Facilities Management, Building Information Management, BIM, Operational Efficiency, Practical Application, University, Human Factor, Information Management

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1 INTRODUCTION:

Building Information Modelling (BIM) has transformed the Architecture, Engineering, Construction, and Operations (AECO) industry, yielding improvements in project delivery, cost-efficiency, and sustainability [1]–[5]. BIM is a shared three-dimensional digital representation of built asset that facilitates design, construction, and operation processes and decision-making. BIM has significant implications for Facility Managers (FM) [6]–[8]. BIM integrates architectural, structural, mechanical, and electrical data into a single model, creating a centralized and intelligent database for FM teams. This integration allows FM to streamline operations or processes, improve decision-making, and enhance collaboration among diverse stakeholders. With BIM's comprehensive digital visualization of built assets, FM professionals can more effectively manage buildings, infrastructure, maintenance, repairs, renovations, and new builds [7]–[10].

While BIM holds immense potential for FM, it is crucial to acknowledge the barriers and challenges associated with its implementation in FM specifically. Factors include initial investment costs, limited expertise and training, resistance to change within FM organizations, and interoperability issues between the large variety of different FM datasets [8], [9], [11]. Recognizing and proactively addressing these barriers is crucial for the successful adoption of BIM in FM. The creation and management of BIM models for FM play a pivotal role in the effective and sustainable implementation of BIM practices in FM [4]. This is especially the case in organizations that are digitally immature, or in developing countries where digitization of the built environment and FM is still in its infancy [11]–[13].

This paper delves into the challenges and opportunities associated with leveraging BIM effectively in FM, with a specific focus on a large university setting in South Africa. By providing valuable insights and strategies to overcome challenges, the aim of this paper is to assist other university organizations in developing countries in optimizing their FM practices and maximizing the benefits of BIM for FM.

2 LITERATURE REVIEW

2.1 Understanding the role of BIM in facilities management

BIM practices have evolved to integrate a variety of datasets and facilitate coordination between large and diverse teams in the built environment. Such BIM teams often operate collaboratively in real-time cloud platforms [2]. BIM model development and project management processes are bound to the ISO-19650 BIM and digital information delivery standards [3]. The ISO-19650 standards consist of five parts, with the initial segment already embraced by the South African National Standards (SANS). This SANS standard is poised to become a mandatory implementation requirement in the foreseeable future. As BIM continues to evolve, new products, plugins, third-party applications, and concepts create a variety of new and complex datasets [1], [2], [9], [10]. This includes aligning project procurement or cost dimensions [11], building energy or performance tracking [12], [13], or drawing on environmental and social indicators [2]. Therefore, due to its data-rich complexity, BIM will likely become a pillar for future scientific research [2].

2.2 Integration of BIM in facilities management work stages

The Royal Institute of British Architects (RIBA) has defined a set of work stages that outline the AECO processes, specifically as it relates to BIM (shown in Figure 1).

Figure 1: RIBA work Stage 6 and Stage 7 relates to BIM in FM (Authors)

Within these work stages, the RIBA Stage 6 and Stage 7 represents *Operations* and *Use* (Facility Management) activities. Ultimately, mature BIM practices aim to encompass the full lifecycle of a built asset, from RIBA Stage 0 (*Concept*), to Stage 7 (*Use*) and ultimately, Stage 8 (*Demolition* or *Deconstruction*, not shown here).

BIM offers significant benefits to facility managers in their day-to-day operations by providing 3D visualization and comprehensive data. Effective management of BIM-FM models is crucial for successful implementation [9], [24]. By utilizing BIM models and data effectively, FM teams gain access to up-to-date information about building components, systems, and maintenance history. This information supports operational and strategic decision-making, streamlines maintenance activities, and optimizes facility performance. BIM enables FM teams to visualize and simulate different scenarios, facilitating efficient space management, energy analysis, and cost optimization. Overall, BIM enhances the ability of FM teams to effectively operate, maintain, and improve building performance throughout its lifecycle.

Real-time BIM models, or digital twins for buildings, may also allow FM teams to optimize energy usage, proactively identify maintenance needs, and ensure regulatory compliance [9], [24]. By integrating *Internet of Things* (IoT) sensors and systems, real-time BIM could enable just-in-time monitoring and predictive maintenance practices, ultimately improving efficiency, reducing costs, improving sustainability, and enhancing the overall performance of facilities and asset portfolios.

3 CHALLENGES IN BIM FOR FM

3.1 Requirements for digital talent, roles, & skills

As BIM technologies and technical solutions mature, so too have BIM modelling and management roles [25]–[27]. To ensure the success, BIM projects require specific new digital management practices. As such, these new roles include digital transformation agents or champions, BIM modelers, coordinators, and managers [19],[26]–[28]. However, being a BIM agent in these roles requires more than just curiosity or technical capability in BIM projects [25], [26]. These roles demand a well-developed set of both “hard” and “soft” digital talents.

Digital talent encompasses a balanced combination of "hard" and "soft" digital skills [21], [28]–[32]. In the 21st century and the era of the Fourth Industrial Revolution (4IR), these digital skills have become essential. "Hard" digital skills encompass proficiencies in data analytics, digital modelling, cloud computing, cybersecurity, artificial intelligence, machine learning, and programming. On the other hand, "soft" digital skills involve operating effectively in ambiguous situations, possessing a “digital-first” mindset, being a digital innovator, leveraging digital technologies for rapid learning, prioritizing customer-centricity, and demonstrating digital leadership. This means that such digital talent requires strong communication and collaboration skills [30], [33], [34]. Mastering this digital talent is crucial for individuals operating in BIM-related roles and aligning with the demands of the modern digital landscape.

3.2 Barriers in the development of digital talent, roles, & skills

The current landscape of BIM training and education tends to place excessive emphasis on the development of "hard" digital skills, such as technical design or operations of BIM software [1], [27], [28]. Conversely, there is a lack of attention on nurturing "soft" digital skills and human-centered BIM management activities [27], [28], [30], [35]. This imbalance in skill development has led to unforeseen consequences, particularly in industries that have been slow to adapt to digitization, such as the AECO and FM sectors.

Within these industries, tensions have arisen between BIM and non-BIM actors [27]. BIM actors perceive their role as coordinators and drivers of change on projects, while non-BIM actors often perceive BIM professionals as merely fulfilling technical roles. This disparity in perception is particularly evident in conventional FM environment, where the creation and maintenance of digital assets and information management are not traditionally part of the core training and day-to-day responsibilities of a traditional facilities manager.

To address the imbalance of the digital skills situation in FM effectively, it is important to acknowledge that an intentional, comprehensive, and holistic approach is necessary. This approach requires the focused development of the digital transformation journey within FM organizations, and both the “hard” and “soft” digital skillsets of the FM talent pool simultaneously. While technical expertise is important, recognizing the significance of "soft" digital skills (such as effective communication, collaboration, and change management) is vital for successful BIM implementation in FM.

Understanding of the present state of these digital skill sets within FM organizations is vital for successfully bridging the gap between them. By doing so, FM organizations can foster improved collaboration, develop sustainable digital transformation practices, and utilize BIM technology effectively. This leads to positive change, enhanced project outcomes, and increased overall efficiency. Embracing a holistic digital development approach allows FM organizations to harness the full potential of BIM, adapt to industry demands, and establish themselves as industry leaders.

3.3 BIM maintenance and digital asset quality control

Multiple issues arise when BIM-FM models are not properly updated and managed, leading to errors and loss of credibility among FM team members [7], [9]. To overcome these challenges, a robust digital management process for BIM-FM models, such as ISO-19650, is essential. This process includes systematic model development, confirmation, modification, and timely delivery to facility owners for FM usage. Updating and modifying BIM-FM models according to process requirements is a critical aspect of model management. Neglecting this step leads to the utilization of outdated or inaccurate model versions, hampering any successful BIM implementation.

Practical problems in FM-based BIM implementation include infrequent updates, lack of necessary non-geometrical information, inadequate staff for FM-based BIM management tasks, lack of facility information linked with BIM-FM models, and a lack of suitable digital platforms for BIM-FM model management [7], [9], [24]. As such it is important to not only articulate BIM management processes, but also articulate new roles in FM for BIM execution such as BIM modelling, management, operations, and BIM maintenance.

3.4 Open or closed BIM: information and data calibration challenges

BIM projects commonly encounter technical challenges due to the extensive range of software variations and variations in information quality among diverse team members. FM is especially vulnerable to issues arising from information and data format disparities, which directly affect data interoperability. This challenge becomes particularly complex when the data and software systems are locked-in with pre-established vendors, leading to “Closed-BIM” environments.

“Closed-BIM” refers to the confinement of BIM data and models within proprietary software or restricted formats, limiting accessibility and compatibility with other systems [15], [36], [37]. This hinders seamless data exchange and collaboration between stakeholders using different tools, limiting the potential benefits of BIM in FM processes. The centralized nature of building data repositories creates information silos, further hindering access and effective use of data the among diverse FM stakeholders.

Furthermore, the majority of BIM adoption has been typically limited to project-specific data, neglecting the implementation of BIM practices in the operation and maintenance phase. This poses a significant challenge for large asset owners like universities, as effectively managing diverse assets and projects necessitates the integration of data and information from various stakeholders. An comprehensive digital strategy that expands the scope of BIM beyond project design and construction phases becomes indispensable for universities. This extension is crucial to skilfully manage vast university asset portfolios and effectively navigate the intricacies stemming from project variations and built asset diversity over extended periods of time. A “Closed-BIM” approach may be a significant limitation for FM of large asset owners, such as universities.

In contrast, “Open-BIM” promotes seamless collaboration and data integration across project stages and domains, facilitated by the open standard exchange format, Industry Foundation Classes (IFC). Through OpenBIM® and buildingSmart initiatives [37], [38], significant advances have been made in solving such data interoperability issues and opening the BIM data and information exchanges for more general and broader use.

In conclusion, the advancement of BIM in FM brings about transformative changes in work processes and project management roles. However, the most critical challenge lies not in the availability of BIM technologies, but in the scarcity of human digital talent capable of effectively coordinate and collaborate in an open and efficient manner. To address these coordination issues, the development of BIM management standards has been crucial. Such BIM standards, including *BIM Execution Plans*, the *ISO-19650 standard*, and the *RIBA BIM Workflows* prioritize effective communication and collaboration among diverse digital teams. By adhering to these data and management standards and emphasizing the concurrent development of both “hard” and “soft” digital skills, FM organizations can ensure the successful execution of BIM projects, with the aim of facilitating seamless handover practices. Within the given context, this paper explores the specific case study of the University of Pretoria in South Africa, with a focus on the application and impact of BIM in FM in university settings.

4 ENHANCING FACILITIES MANAGEMENT THROUGH BIM: A CASE STUDY OF THE UNIVERSITY OF PRETORIA

The Department of FM at the University of Pretoria plays a critical role in the planning, building, maintenance and operations of 729 buildings on 1,165 hectares of land across seven campuses. The portfolio consists of 1 043 655m^2 gross floor area of various types of buildings, laboratories, lecture halls, residences, offices, and sporting facilities etc. Of these assets, 40% of buildings are heritage protected. In addition to the building portfolio, various bulk infrastructure facilities need to be monitored. This includes over 80 standby generators and various water tanks, boreholes and fire systems. There are also facilities owned by others but managed by the university. These include, for example, clinical training platforms at Kalafong and *Hans Hoheisen Wildlife Research Centre* at the Kruger Park Orpen Gate. All these facilities support the teaching and learning objectives of the university, and the management thereof has a direct bearing on the success of the institution.

With the aim of ensuring efficient planning, construction, operations and maintenance of these properties, the Facilities Management department relies on accurate and up-to-date information. However, the challenges associated with managing a vast property portfolio are evident, including the need for effective data management, streamlined processes, and reliable collaboration among various stakeholders. BIM was identified as a tool that can assist with managing the property portfolio for FM.

In this case study, the challenges facing the implementation of (BIM) in the context of the University of Pretoria FM Department was explored.

Understanding the effort required for the implementation of BIM as one true source of information requires an understanding of the unique and specific barriers to implementation at this university. Planning and strategizing for these barriers in advance should ensure a smoother roll out of the project. The possible challenges to BIM adoption are grouped into three categories: *information-related barriers*, *technology-related barriers*, and *organizational barriers* [39],[40].

BARRIERS TO BIM IN FACILITIES MANAGEMENT AT THE UNIVERSITY OF PRETORIA

4.1 Information-related barriers

4.1.1 Data Integration and Interoperability

Effective management of FM relies on diverse sources of information including building components, systems, equipment, maintenance requirements, contracts, bulk infrastructure, and drawings. Integrating this information into a BIM model can be complex and time-consuming. Inconsistent data formats, fragmented systems, and limited interoperability between BIM software and FM tools further hinder seamless data exchange, which all pose a significant barrier to the widespread adoption of BIM in FM. This practically occurs where there are data silos within the FM Department. Currently, there is a lack of an integrated information nor information platform that could manage information distributed in different databases and support various activities. Figure 2 below illustrates the siloed information of the FM Department, to which FM Department the systems belong, and in what format information is available.

Figure 2: Fragmented systems which have a bearing on Facilities Management operations at the University of Pretoria

Impact of Fragmentation

At this FM Department, accurate information not readily available and dated. It is a tedious process to capture and update any information. Information siloes are resulting in critical information losses, meaningless duplication of the same information, and burden to obtain additional resources to simply get the clarity in information again. Thus, data is currently available, but is inefficient and fragmented.

Resolution to Fragmentation

It is expected that BIM will allow easy access and management of critical FM information. A BIM platform will centralise the information and standardise formats that will lead to more efficiency. Thus, BIM will assist with more effective decision-making, coordination, and collaboration.

Outcome of Resolution

To demonstrate BIM implementation, the FM Department decided to test the BIM implementation concept on a Pilot, outlined below. This Pilot will follow the ISO-19650 standard. The first *information need* is to define the scope of the Pilot in relation to building, infrastructure, and organizational information. Next, it is important to determine what information must be directly and/or indirectly integrated within the available technologies in the BIM-enabled environment. Thereafter, the FM team must design a detailed data capturing and governance framework, where they distinguish what information is critical, important, and non-essential, where data is currently located, and how data will be managed throughout its lifecycle. This will be done for each division in the Department of FM. The *information needs* will be captured on a shared BIM platform (command data environment) or an ecosystem of products that can align with the broader digital transformation of the FM Department. Using BIM for FM service optimisation can greatly assist a FM team to serve clients, optimise utilisation, planning, and development like AECO industries, but also, streamline the broader the digital transformation activities from within the department.

Example of Resolution

The FM Department aims to test and benchmark the improved data sharing and utilization practices against lower utilities accounts, reduction of impacts on the natural environment, and the realisation of smart asset management initiatives in select buildings. With smart asset management in particular, BIM should reduce the time for updating databases in the operations and maintenance phase by 98% [41]. Furthermore, visual representation of the property portfolio for FM can greatly simplify the communications, contracts, property account management, and tenant tracking issues, which are currently locked in isolation in several excel-based storage tracking documents.

4.1.2 Data management platform throughout the building lifecycle

Building management in any portfolio has a vast amount of data/information over the lifecycle of the asset. This includes information from inception, construction, occupation, management and beyond. The number of stakeholders involved in this process (from new build to occupation) generates an overload of information which is often fragmented, miscommunicated, or lost between stakeholders and across time. BIM for FM faces the same challenge in that the application of BIM could be quite broad. Even within a BIM strategy, different BIM models are created for different purposes. For example, a construction BIM model, or a maintenance and operation BIM model (with services and space utilization properties), might look very different from each other.

A key challenge is to determine what *information needs* should be captured, exchanged, used, and managed at what phases of the buildings' lifecycle. Each lifecycle stage from design, construction, operations, and maintenance and with refurbishment/renewal projects, is unique. Traditional FM approaches this problem in a linear way, where one phase close out to the next, without consideration for full lifecycle activities. However, a BIM FM team approaches this challenge with a feedback loop approach, where the full lifecycle of an asset is considered holistically. This is indicated in figure (3).

Impact of a non-BIM Approach

Practically the need to find information between several stakeholders, locations, and physical files wastes considerable time. This is time that could otherwise be used for a multitude of aspects within the FM sphere. This coordination waste causes additional strain and fatigue on the personnel within the department. Working on decentralised files on any project or day to day operation gives the high possibility that each person works on its own version requiring manual integration. Even just sending files between the relevant parties wastes unnecessary time when working from a centralized source is far more efficient.

Resolution for a BIM Approach

With BIM as the tool to manage FM information, a centralised *common data environment* (CDE) platform is critical. This CDE environment must be capable of integrating multiple datasets from multiple authors and sources over time. The CDE will decreases the time required to find data as it will be available to all from this central point. CDE's will become a legislative requirement and the ISO 19650 will be a guide to successful implementation for FM teams.

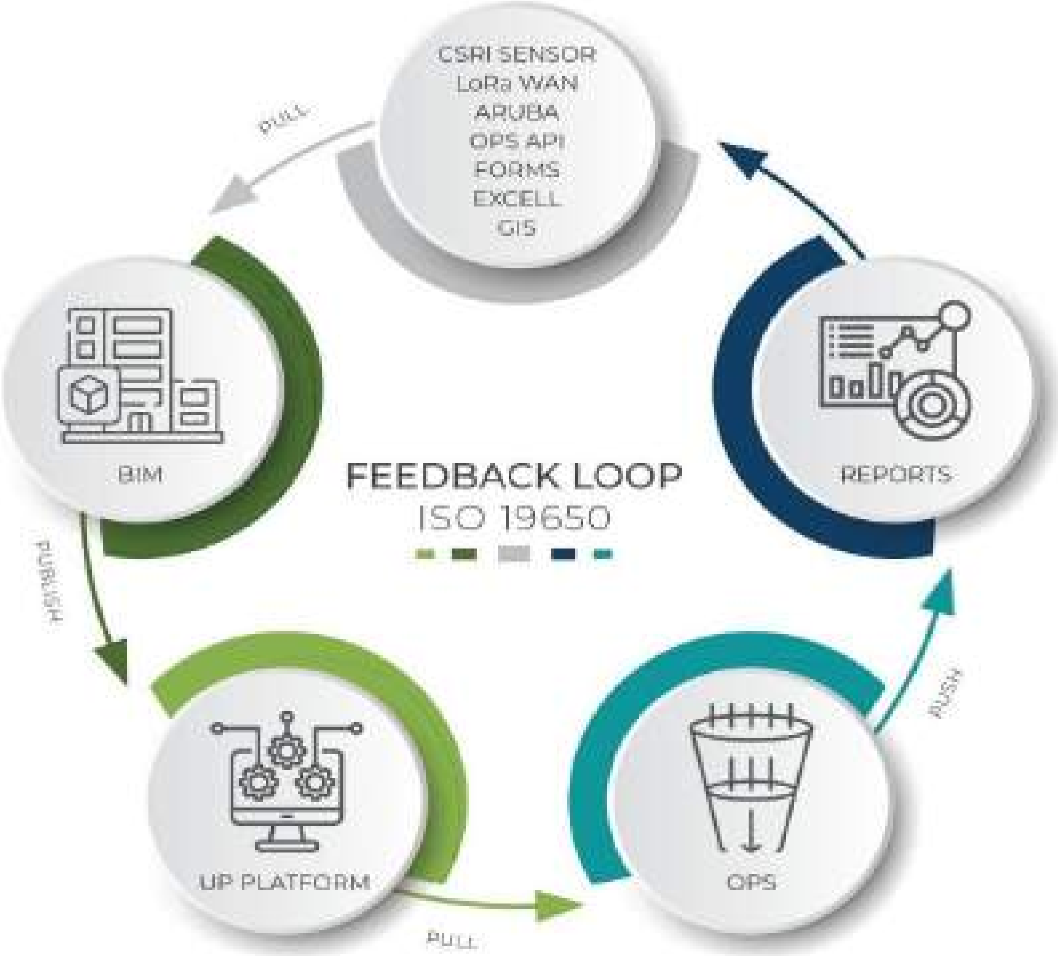

Figure 3: Diagram of proposed BIM execution plan governed by ISO 19650 standards for the University of Pretoria's Department of Facilities Management teams.

Outcome for a BIM Approach in FM

The successful implementation of BIM within FM requires the formulation of a BIM execution plan. This will require intensive workshops to map all data sources, information needs between the owners and stakeholders, and the integration requirements for contracts and procurement.

4.2 Technical-related barriers

4.2.1 Cost and Resource Constraints

Adopting BIM for FM may require substantial investments in technology, software licenses, hardware, and mostly, training. Small-to-medium-sized FM organizations in particular, may face financial constraints that impede their ability to fully embrace BIM. Additionally, the availability of adequate computing resources and IT infrastructure to support BIM implementation can be a limiting factor for some organizations, further exacerbating the cost and resource barriers.

At the start of the FM digitisation journey, a quotation was requested from an industry leader to configure a smart platform for a particular academic building, add sensors and create a platform for live building monitoring. For this service, 1 million ZAR (South African Rand) was quoted for the only one building with an additional ZAR 17 000.00 monthly subscription. This cost would obviously decrease as the project was rolled out across the portfolio because of a presumed economy of scale. However, across a large asset portfolio of over 700 buildings alone, this economy scale is practically infeasible. The quotation was not accepted, and it was decided to prepare a cost estimate for in-house development instead. This naturally results in staff upskilling, hardware, sensor, and software acquisitions. The decision to turn inward advances something more important: even if the “out-of-the-box” solution could be “faster,” it would exclude upskilling of both the “hard” and “soft” digital skill development of current staff.

Through research and collaboration with various other internal departments the initiation cost was reduced by ZAR 192 400.00. It was also decided to test the various platforms before purchasing them, thus also reducing the operational expenses. The estimates will remain a baseline and will be updated accordingly. The only expenditure to date has been a gateway and antenna (hardware) ZAR 4,745.00.

Resolution for BIM Cost Constraints

In order to demonstrate that adopting BIM is cost effective, the cost plans will be updated, monitored, and benchmarked with commercial property developers who have adopted BIM already. Other factors, will also be benchmarked, on of these factors is *inefficient maintenance planning and execution*, which often leads to cost effects captured as higher energy consumption, increased repair and replacement costs, and a burden and cost shocks in the lack of proactive maintenance, frequent breakdowns and disruptions, etc. It is presumed that BIM will be measured against these benchmarks for a fair comparison in return-on-investment.

Outcome of BIM Cost Constraints

It is expected that tracking BIM investment costs by benchmarking against industry leaders, or commercial property developers, will greatly advance the implementation of BIM in FM for universities. For example, such benchmarks are reporting cost savings on existing property portfolios from operational cost reductions of ZAR 30/m^2 to ZAR 22/m^{2,} to as much as ZAR 12/m^2 saving (over 50% savings).

4.2.2 “Hard” and “Soft” re-skilling for BIM

The next aspect is for implementing BIM in FM is improved skills and training within the workforce. This includes both “hard” and “soft” skills in BIM methodologies, technologies, and FM practices. However, the FM industry often faces a shortage of trained professionals who deeply understand BIM technology and its application in FM. Limited access to comprehensive training programs, inadequate knowledge transfer, and the need for a multidisciplinary skill set present significant barriers to effectively utilizing BIM in FM operations. This re-skilling requires sufficient time allocation to both upskill and cross-train relevant internal personal to be familiar with the BIM practices. It will also require patience and time, as it is a learning curve for all to become proficient in the new roles, software, and workflows required for BIM implementation. The technical implementation and integration require new sets of skills, management roles, as well as the appropriate IT hardware resources for each team member illustrated in Figure 4 below.

Figure 4: Current Professional Services Office organigram (Authors).

There is a current skills gap and job description (role) in built environment professional services in FM in South Africa. Temporarily, need for a BIM Manager was identified and the vacant position for “architectural technologist” advertised fill the gap. Another architectural assistant position will be assigned to the BIM project as supporting staff. Furthermore, all other staff will be upskilled to support the adoption of the BIM initiatives across the department. This will require that management recognises a reduced workload for the staff in support of the digitization initiatives learning. It is important to emphasis patience and empathy for this upskilling process.

Impact of re-skilling for BIM

To motivate staff learning, it will be critical to show the reduction in manual processing required for several functions across the Department of FM. This can be measured against adoption of automation practice or the reduction of the load on the human resources (time and effort). For example, meter readings processing monthly currently takes three days of manual processing. After automation, it has been reduced to around 2 hours, including verification. As such, the BIM data manager (architectural assistant) can switch from value-less and time-consuming drawing or meter capturing tasks, to other value-added activities instead.

Resolution of re-skilling for BIM

It will be important to benchmark against other university and industry institutions to determine which skills are required in-house and which skills can be outsourced (contracted) to expedite implementation.

Outcome of re-skilling for BIM

Likewise, it is important to benchmark technical skills required to implement BIM against other university and industry institutions. The university's FM Department has several organisations that aim to assist in fulfilment of individual and institutional goals. This includes the South African has the Higher Education Facilities Management Association (HEFMA), and the United Kingdom Association of University Directors of Estates (AUDE). Benchmarking against these institutions will give the opportunity to learn and determine the relevant skills that are required and upskill the current staff complement.

4.2.3 Platform consideration (Open or Closed BIM)

The professional service office in the department already utilizes BIM software for the professional design tasks. As discussed above, a Closed-BIM approach may be a significant limitation for FM of large asset owners, but the support of the Closed BIM system is enticing for other reasons. Closed-BIM practitioners typically have the necessary technical maturity to be effective in establishing the BIM platforms in a protected and secure way.

Impact of Open or Closed-BIM

The temptation is there to purchase multiple Closed-BIM software packages and to test and practice the larger BIM transformation roll out. Once a decision has been made, however, it will be very costly to switch to other BIM platforms as it is estimated to take quite a lot of time to establish the reliable and fixed standards and processes. As such, it may be helpful to explore Open BIM as a process, rather committing to a series of Closed-BIM products.

Resolution of Open or Closed-BIM

To follow the University's procurement process and to procure the correct software is a challenge. There is uncertainty as to what the BIM platform must be able to do, and how it will tie into other systems. Therefore, it was decided to put various software to the test and do comparisons between Open and Closed-BIM. Also, as an academic institution we have the privilege to experiment with various BIM and GIS platforms. Various consulting and commercial property developers were consulted, and a comparison must be drafted for review. The resolution is thus to hold off on purchasing any software for a year and experiment with educational versions and free versions and document the process so that a technical evaluation report can be submitted to procurement when the time comes.

Outcome of Open or Closed-BIM

The Pilot will test both Open and Closed-BIM software. In this way we will know what the limitations and return on investment of each system will be.

4.3 Organisation-related barriers

4.3.1 Organisational Culture, resistance to change, and "soft" digital skills

The successful implementation of BIM in FM necessitates a radical cultural shift within organizations. BIM for FM requires embracing new processes, technologies, and collaborative workflows. Resistance to change and a lack of awareness about the potential benefits of BIM can impede BIM adoption in FM. Siloed organizational structures, hierarchical decision-making processes, and a lack of cross-functional collaboration can hinder the integration of BIM into FM practices.

The day-to-day operation and crisis management, which is common in an FM environment, is not conducive to investigate or implement new technologies. This is especially true in the South African context with unpredictable load shedding (energy blackouts) as a norm. The crisis mode does not allow for the mind shift towards digital change to happen easily. Additionally, the generational gap within the current staff ensures that there are many staff members are less technologically or digitally inclined. This requires much more time spent on workshops, meetings, and training to successfully implement BIM and digital transformation.

The size of such an FM organization, in addition to being a parastatal of government, has a large impact on the implementation process of any new system. This is especially true with systems that require a financial commitment and re-skilling. The bureaucratic process and procurement processes, while essential, can significantly delay implementation of any new system, such as digital transformation or BIM.

Impact of Resistance to Change

As a result, FM management does not take responsibility for the use/implementation of new systems and processes, especially digital ones. By lack of understanding and resistance to change, technical debt and time required for adoption is extended or aborted.

Resolution of Resistance to Change

At the FM Department, we are resolving to take the executive suite on a BIM journey. We are placing extra effort presenting key milestones and show the benefit of implementation in stages. We have hope that with this incremental approach, we can produce slow and regular updates, which will drive trust and digital change in the larger FM Department.

Outcome Digital Transformation Journey through BIM

As such, we will drive continuous communication to ensure collective ownership of the implementation of the BIM process in incremental ways, as illustrated by Figure 5 below.

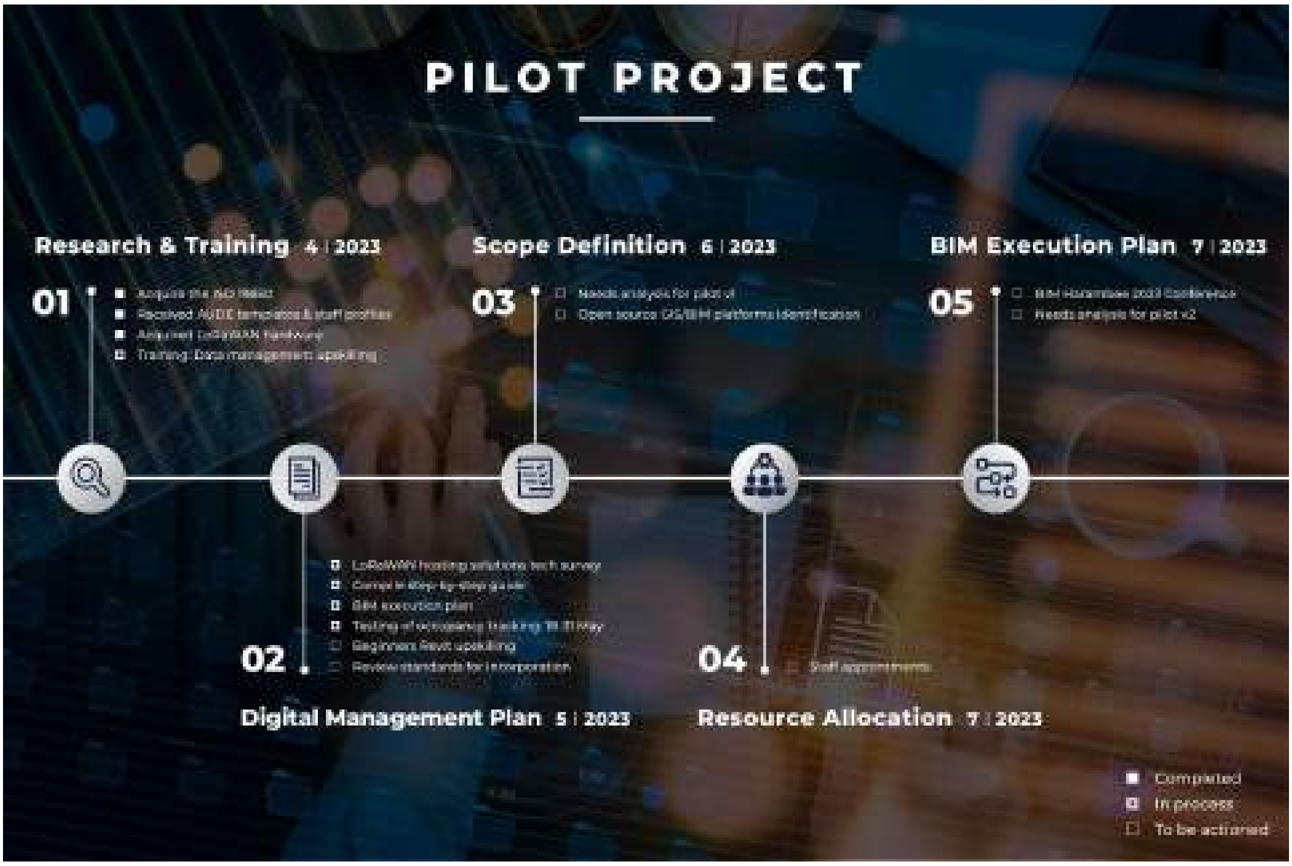

Figure 5: Pilot Implementation report with progress circulated monthly to management.

4.3.2 Slow and incremental implementation of BIM in full lifecycle management

The possible reasons for resistance to change and digital transformation in FM in South African universities can be the lack of awareness about BIM overall. This includes the misunderstanding of the benefits of BIM in the operational and management of assets, the lack of demonstrable projects in the real world of BIM-enabled asset management locally, and the lack of a digital framework that fits a customised asset management platform.

Impact of lack of BIM adoption in FM Department

BIM facilitates effective lifecycle management of facilities, allowing FM teams to plan for maintenance, renovations, and future expansions. Without BIM, the FM Department is already struggling to maintain an accurate and up-to-date understanding of the building's components, systems, and history. As such, the department is over-burdened regardless. This is leading to challenges in long-term planning, budgeting, and decision-making for renovations and capital projects, staff fatigue, and many other issues. This is becoming more important as financial resources are being put under severe pressure because of the current economic climate in South Africa.

Resolution for BIM adoption in FM Department

A real-world case study is required, by means of a Pilot study, that can give insight and trust BIM processes in facility performance. This Pilot can identify inefficiencies into the facility performance teams, which in turn will assist in optimal resource allocation and make informed decisions for enhancing facility performance.

Outcome BIM adoption in FM Department

The Pilot outcome will determine key areas to demonstrate BIM capabilities for large-scale adoption. This Pilot will also give the opportunity to work with several different stakeholders and address more detailed *information needs* than initially conceived.

As such, a road map for the Pilot was prepared and comprises of three phases over three years. The Pilot Preparation Phase will take approximately five months, and comprises of research and training, data management plan, scope definition, resource allocation and a BIM execution plan.

The Pilot Implementation Phase is expected to take 23 months, and will include database integration, infrastructure integration, IoT integration, Geo BIM, Landscape integration, build dashboards, data verification, data analysis, documentation integration and presentation. Thereafter, five more months are needed post Pilot to formalise reporting, summarise and review the findings to compile requirements for roll-out, stipulate process flows and procure the necessary software.

4.3.3 Nature of the organisation – lack of collaboration and communication

The various sources of data are fragmented, siloed and located in the multiple divisions in the department of facilities management. Each division has its own focus and need for processing the data and to use it for different purposes. None of this information need is coordinated. Currently, building plans, utility usage, and venue usage is not integrated and therefore oversight is difficult and costly. Building information is not live, nor digital, and manual updates of building and services information means that information is inaccurate, costly, and difficult to obtain or service.

Impact of collaboration and communication alignment

BIM fosters improved collaboration and communication among FM teams, architects, contractors, and other stakeholders. The absence of BIM can lead to fragmented communication channels, manual processes, and limited visibility into project information over time. This can result in miscommunication, delays, errors, and rework, affecting project timelines, overall operational efficiency, cost and fatigue.

Resolution for collaboration and communication alignment

The need to establish a BIM task team (Business Intelligence Unit) in the business optimisation leg of the FM Department can cut across the various divisions and assist with project implementation, as indicated in Figure 6. This mandate will enable the FM Department to digitise and integrating the asset management portfolio and implement the following key milestone activities: 1) BIM and data consolidation; 2) document governance structures and process flows; 3) ensure proper information workflows through digital governance and privacy protection measures; 4) configure appropriate application programming interfaces, including implement IoT, dashboarding, general analytics, reporting on the Universities property portfolio.

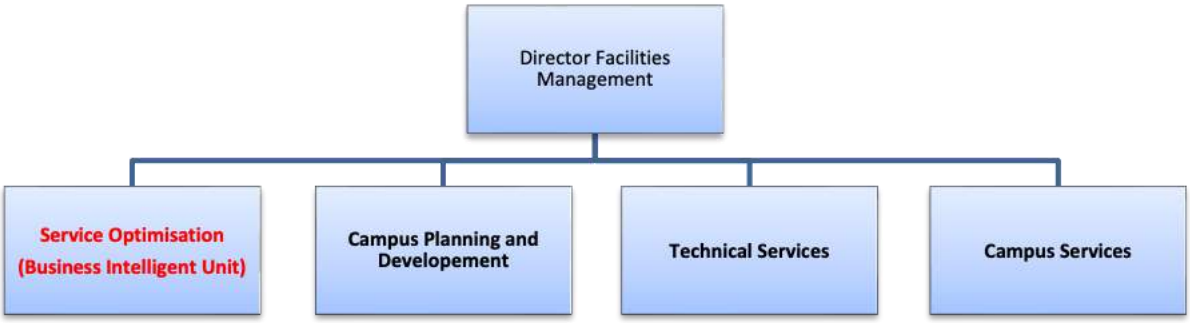

Figure 6: Organigram, formulation of a Business Intelligent Unit in the service optimisation division which will be responsible for service optimisation across the FM Department.

Outcome for collaboration and communication alignment

The Business Intelligence Unit is earmarked to be permanently established in the Service Optimisation division of the FM Department. Currently a dedicated task team has been assigned to drive such digitization strategies. The challenge for the task team was threefold: 1) how to start, 2) where to start; and 3) what specific *information needs* to address.

4.3.4 Outcome of the Pilot

The intention of this Pilot is to demonstrate the process of adopting BIM, test and benchmark assumptions and determine how difficult it would be to implement the digitisation strategy of the Department of FM.

The study area will include the South Campus and two buildings on the Hatfield Campus in Pretoria (shown in Figure 6). The area was specifically chosen because of the ease of locating bulk and building services and there are various typical types of facilities in the study area (offices, laboratories, and lecture spaces). Additionally, two lecture facilities in are not yet on the Universities central booking system and the impact of this change to BIM can be measured. Through visual inspections and scrutinising HEMIS (Higher Education Management and Information System) norms and standards, it is presumed that the facilities on the University of Pretoria are underutilised, and the laboratories are outdated and not fit for purpose.

A road map was prepared as a planning mechanism and broken down into monthly intervals, whereby progress and reporting can be documented and escalated to senior management. The duration of implementation of the Pilot project is estimated to take two years, spanning from April 2023 - December 2025. Once the Pilot is successfully implemented, the FM project team would be able to confidently request resources and present a business plan to senior management. The Pilot site is indicated in the Figure 6 and Table 1 below, with the description of the Pilot study milestones. The types of barriers are also listed in the Table 1, with an articulated plan on how to overcome the expected barriers.

Types of Barriers [39]-[40]	Articulate the plan to overcome barriers, summarising the outcomes per barrier type.
INFORMATION-RELATED BARRIERS	▪ Define the scope for a Pilot ▪ the formulation of a BIM execution plan (BEP)
TECHNICAL-RELATED BARRIERS	▪ Update cost plans against initial estimate ▪ benchmarking cost saving against industry leaders ▪ Benchmark technical skills required to implement BIM and rationalise needs in own environment (upskill staff and outsource of certain aspects) for fast adaptation and testing ▪ Pilot to test open and closed-BIM systems and software
ORGANISATION-RELATED BARRIERS	▪ Continuous communication to ensure collective ownership of the implementation ▪ Determine key areas for the Department of FM portfolio, determine if they can be incorporated in the BIM environment and address the needs of the Pilot. ▪ Business Intelligence Unit establishment (move human resources to independent place in the structure & mandate the unit to drive digitisation initiatives)

Table 1: Summary of Types of Barriers and plans to overcome them

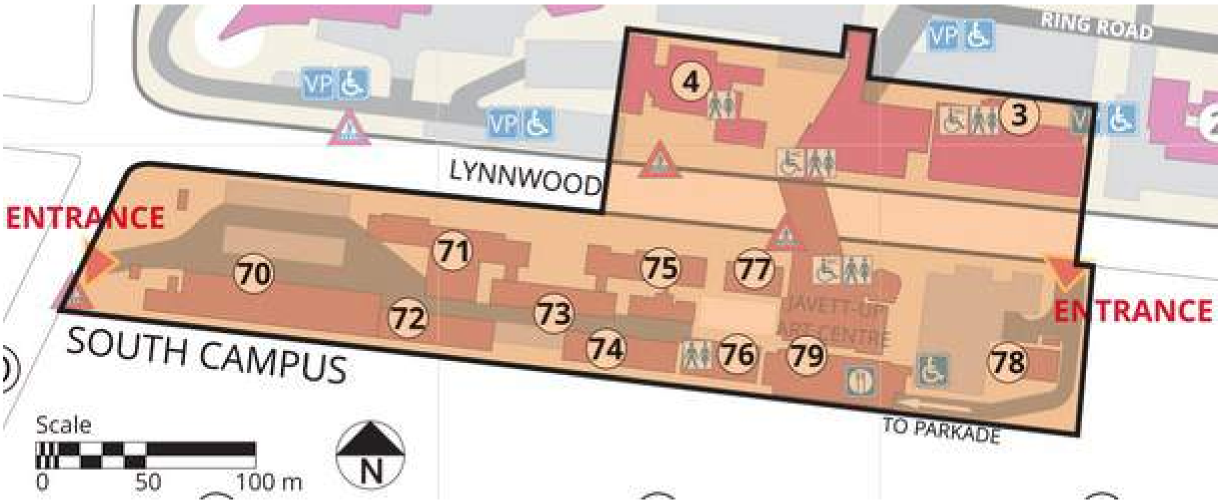

Figure 6: Locality plan of Pilot study

There are specific aspects that will be tested with this Pilot. This includes GIS/BIM capabilities, data management capability, data access management, API capabilities, IOT platform data collection, infrastructure drawing integration, dashboarding from multiple data sources, report automation, documentation inclusion, data analytics capability, comparison of ecosystem tools, effectiveness and adaptability to incorporate additional information needs and documentation review to resolve new issues as they emerge.

5 CONCLUSION

With this journey, we've discovered that the main aim to overcome the barriers to BIM adoption in FM, is to follow an incremental and adaptive management approach. For FM organizations to being to embrace technology and innovation without fear, it is important to demonstrate the benefits of BIM by building trust, challenge the competitive edge, explore financial robustness over time, and align to internal sustainability performance targets for the FM Department. The first step, the centralisation of data, is critical to ensure one true source to work and information that will benefit all. These perceived benefits can be tested empirically, and includes time saving, optimization of services, improve environmental impact and sustainability goals, assist in planning and resource allocation, and the radical reduction of departmental silos (which impede on service delivery to all).

By leveraging BIM's capabilities, the FM Department can optimize internal FM practices, enhance data integration, and maximise the potential of digital tools and processes in improving overall operational efficiency and decision-making. This will not only support the reduction of wasteful practices, but also improve the identification and implementation of valuable sustainability measures in FM. This will allow the FM talent to focus on important pro-active work instead (such as energy-efficient retrofits, waste reduction strategies, and green building certifications), and move away from re-active FM practices.

We believe that starting a BIM journey in FM can give a university a competitive advantage. These BIM advantages can result in leveraging and coordinating inefficient FM practices, improve real facility performance, and ultimately, deliver better user experiences for all. This type of impact can greatly advance the institution's reputation, attractiveness to students and faculty, and ability to attract funding and partnerships.

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THE APPLICATION OF LEAN TOOLS IN KAIZEN EVENTS: THE CASE OF A HARNESS-MAKING COMPANY IN SOUTH AFRICA

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ABSTRACT

The purpose of this study is to understand how a harness-making company in South Africa is benefiting from the application of lean tools in Kaizen events. The study also focuses one's attention on challenges encountered during the application of the lean tools. The harness-making company implemented lean tools to improve lead times, Inventory, and Quality. The benefits of Lean tools extend far the project success, reduced cost, and increased team morale. The study was qualitative, and historical data was collected from company documents. The researcher used retrospective studies to evaluate the results of the lean tools application during the kaizen events. The studies were followed, and the researcher identified the results through observation. The application of lean tools in Kaizen events helped the company achieve; high efficiency, low scrap rate, and low reworks developed the ergonomics of the work and saved costs. The improvements serve to identify the effect of lean tools in the Kaizen events and show the exclusive accomplishments of the Kaizen events.

Keywords: Lean tools, kaizen events, Harness making company

1. INTRODUCTION

* Corresponding Author

Manufacturing companies are under tremendous pressure to achieve operational excellence and boost their performance as the global market becomes more competitive. This is done to cut costs, deliver quality goods within short lead times, and reduce operational risk. Manufacturing companies employ lean manufacturing ideas and practices to accomplish these goals and gain an advantage over their competitors (1).

Any business that wants to compete successfully in the market must concentrate on what the customers want. To survive the fierce corporate rivalry, organizations must be competitive locally and globally (1). One approach for businesses and organizations to be competitive is to increase the effectiveness of their processes through kaizen (2).

The Kaizen technique has been widely utilized in business organizations to enhance product quality, lead times, reworks, cost reduction, waste elimination, productivity, workplace environment, and efficiency (3). Kaizen is used in both the industrial and service industries (4).

According to manufacturing experts, Kaizen is a key element of the "lean" production processes It seeks to boost efficiency by fostering teamwork through a culture of discipline, good morale, quality work, and improvements (4). Including everyone in the process and decision-making improves teamwork. Waste is reduced and worker productivity is raised (5).

1.1 THE CASE COMPANY

Company XY was founded in 1905 and has its origins in Germany. Ever since it was founded, it experienced rapid growth, and currently, its staff complement is more than 40,000 people worldwide. Its manufacturing facilities are more than 30, and it is a top manufacturer of harnesses. The harnesses are designed for German automotive assembly factories only. Some of its customers are Bavarian Motor Works (BMW), Daimler, Ford, and Opel.

1.1.1 The implementation of Lean tools in the company

Company XY introduced numerous lean programs through the Process Optimisation Worldwide Resource (POWER) lean system in 2008. This system was introduced after the company realized that its employees did not utilize the lean tools to their full potential and that they did not appreciate the tools in their current state. To advance the usage of the lean tools, Company XY transitioned from using POWER to using Operational Excellence. With this technique, Company XY sought to boost employee engagement and satisfy customer demand by delivering a product with high quality and zero defects. Operational Excellence allowed Company XY to apply lean tools. With the application of the tools, Company XY was able to provide the tools, and resources needed to build a lean system environment and to develop a lean culture.

Company XY then expanded its lean system by implementing the Toyota Production System. Its objective was to incorporate lean tools in its monthly Kaizen events. Company XY was committed to holding these events regularly and it spent money hiring events coordinators or creative drivers.

1.2 Problem statement

Although Company XY has procedures that guide the execution of processes and the application of lean tools, the diversity of the company's employees occasionally makes it difficult to implement them. This results in subpar performance in other plants owing to local laws and cultural norms.

The use of lean tools requires a change of mindset, yet some people in the company are still reluctant to change because they don't comprehend it or because they lack information. Procedure implementation is also impacted by a lack of desire and lack of top management involvement. Implementation of lean tools was also hindered by the organization's need to hold workshops during peak production periods.

1.3 The aim of the study

The study aimed to analyse the application of lean tools in Company XY. Special focus was on understanding:

- how lean tools were used in the conduct of Kaizen events in Company XY.
- the extent to which Company XY implemented the Kaizen events.
- the challenges experienced by Company XY in transforming its practices following the Kaizen events and lean tools applied.

2 LITERATURE REVIEW

Kaizen, a Japanese phrase that means change for the better is a company-wide continuous improvement process used in a business to develop methods to increase staff knowledge and experiences in the business processes (6). Kaizen is essentially a set of tools and a mindset. Without active care, the advancements will degrade.

The Kaizen approach was developed to increase the productivity and the standard of Japanese goods. This was in the mid-1940s when the Japanese manufacturers wanted to catch up with the American and European producers. First, efforts were made to understand the statistical quality control techniques used in Western management systems (7). The Deming Prize, an annual award for introducing quality management, helped raise awareness among businesses and allowed studying best practices. This technique eventually led to the eventual development of the Kaizen system by fusing Western and Japanese management methodologies (7).

Small improvements done as part of the routine work (Kaizen) can range from single actions to entire value streams (8). Kaizen events result in beneficial changes in business outcomes and human resource outcomes, but it can be challenging to maintain or enhance such achievements over time. Sections 2.1.1 to 2.1.4 discuss some of the lean tools that are used during the Kaizen events.

2.1.1 5S Concepts

The 5s methodology was created by the Japanese, and it made just-in-time production possible. The 5s concepts' acronyms are sort, set in order, shine, standardize, and sustain (10). Figure 1 gives a pictorial view of the concepts.

Figure 1: 5s concepts (Takashi,1995).

Although the concepts are executed individually, one concept leads to another as follows:

- *Sorting* - entails removing any unnecessary tools, information, materials, and parts and objects so that only what is required is retained (10).
- *Set in order* – is about keeping things in order and in their proper location. The workspace is organized so that everything needed is readily available (10).
- *Shine* - emphasizes the importance of keeping an area clean. This incident reduces waste and accidents (10).
- *Standardize* – is the forth "S" that represents continuing with tried-and-tested methods. The established methods and procedures must consequently be respected and followed by all team members (10).
- *Sustain* - entails adhering to workplace norms and regulations, such as audits and job instructions (10).

2.1.2 A3 Problem Solving

The Toyota Company was the first to use the A3 technique. A3 is a systematic approach to solving problems and effects ongoing development. The technique includes images, diagrams, and charts in addition to text, and all of them enhance and clarify the problem statement (11). It is an effective instrument for ongoing organization-wide improvement. The problem-solving process consists of the following five steps:

1. *Identify the problem* – the problem is identified based on facts and not opinions. It is crucial to identify the problem type, and establish what went wrong when it occurred, the magnitude of the failure, and the frequency of occurrence of the failure (12).
2. *Root cause analysis* - To effectively stop a problem from happening again, the problem's root cause must be identified. It is crucial to analyse the problem using tools such as the Pareto chart, the 5whys technique, or the cause and effect analysis. The tools allow you to effectively respond to the questions (12).

3. *Select corrective measures*— the aim is to eliminate the underlying causes and stop the issues from recurring. After corrective measures have been performed, it is not necessary to re-evaluate the issue (12).
4. *Implement permanent corrective measures* - The goal of this phase is to determine whether the root cause has been permanently eradicated (12).
5. *Prevent repetition* - No matter what methodology you choose, the root cause analysis is the beginning of the problem-solving process. According to Harrison, specific problems inspire people to consider additional issues. Once the problem is identified, you can then put a remedy in place and carry out routine checks to ensure preventive measures are taken (12).

2.1.3 Value stream mapping

Customers' requirements for a particular product determine the value stream mapping (13). The process of mapping the value stream, or all the steps and processes required in bringing a specific product from raw materials to the client, comes after the value has been established. Value stream mapping is straightforward that reveals all the steps that move a good or service through a value-stream mapping process (13-14).

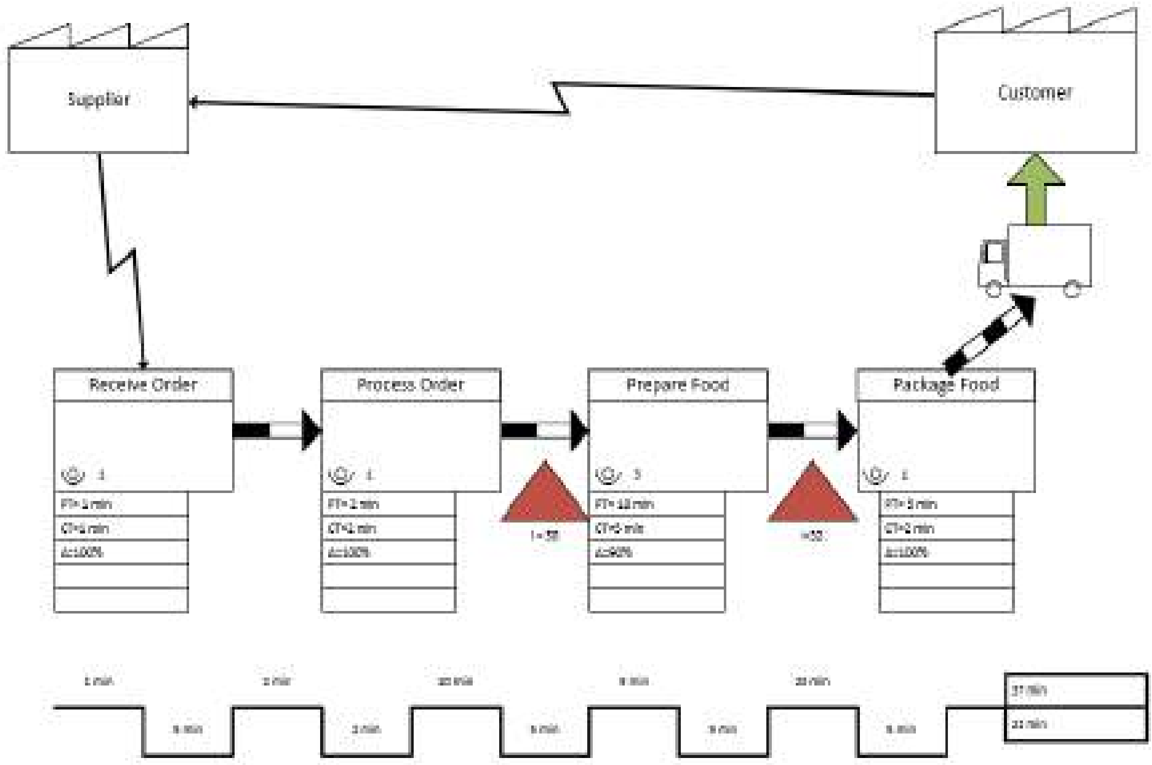

Figure 2: Value stream mapping Process

Figure 2 depicts the process and the material and information flow mapping that was used to analyse the present state and plan a future state for the sequence of actions that took a good or service from its inception through a every processes until it reached the client (14; 15).

Figure 2 shows an example of cycle time, production time, and the downtime that was applied when mapping the processes (14).

2.1.3.1 Information flow - this section demonstrates the data transmission and exchange of process-related information (14-15).

2.1.3.2 Product Flow - is the development lifecycle from concept to delivery. Nevertheless, depending on one's objectives, this can be refocused on the individual steps in the process (15).

2.1.3.3 Cycle time *(C/T)* - the average amount of time from the end of one unit's creation to the end of the next. It is the average length of time it takes between the completion/deployment of one item's request to its completion (15).

2.1.3.4 Setup Time (*S/T)* - is the time required to get ready for a specific step. This can be used in software development to indicate how much time is required to comprehend a given request or to configure it, spin up, or allocate a test environment, depending on the phase (15).

2.1.3.5 Uptime *(%)* - provides a notion of how much of the time the processes or the systems are in use. This demonstrates a system uptime or employee availability in our instance (15).

2.1.3.6 Lead Time - is the measurement of the typical time required for one item's request to progress from conception to delivery, or from the starting point to the finishing point, during the full development cycle (15).

2.1.3.7 Takt Time - is a phrase that is frequently used with value stream mapping. It speaks to the pace at which you must generate your goods to keep up with demand from customers (15).

2.1.4 Single Minute Exchange Dies

The setup times are a typical example of waste. Since they are associated with activities that do not add value and that are associated with hidden expenses. SMED is essentially a methodology for analysing and improving the time lost in manufacturing due to the execution of setups (16). In its original definition, it requires that the tool changes are done in a production line in less than 10 minutes. Setup time is defined as the period from the time when the last good product from the previous production order leaves the machine to the time when the first good product from the next production order is produced (17). Changeover time is defined as the time needed to set up a given production system to run a different product with all the requirements (16).

2.2 Challenges and Barriers Faced During Kaizen Implementation

Despite the successes that the implementation of Kaizen projects has produced, several obstacles to the adoption of Kaizen have been found (18). Implementing Kaizen can be challenging, and this is caused by: the inability to inspire staff members to participate in Kaizen activities; the lack of clear procedure, guidance, and understanding; the poor communication; the failure to view consumers as the foundation of one's company; and the failure to facilitate the customers' direct involvement in its business activities (18). Senior management's dedication and participation in implementing new techniques and technologies also contribute to the successful implementation of Kaizen events and projects (4).

2.3 The impact of Lean tools in Kaizen events

Otsuka argues that employees of a company should constantly reflect on how to maintain and boost improvements inside their organizations, as well as on how much they should play in these improvements (19). There are two different approaches to making progress: incremental improvement (Kaizen), and improvement based on the huge leap (innovation) (19).

Kaizen and innovation are tools used to improve operational processes and performance; in other words, Kaizen refers to incremental modifications. Employee innovation and creativity often have subtle, barely perceptible impacts in the short run (20).
The phrase "lean strategy" describes a group of methods and tools used to improve an organization's operational efficiency. To show the financial benefits of applying a lean approach, Hofer, Eroglu and Hofer investigated the effects of lean tools on an organization's financial performance as well as the mediating function of inventory leanness (20). They also investigated the effectiveness of both internal and external lean methodologies. Employee education and familiarization with tools and approaches for continuous improvement are required for their productive participation in Kaizen activities (21). Numerous tools and techniques, including those for problem-solving and quality control as well as those that necessitate employee training and education support Kaizen activities. Inadequate training and lack of problem-solving abilities lead to a failure of lean application (21).

3 RESEARCH METHODOLOGY

This methodology begins with the analysis of the Automotive organisation the Kaizen approach has significantly enhanced in Company XY's organizational work as well as the actual manufacturing processes. The researcher made use of internal continuing continuous improvement, incentives, and Kaizen events with observable results. Performance indicators derived from direct observation, plant-developed metric systems, and published records are used by the resource planning and research centres of the company to assess the degree of Kaizen awareness, the implementation process, and the results of utilizing this strategic management system in the companies.

In order to determine the influence and impact of lean tools in kaizen events, the research was conducted based on the relevant of literature reviews, including journal articles, conference proceedings, books, and official websites. The primary data were gathered by looking over old records and observing at kaizen event workshops. The Researcher requested written consent from Company XY, had access to all pertinent records and historical information connected to the study, and confirmed the information through the observation of kaizen events and in-depth inspections of the manufacturing facility.

4 FINDINGS

Kaizen events in Company XY were structured using the DMAIC cycle. The DMAIC is an acronym for define, measure, analyse, improve, and control. The goal of introducing the Kaizen event is to have rapid change by focusing on a narrow project. It uses the ideas and motivation of the people who do the work. During the start of the kaizen event, the coordinator at Company XY does the following:

Maps the value stream of a chosen process before the event – see Figure 4. The mapping allows the event coordinator to identify the waste generated during production, material flows, and machine utilization. Additional information provided by the value stream maps is efficiency, quality, current production output, and bottlenecks in the value stream. In Company XY the coordinator conducts Muda analysis, and the findings are presented to the participants before the event the purpose of this is to make the participant to understand about the waste and tools that’s needs to be used .

In one typical value stream mapping that was conducted in Company XY (Figure 4), it was found that there were problems with the product line and it was not balanced. There were delays at cutting area causing the rest of the workstation to have a bottleneck, and this resulted in the accumulation of work in progress between work station preparation area, Plugging/Testing area And packing area (Figure 4).

The Coordinator covered the following topics: lean fundamentals or basics, all necessary lean tools to be used during the event, the significance of the kaizen event, and the event's rules. Furthermore, the Coordinator introduces the event's topic, key performance indicators, and expected outcome. Participants must be familiar with the kaizen event before proceeding to the shop floor. All of this information will help the participants with their investigation and problem-solving abilities.

Figure 3: Kaizen event scope

Company XY conducts regular Kaizen workshops, and each workshop is run for five consecutive days. Figure 3 shows how Company XY defines the scope of the Kaizen events during Kaizen workshops. On the first day of the Kaizen Workshop, problems on the shop floor are identified through Gemba walks. The Kaizen event participants go to the shop floor to conduct Gemba walks and collect data on the problematic area and they generate initial ideas on how to attend to eliminate the problems. Once they have done so, the participants in kaizen events brainstorm the problems areas identified through the Gemba walk that they have to solve. During the second day of the Kaizen event workshop, the participants examine the ideas, and by the end of the second day, the participants identify quick wins/ideas presented during the event and classify them into short-term, middle-term, and long-term activities and be able to set a timeframe to resolve them. The coordinator conducts basic training on lean tools that will be used during the Kaizen event. Typical lean tools that are included in the program are Muda hunting, value stream mapping, 5S, and A3 problem solving.

The Kaizen event's scope is also defined by the participants. The participants are at this time focused on the 'measure', 'analyse', and 'improve' components of the DMAIC cycle.

Value stream maps like the one in Figure 4 are then used to help identify and isolate the problems that the company is experiencing. In the case of Figure 4, the value stream mapping was developed for the current state Process. The value stream map showed that the values of scrap rate, downtime, efficiency, overall effectiveness, overtime and cycle times these were the problems that influenced through output and set the agenda for problem-solving.

The participants continue to analyse and locate the improvements on the third, fourth, and fifth days. The final activity of the Kaizen event is to conduct another Gemba walk to examine the effects of interventions implemented on the shop floor. On the last day, the participants also conduct the following three DMAIC control and follow-up Actions:

- Review the implemented interventions and quick-win suggestions. Summarization of achieved benefits achieved and of the follow-up or long-term activities that would be done in the future.
- Confirmation and presentation of results achieved, and lessons learned.
- The reports generated are then sent out to the process owner or responsible personnel.

4.1 The application of Lean tools value stream mapping

One typical value stream that was conducted in Company XY in the Production department on the Main line . When the event was conducted the company had experienced problems with presents of managers, resistance to lean concept and participants fully committing to the event. The management team of Company XY unanimously invited workers from all departments to the event. By using the value stream mapping, the coordinator and Kaizen event team were able to analyse the current situation. They found out that the overall effectiveness of the cutting area was at 42%, which caused the scrap to increase to 50% of the jobs in the machine shop. The value stream map in Figure 4 illustrates the process downtimes (time lost) from beginning to end.

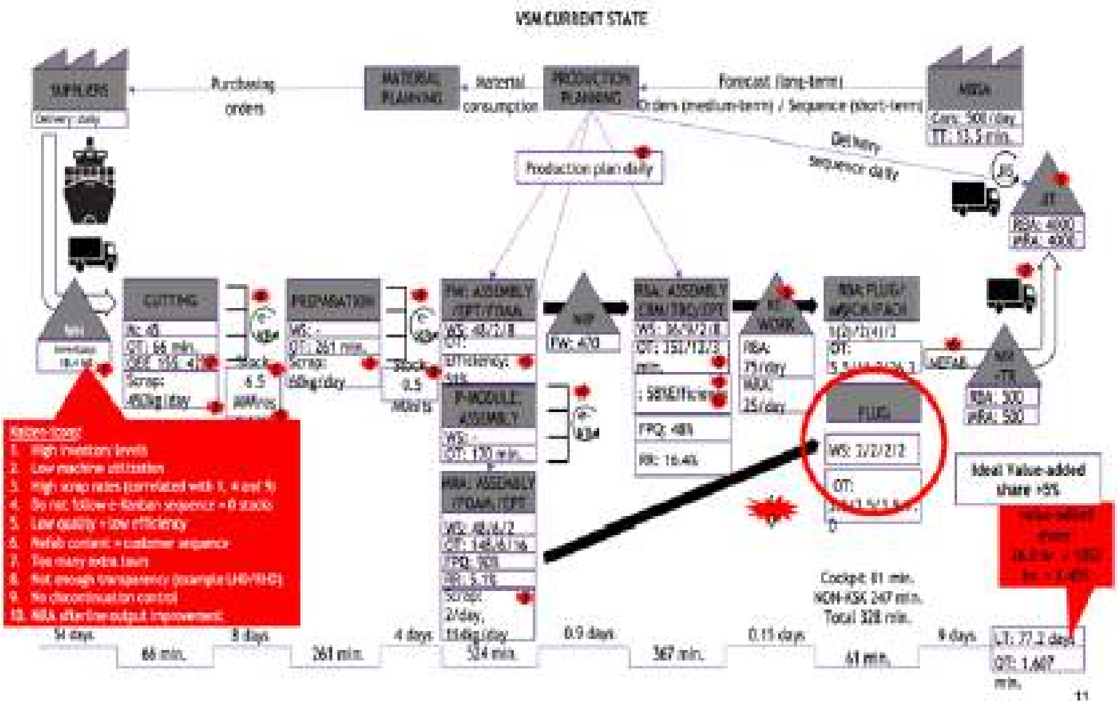

Figure 4: Value Stream Mapping Tool Coordinate System

The major issue was that there were 470 pieces of work in progress between the foaming workstation and the assembly test board (EPT). This generated delays and required rework after each shift. There is usually a delay of one to two hours at the plugging and packing station due to the bottleneck created by the workstation before shipment. The participants had to examine the root cause on that area during the Kaizen event. Knowing the root cause assisted in identifying the solution. From the outcome of the value stream mapping, the future state map was ascertained using the cause and effect analysis and the A3 problem-solving technique.

4.2 The application of the A3 problem-solving technique

The A3 problem-solving execution plan was created to determine what is required to maintain an improved process at its current level, as well as to get an overview of a project about its history, purpose, goals, activities, and crucial deadlines. The obligations and skills that each team member is responsible for are listed in detail in the plan. Company XY utilized this method at the Kaizen event discussed in section 3.1 to describe their problems before seeking solutions. A root cause analysis was then developed based on observations made during the Gemba walks (Table 2).

The team's next task was to put the action plan in writing so that it could be escalated to the appropriate parties. In addition to putting the suggestions into practice, the moderator also monitored the effectiveness on a monthly or daily basis to see whether any meaningful changes had been made to the workstation. The A3 problem-solving exercise from the Kaizen event is shown in Figure 5 and a clear explanation of each document on one pager example is detailed below.

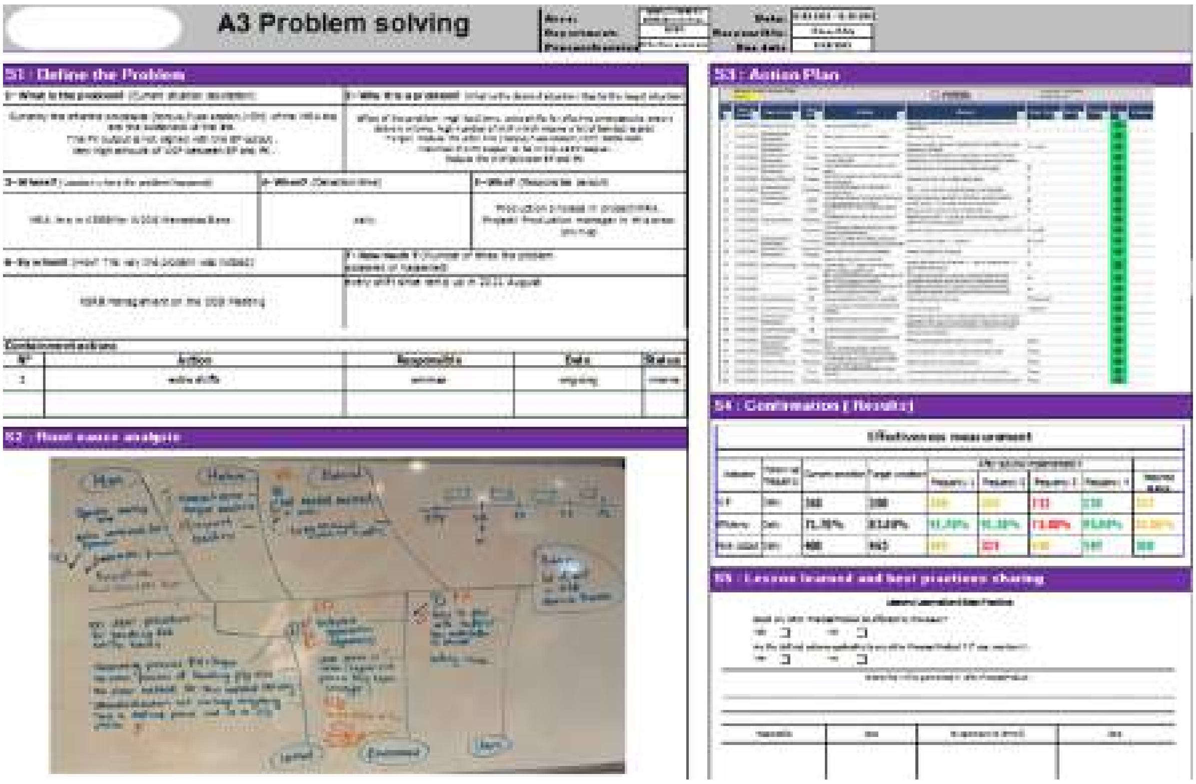

Figure 5: Example of A3 problem solving during the kaizen event

4.2.1 A3 Problem solving (S1)

In the value stream mapping the team explained how the packing area wasn't aligned with the test board, and this caused a delay in the dispatch area's ability to deliver goods to customers. The A3 problem-solving method was used, and the Ishikawa results shown in Table 2 show; that the operator had to wait while moving from one workstation to another, that the torque machine had a timeout error, that there was a lack of standards, and that the procedures were not clearly defined in that area which led to confusion among the employees.

The group also learned that Company XY had put in extra effort to avoid delivering the goods to the client late. Additionally, they identified the bottleneck's location by analysing the value stream mapping and the frequency of occurrence.

Table 1: Description of the problem

<table>
<tr><td colspan="3">1- What is the problem? (Current situation description)</td><td colspan="3">2- Why it is a problem? (What is the desired situation/ Gap to the target situation)</td></tr>
<tr><td colspan="3">Currently, the after-production line processes (torque, Fuse station) of the company XY are the bottleneck of the line.
The Packing output does not align with the test board output.
A very high amount of WIP between EP and PK.</td><td colspan="3">Effect of this problem: High lead time, extra shifts for after-line processes to ensure delivery on time, the high number of works in progress (WIP)
Target:
Reduce the after-line (torque, Fuse station) bottleneck.
Maximize the packing output to be in line with the test board output.
Reduce the work in progress between the test board and packing.</td></tr>
<tr><td colspan="2">3- Where? (Location where the problem happened)</td><td colspan="2">4- When? (Detection time)</td><td colspan="2">5- Who? (Responsible person)</td></tr>
<tr><td colspan="2">After the production line in company XY</td><td colspan="2">daily</td><td colspan="2">The production process in the plant
Project/ Production manager in this area</td></tr>
<tr><td colspan="3">6- By whom? (How? The way the problem was noticed)</td><td colspan="3">7- How much? (Number of times the problem appeared or happened)</td></tr>
<tr><td colspan="3">Management noticed it on the Daily Direct Setting (DDS) Meeting</td><td colspan="3">Every shift since ramp-up in 2021 August</td></tr>
<tr><td colspan="6"></td></tr>
<tr><td colspan="6">Containment actions</td></tr>
<tr><td>N°</td><td colspan="2">Action</td><td>Responsible</td><td>Date</td><td>Status</td></tr>
<tr><td>1</td><td colspan="2">extra shifts</td><td>Production Manager</td><td>ongoing</td><td>ongoing</td></tr>
<tr><td></td><td colspan="2"></td><td></td><td></td><td></td></tr>
</table>

4.2.2 A3 problem S1: Root Cause analysis

To identify the underlying causes of the problem, the Kaizen event team employed the Ishikawa diagram. Here is an illustration of a discovery made at the event. The team realized that while they could have provided the workers with equipment that would have made their work easier, they were spending time removing bins from the conveyor belt. The Torque machine is mostly responsible for delays by reflecting erroneous codes, which indicates that the machines are not being properly maintained. The unnecessary materials on the workstations appear to be dispersed and not in their proper locations. Because their job instructions did not adequately explain the processes for packaging the product, the workers had to work in a way it suits them.

Table 2: Ishikawa or Cause and Effect diagram

Cause			Effect
Man	**Machine**	**Material**	The high amount of work in progress between the workstations in the after-line processes in the area
Operator waiting time The extra workload for the operator	Timeout error for torque machine	Not needed material remains in the area	
1. No clear procedure for handling full Nerf bar boxes 2. Scanning process packing/Torque 3. No clear procedure for handling empty grey boxes 4.No clear method/procedure for the raw material delivery system 5.Lack of standard	1. Workplace organization (ergonomic) 2. Less space in the area	1. How to deal with buffers/no marking of "How much is allowed" 2. Safety issues	
Method	**Environment**	**Others**	

4.3 The results of Kaizen events

The Kaizen event moderator monitored the results of a particular region from the event's current state to the follow-up frequency time. The findings show a considerable improvement in work in progress. It decreased from 348 to an average of 257. Efficiency improved from an average of 71% to 82% weekly. Processes upgraded their packaging area and were now able to produce 500 units daily. Table 1 shows the outcomes of the kaizen events.

Table 3: Kaizen event follow-up figures

Effectiveness Measurement								
Indicator	Follow-up frequency	Current condition	Target condition	After actions implementation				
				Frequency 1	Frequency 2	Frequency 3	Frequency 4	Frequency 5
WIP	Daily	348	200	248	230	313	138	257
Efficiency	weekly	71,70%	83,00%	92,70%	91,10%	71,00%	95,00%	82,00%
Pack output	Daily	400	465	449	339	449	549	500

If the moderator finds that the root cause has not been eliminated, then the team goes back to the root cause analysis, and through the cycle of problem-solving once again. This is done to identify the systemic underlying causes.

To design a workspace suitable for visual control, as seen in Figure 6, the team implemented 5S. 5S was used to define the area, move things around, organize things, and make space-thereby reimagining the layout.

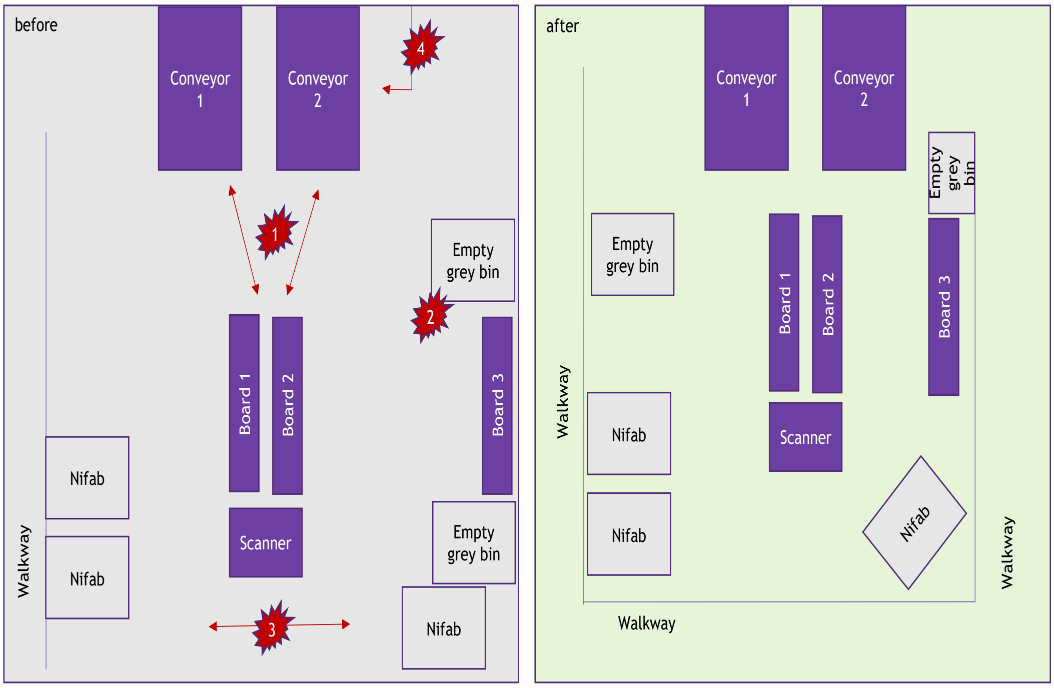

Figure 6: After the Production line before and the proposed layout

Previously, there were spaces between the conveyors and the boards, which led to needless movement (stacking boxes). The team was able to close the gaps to create greater space. Since moving the empty bins to the warehouse was a challenge from the start, they constructed the route as seen in the “after” photo adjacent to the wall (Figure 6). Since the material couldn't be supplied, a small portion was chosen, and a new route was constructed.

4.3.1 Lesson learned after the kaizen events.

The team met on the final day of the event to discuss the shortcomings of the occasion and things that prevented them from meeting a particular objective. The team realized that they ought to have spent more time on the shop floor than in the training room debating. When the moderators spend more days talking about the same topic, the participants become disinterested.

Moderators realized that it was not necessary to discuss all the lean tools in detail in one event. Some lean tools were irrelevant to the project such as makigami, Muda hunting, SMED, and Kata. Even though the application of a few Lean tools Company XY managed to achieve some of its key performances but failed to improve its quality as they anticipated.

5 CONCLUSION

The study showed that even though combining Kaizen events with the aforementioned lean methodologies is technically possible, doing so is acceptable and appropriate in the Company XY that applied it. The managers' involvement in the undertaking and their communication with the team originally served to demoralize it, but finally, everyone agreed to take part in the Kaizen event. Thus, the kaizen event promoted openness and effective communication by encouraging the shop floor employees to discuss their everyday struggles and the managers to do the same. Due to the concept's successful implementation, company XY was able to accomplish other strategic goals, such as establishing a culture of continuous improvement and increasing efficiency, which are evident in their results.

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FINANCIAL FEASIBILITY OF BINDER-JETTING FOUNDRY APPLICATIONS IN SOUTH AFRICA THROUGH SAND LOCALISATION

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ABSTRACT

Despite the numerous advantages of binder-jetting process to metal casting, its adoption as mainstream process for producing sand moulds and cores is still limited in the South African foundry industry. One of the critical reasons is the high cost of both the equipment and the operational costs. When assessed using metrics such as the net present value and the internal rate of return, these costs compromise the financial feasibility of using binder jetting in foundries. This investigation uses a case study of additive manufacturing of an impeller sand mould using Voxeljet VX1000 printer to assess the financial feasibility of binder-jetting project. The results of the analysis of the scenario in which an imported silica sand is replaced by local Cape Flats sand showed a substantial increase in the project's NPV and IRR. To that end, localization could contribute to reducing high running costs of rapid sand casting in South Africa.

Keywords: additive manufacturing, binder jetting, financial feasibility, silica sand moulds, Voxeljet VX1000

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1 INTRODUCTION

Additive manufacturing (AM) is one of the widely popular technologies that constructs a three-dimensional (3D) part from a digital 3D model using a layer-by-layer mechanism. It has the capability of replacing the current conventional processes as it manufactures a part by adding material rather than removing it. This new technology can result in the flourishing of new business models, new supply chains and a variety of new product designs [1]. In recent years, the development and commercialization of AM processes has made significant progress through comprehensive research as well as practical applications in various sectors, including the aerospace, automotive, biomedical and energy fields [2]. Through these practical applications, AM technologies have been categorized as part of the fourth industrial revolution (4IR) [3] due to their revolutionizing of the ways products are designed and produced.

AM methods vary in different ways: in the techniques used to construct the layers, in the bonding layer procedure, in the speed at which each layer is manufactured, in the layer thickness and in the material used [4]. Guo and Leu [2] and Negi et al. [5] also confirmed that AM processes are classified based on the deposition mechanism of the raw material used and how particles are directly or indirectly melted or bonded together to form a 3D part, as shown in Figure 1. The technology used to manufacture a part has moved the manufacturing process from mass production to mass customization.

Binder jetting is one of the AM techniques that can be adopted by the local foundry industry to produce sand moulds and cores for casting. The application of 3D printing to sand casting is called rapid sand casting [6]. This process adopts the binding mechanism of sand particles where silica sand mixed with a catalyst is coated with resin. The resin is deposited onto thin layers of the mixed sand, coating the build platform, and a laser selectively melts the resin coating which causes sand grains to stick together [7]. The coated sand layers are continually bonded together until the mould or core is complete. Figure 2 depicts the typical workflow of binder jetting, a 3D printing technique that eliminates the need for support structures during the production of a 3D part. In this process, two primary materials are employed: silica sand, serving as the powdered material, and a liquid binder. The method showcases silica sand being evenly distributed across the build platform via the powder roller. Simultaneously, the inkjet printer head strategically applies the liquid binder onto the sand in precise locations as per the design.

Following this initial step, the build platform is lowered in accordance with the specified layer thickness of the model. Subsequently, another layer of silica sand is dispersed over the previous layer, and once again, the liquid binder is distributed based on the composition of the sand mold or core being manufactured. Throughout this process, any silica sand that remains unbound is retained in a powdered state, creating a bed encircling the printed sand mold or core. This sequence of the process is then repeated until the entire sand mold or core has been successfully produced [8].

The rapid sand casting process has proven to have several advantages over the traditional sand mould manufacturing processes. These advantages include the elimination of the hard tooling of patterns. Using 3D printing, certain complex parts that would have been assembled from several components can be consolidated into one [9]. Because rapid sand casting uses computer aided design (CAD) systems, the costs and time spent on designing and making the pattern are also reduced [10]. This technology also has the potential to reduce the energy used and waste produced due to the reduced amount of raw material required to build a part layer by layer [11], thereby reducing AM manufacturing costs [12]. Parts can now be printed with high precision and high dimensional accuracy irrespective of the complexity of the design [13].

Yet, despite the advantages of AM over traditional methods of manufacturing, its costs are still regarded as a barrier to its adoption. However, the value added by AM often outweighs the costs incurred [14]. Literature on investment in and adoption of AM is insufficient but technical and economic assessment, including printer and material costs, can be used for its comprehensive evaluation [15]. Other authors, including Schröder et al. [16], have identified a cost structure for AM processes, which can be used to evaluate investment potential. In this cost structure, parameters of the cost structure were identified through a sensitivity analysis. Costs relating to AM processes and its adoption are seriously considered in various industries around the world, therefore understanding its feasibility both technically and financially will inform investment decisions.

Rapid sand casting has not yet been adopted by the local foundry industry due to the high cost of purchasing the printer and the unknown financial economic feasibility if it is adopted. Rapid sand casting is only available at some of the higher education institutions in South Africa for research purposes and to assist foundries' product development and solve existing challenges through innovative solutions [17]. Some of the innovative solutions include selling printed sand moulds or cores to the local foundries. The adoption of rapid sand casting by local foundries will reduce lead time, which will ultimately improve their global market share [18].

The Vaal University of Technology (VUT) is one of the institutions in SA that has adopted rapid sand casting for printing sand moulds and cores. This institution uses the Voxeljet VX1000 printer with 300 litres in build volume and a high quality performance printer head of 600 dpi resolution [19]. Sand moulds are printed using imported silica sand. The cost of the imported silica sand is much higher than that of local silica sand, which contributes to the higher cost of adopting this technology. The localisation of silica sand can reduce this high cost. In fact, localisation has been one of the SA government's key economic policies since 2014. It is aimed at the growth of the industrial economy where local industry capacity in the domestic and export markets is built by creating resilience and innovation, increasing competitiveness, galvanizing economic reforms, creating economic inclusion and jobs for women and youth, providing greater benefits from mineral resources, etc. [20].

The market size of silica sand in South Africa witnessed a 1% growth in 2022. Meanwhile its production remained consistently lower from 2015 to 2022, notably the import values experienced a significant increase during this period. The import of silica sand is projected to reach approximately 5 million kilograms by the year 2026, while the import of sand is anticipated to decrease to 1.3 million kilograms by the same year [21]. This represents a decline of 9.5% from the import figures observed in 2021. Utilising local silica sand for rapid sand casting process can serve a valuable option in accelerating this process. This can effectively replace the need for imported sand which has the potential to ultimately influence the operational expenses associated with this manufacturing process [22].

This study assesses the financial feasibility of rapid sand casting using binder jetting by localising the silica sand. The feasibility is studied though the financial metrics, NPV and IRR, which compare the results of using the imported silica sand with those of the local Cape Flats silica sand.

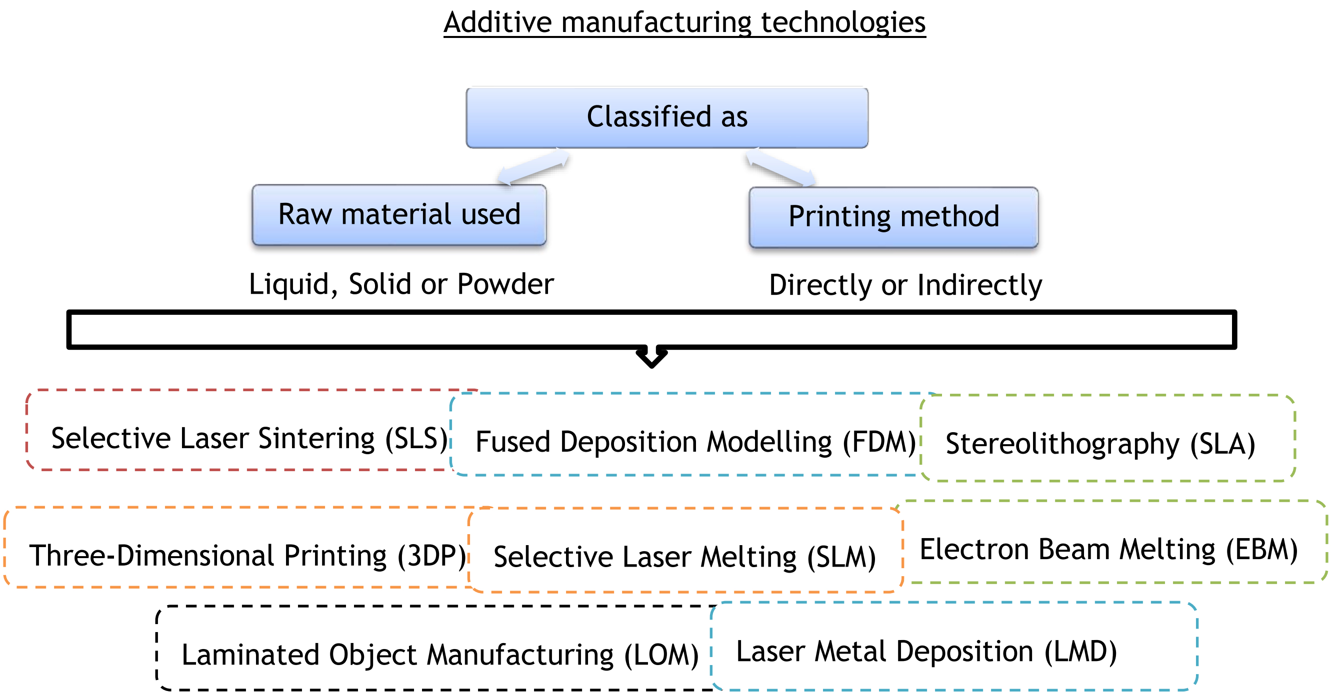

Figure 1: Classification of additive manufacturing [2], [5].

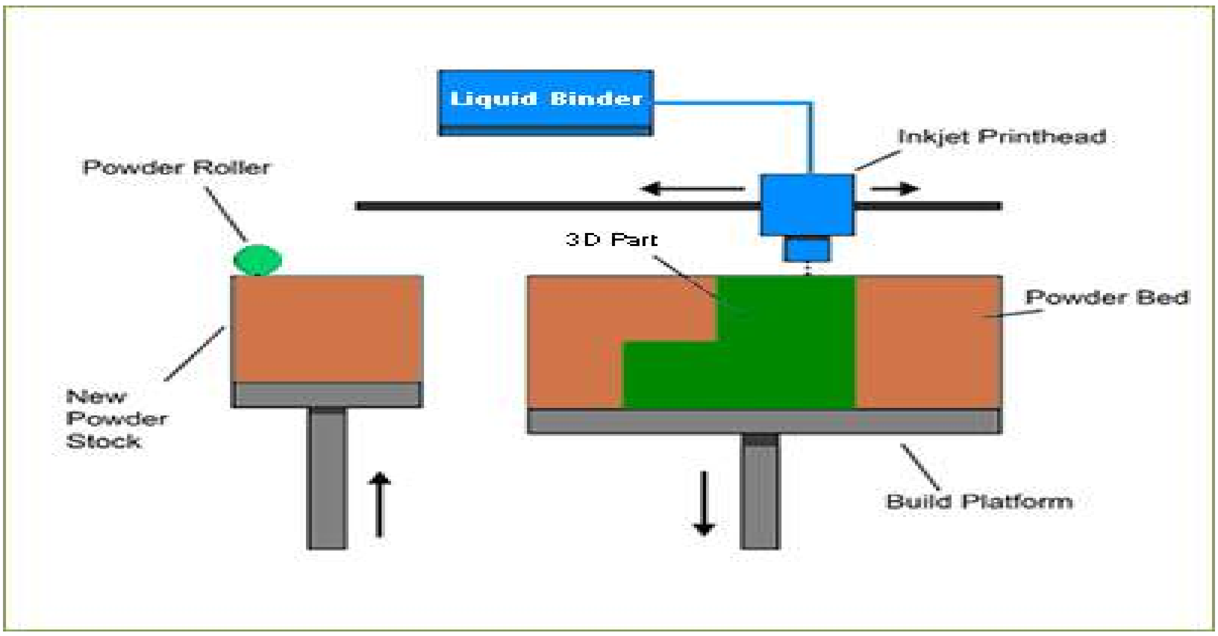

Figure 2: Typical binder jetting process [8].

2 METHODOLOGY

In order to ascertain the financial feasibility of localising the silica sand for binder jetting, an impeller sand mould printed by a VX1000 printer was used as a case study. The cost of printing this mould was calculated based on four components: sand cost, binder cost, cleaner cost and printer head operational cost. A financial analysis and a scenario analysis were carried out to ascertain how the NPV and IRR of the localised sand compared to the imported sand. Figure 3 illustrates the methodology that was followed to analyse the NPV and IRR of localising the silica sand for rapid sand casting applications in SA.

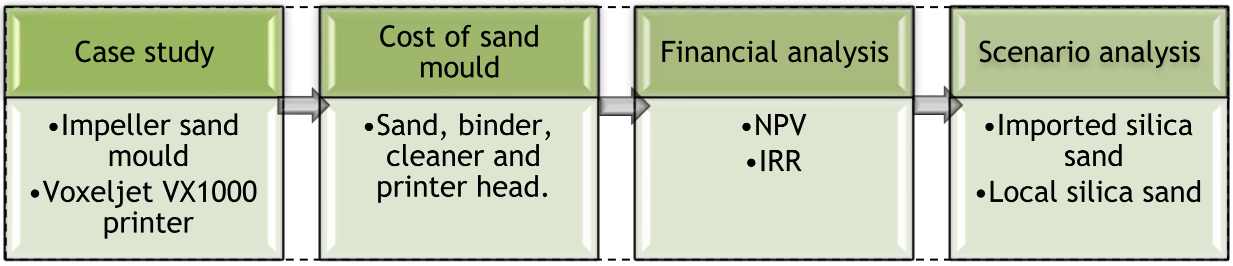

Figure 3: The methodology of the study.

2.1 Case study

For the technical and financial assessment an impeller sand mould was chosen for the case study. Impellers are widely used in pumps across a variety of industries, including the mining industry. Due to the impeller's critical role and complex structure, the quality of the sand mould is essential to produce an impeller that performs perfectly. Impeller components are currently cast in SA foundries using traditional methods. However, impellers can be 3D printed directly, but this is a difficult and expensive process. It is cheaper and easier to print a sand mould in which the impeller can be cast. A sand mould also enables back up parts, essential to the industry, to be cast [23]. Figure 4 shows a drawing of a typical semi-open impeller of the type used for this case study. From the drawing in Figure 4, a casting simulation was then performed to determine the optimal method required to create the sand mould and the final casting of the impeller. The method included the optimal geometric design of the runner and feeder system for the impeller sand mould, and the optimal casting to achieve a high yield with reduced porosity. From the optimal design and the optimal casting system, the STL file of the impeller sand mould was determined using Magix software, which determined the optimal position of the sand mould on the build platform and its printing properties.

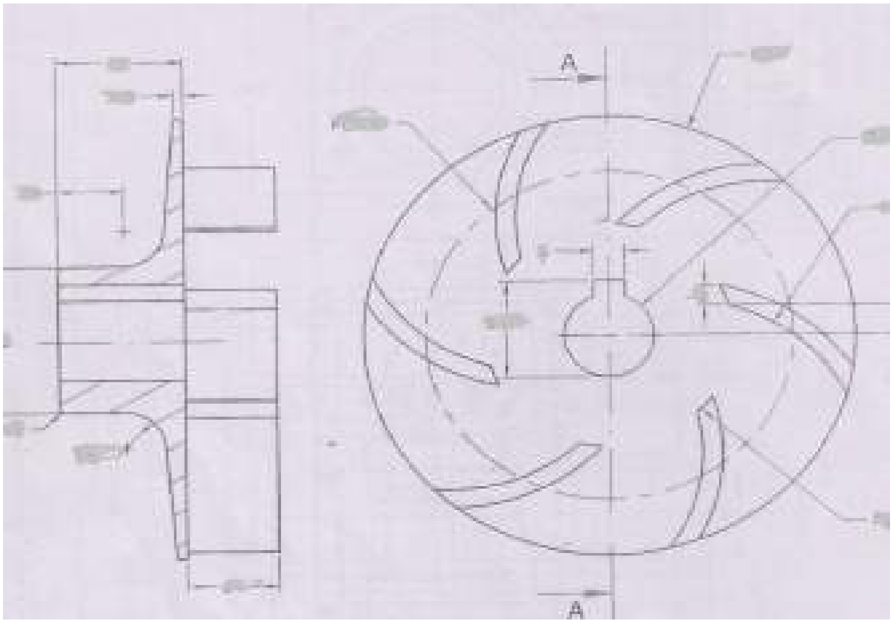

Figure 4: Semi-open impeller casting 2D drawing.

The research was conducted using the Voxeljet VX1000 printer (Figure 5A) and its build platform (Figure 5B) at the Metal Casting Technology Station, VUT. This printer uses the binder jetting process to print sand moulds and cores. The dimensions of the printer's build platform, its printing characteristics and properties, presented in Table 1, were considered for the study. The properties and characteristics include the length (L) of the VX1000 build platform, its width (W) and height (H) which accommodated the support and auxiliary structures of the build chamber during printing, hence the increase in length and width. The properties also included the time it takes to print one layer (Pt), the layer thickness (Lt), the volume per layer (Vl), the weight per layer (Wl), the silica sand density (Sd), the mixing ratio of the silica sand (Mr), based on the new and old sand used, the binder per mm^3, the cleaner per layer (Cl) and the safety factor of binder per layer, to account for any variability when binding the sand particles. These printing properties and the dimensions of the impeller sand moulds, determined after the casting simulation using Magix software, were then used in calculating and determining the total cost of printing the impeller sand mould.

Image A Image B

Figure 5: Voxeljet VX 1000 printer and its build platform

Table 1: Voxeljet VX1000 printer characteristics and its printing properties

Name	**Printing characteristics and properties**
Length of the build platform (L)	1 100 mm
Width of the build platform (W)	637 mm
Height of the platform (H)	500 mm
Printing time per layer (Pl)	35 s
Layer thickness (Lt)	0.3 mm
Volume per layer (Vl)	0.210 21 L
Weight per layer (Wl)	0.336 kg
Silica sand density (Sd)	1.6 kg/L
Mixing ratio of sand in the machine (Mr)	80% new sand and 20% reclaimed sand
Binder per mm^3	2.516 669 620 348 19 x 10^{-8} L

Cleaner per layer (Cl)	0.001 566 563 L
Safety factor of binder per mm^3 per layer	10%

2.2 Cost of the impeller sand mould

The cost model for printing the impeller sand mould from both the imported and the local silica sand was generated to determine the total cost of the impeller sand mould when printing using the VX1000 printer. The study analysis was then based on the costs of both these sands. At the time of the study the imported silica sand was R20 per kg while the local silica sand was R3 per kg. the latter prices exhibited a gradual increase over the past 5 years in line with the average inflation rate of 5% as per South African consumer price index [24].

This study used four main components of the binder jetting process from which the costs of printing both sand moulds using the VX1000 printer were calculated. These components included the sand cost (Scost), the binder cost (Bcost), the cleaner cost (Ccost) and the printer head operational cost (PHcost).

Sand cost (Scost) - sand is one of the powder materials that is used in binder jetting. The Scost is calculated from the sand cost per kg and the sand used when printing a mould, taking into consideration the properties and the characteristics of the VX1000 printer (discussed in Section 2.1 and shown in Table 1) and the dimensions of the impeller sand mould to be printed. The Scost is the function of the volume of the sand mould on the build platform, which includes the length of the platform (L), the width of the platform (W), the height of the sand mould to be printed (Hp) and the sand cost per kg. The sand density (Sd) and mixing ratio of sand (Mr) is also considered.

$$Scost = Sand\ used\ (Su) \times Sand\ cost\ per\ kg$$

$$= (((Hp \times L \times W)/1\ 000\ 000) \times Sd \times Mr)) \times Sand\ cost\ per\ kg \quad \textbf{(1)}$$

Binder cost (Bcost) – binder is the liquid used to bind the sand particles, it acts as an adhesive between the sand layers and is applied by the printer head nozzles after each layer is distributed by the recoater. The Bcost is the function of the binder per mm^3, the safety factor, the volume of the sand mould to be printed (V) and the binder cost per litre. The number of layers (Nl) to be printed determines the binder cost, the more layers printed the more the binder usage and the higher the cost of the binder. The number of layers is determined after the casting simulation by the Magix software, which has been used to determine the volume of the sand mould. At the time of the study the price of the binder was R1 923.24 per L.

$$Bcost = (binder\ per\ mm^3\ (L) \times V \times binder\ cost\ per\ litre) \times (1 + safety\ factor) \quad \textbf{(2)}$$

Cleaner cost (Ccost) – after each pass of the printer head nozzles, cleaner is sent through the nozzles, as the binder is a viscous material that can block the nozzles and impede the binder's flowability during printing. The Ccost is dependent on the number of layers to be printed and the amount of cleaner used after each layer. At the time of the study the cost of the cleaner per litre was R44.

$$Ccost = (Nl \times cleaner\ per\ layer) \times cleaner\ cost\ per\ litre \quad \textbf{(3)}$$

Printer head operational cost (PHcost) – is the printer part that supplies the binder to the sand layer through the nozzles and it is a function of the replacement cost and the lifetime of the printer. The PHcost depends on the time taken (Tp) to print the sand mould and the operational cost per hour. The time taken to print the sand mould (Tp) is determined by using the dimensions of the sand mould after the simulation process. At the time of the study the replacement cost of the VX1000 printer was R750 000 while the lifetime was 6 000 hours, making the operational cost R125 per hour (i.e. R750 000/6 000 hours).

$$PHcost = \text{printer head cost per hour} \times Tp \quad (4)$$

The cost of printing the sand mould using the binder jetting technology of the VX1000 printer was calculated from the above four components. From the cost of the impeller sand mould the price was calculated using the benchmarked mark up of 39.9% plus VAT at 15%, as shown in Figure 6.

A cost contribution analysis was performed on the mould using the imported silica sand and the one using the local silica sand in order to determine the highest contribution factor of the above four components.

2.3 Financial analysis

After calculating the cost of printing the impeller sand mould and its price, the financial analysis was conducted which considered the generation of an income statement to determine the cash flows for both the imported silica sand and the Cape Flats silica sand. The methodology approach to the financial analysis is shown in Figure 6.

2.3.1 The income statement

The cash flows for the study were calculated over a period of five years, with the cost of purchasing the VX1000 printer being the initial investment. The calculations included certain assumptions, namely, the number of impeller sand moulds printed per year, the discount rate, the inflation rate and benchmarking. The number of impeller sand moulds printed was assumed to be two moulds per day, as shown in Figure 7. Assuming 260 operational days per year, excluding weekends and holidays, the total number of moulds that could be printed by the VX1000 printer are 520 per year (two impeller sand moulds printed per day x 260 days). The discount rate considered was 7%, based on the SA interest rate. The inflation rate used was 5% which was the average SA inflation rate from 2019 to 2023, as per the consumer price index (CPI), and the income statement cash flows were analysed from 2019 to 2023 (as per Appendix B). The benchmarking used was based on the median gross margin ratio for the manufacturing industry of 39.9% from 2019 to 2023. From the cost and selling price of the impeller sand mould and the above-mentioned assumptions, the three sections of the income statement were calculated, namely, the revenues, the cost of goods sold (GOGS) and the gross profit (GP). Appendix B shows in detail the calculation of the three sections of the income statement.

- Revenue for year 1 was calculated from the number of sand moulds that could be printed per year multiplied by the price of the mould. The revenues were then escalated annually from year 2 to year 5 using the inflation rate.
- COGS for year 1 was calculated from the total cost of printing the impeller sand mould multiplied by the number of moulds produced per year. From year 2 to year 5 the cost of goods sold were then escalated annually in line with the inflation rate.
- GPs were considered the main cash flow in the entire financial analysis. GP is considered a good indicator of the profitability of a process as it is directly related to the cost of printing the impeller sand mould, and it was calculated by subtracting the cost of goods sold from the revenues from year 1 to year 5.

The financial analysis, using NPV and IRR, was used to determine the effect of using the local sand on these financial metrics.

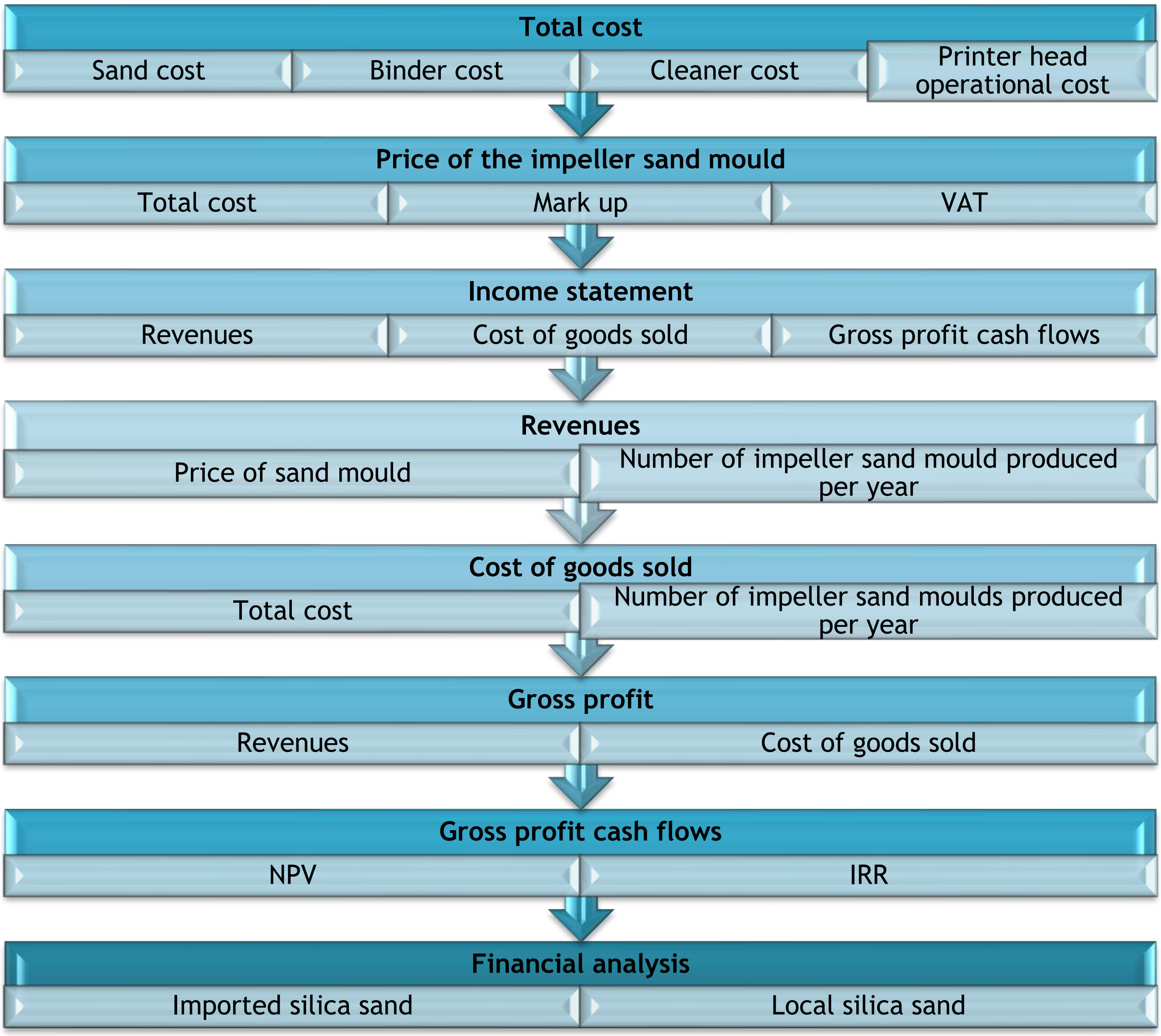

Figure 6: The financial analysis methodology flow chart

3 RESULTS AND DISCUSSION

This section presents, analyses and discusses the results of the financial feasibility and scenario analysis obtained through silica sand localisation.

3.1 Impeller sand mould dimensions

Figure 7 shows the impeller sand moulds' dimensions with their position on the build platform, which were determined using Magix software after the STL file was constructed. Table 2 shows the dimensions of the impeller sand moulds and their printing properties, which include the height (Hm) of impeller sand mould, the combined volume of the impeller sand moulds (Vm), the bottom plate size for printing both moulds, the total volume of the combined impeller sand moulds, printing time, the total number of layers and the nesting density. The nesting density presents the percentage space occupied by the entire sand mould in the printer's build platform. Based on the nesting density obtained after stacking the sand moulds using the Magix software, it was evident that two moulds of this nature could be printed simultaneously. The study analysis results were then based on the assumption that two moulds could be printed at the same time as per Figure 7.

Table 2: Impeller sand mould dimension and its printing properties based on Figure 7.

Name	Dimension or printing property
Height (Hm)	310mm
Sand mould volume (Vm)	137 937 929.136 mm^3
Bottom plate size	5 mm
Total volume of sand moulds	141 087 929.136 mm^3
Printing time of the sand moulds	10.21 hours
Total number of layers	1 050
Nesting density	69.96%

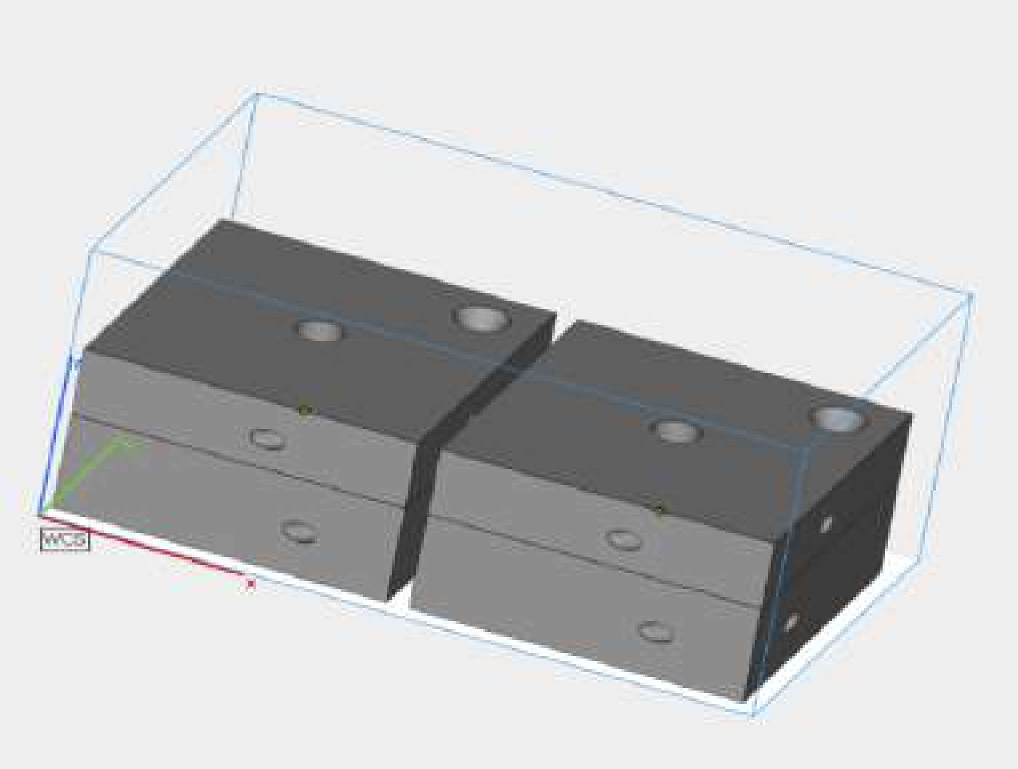

Figure 7: Two impeller sand moulds positioned in the build platform.

3.2 Cost of the impeller sand mould

Applying Equations (1), (2), (3) and (4), discussed in Section 3.2, the cost of printing the impeller sand mould and its price were calculated using the measurements laid out in Table 2. Appendix A illustrates in detail the application of the above-mentioned equations where the cost related to printing the impeller sand mould and its price were calculated, both for the imported and the Cape Flats sands. The local Cape Flats silica sand costs less than the imported silica sand. The price of the sand mould would remain the same due to the printing costs, excluding the local sand, remaining the same, thus increasing the profit.

Table 3: The total sand mould cost and price of the impeller sand moulds

Silica sand	Imported	Cape Flats
Number of moulds	2 moulds per print	2 moulds per print
Silica sand cost per kg	R20.00	R3.00
Sand cost	R5 560.76	R834.11
Binder cost	R7 511.76	R7 511.76
Cleaner cost	R72.38	R72.38
Printer head operational cost	R1 276.04	R1 276.04
Total cost	**R14 420.93**	**R9 694.29**
Total price + Markup (39.9%)	**R20 174.89**	**R20 174.89**
Price of the impeller mould (incl. VAT 15%)	**R23 201.12**	**R23 201.12**

3.3 Financial analysis results

Table 4 and Table 5, respectively, show the results of the three sections of the income statement for the imported silica sand and the local Cape Flats silica sand, after the price and the cost of the impeller sand mould have been determined. Appendix B shows in detail how the three sections were calculated using an income statement. The local Cape Flats silica sand has a higher gross profit which results in a higher gross margin, meaning more profit on the direct cost of printing the impeller sand mould. This means greater economic feasibility when printing with the local sand than the imported sand.

Table 4: The three sections of the income statement for imported silica sand

Year	Revenues	COGS	GP cash flows
0	R0	R0	-R15 200 000,00
1	R12 064 581.94	R7 498 885.50	R4 565 696.44
2	R12 667 811.04	R7 873 829.78	R4 793 981.26
3	R13 301 201.59	R8 267 521.27	R5 033 680.32
4	R13 966 261.67	R8 680 897.33	R5 285 364.34
5	R14 664 574.75	R9 114 942.20	R5 549 632.56

Table 4: The three sections of the income statement for the localised silica sand

Year	Revenues	COGS	GP cash flows
0	R0	R0	-R15 200 000,00
1	R12 064 581.94	R5 041 031.71	R7 023 550.24

2	R12 667 811.04	R5 293 083.29	R7 374 727.75
3	R13 301 201.59	R5 557 737.46	R7 743 464.14
4	R13 966 261.67	R5 835 624.33	R8 130 637.34
5	R14 664 574.75	R6 127 405.54	R8 537 169.21

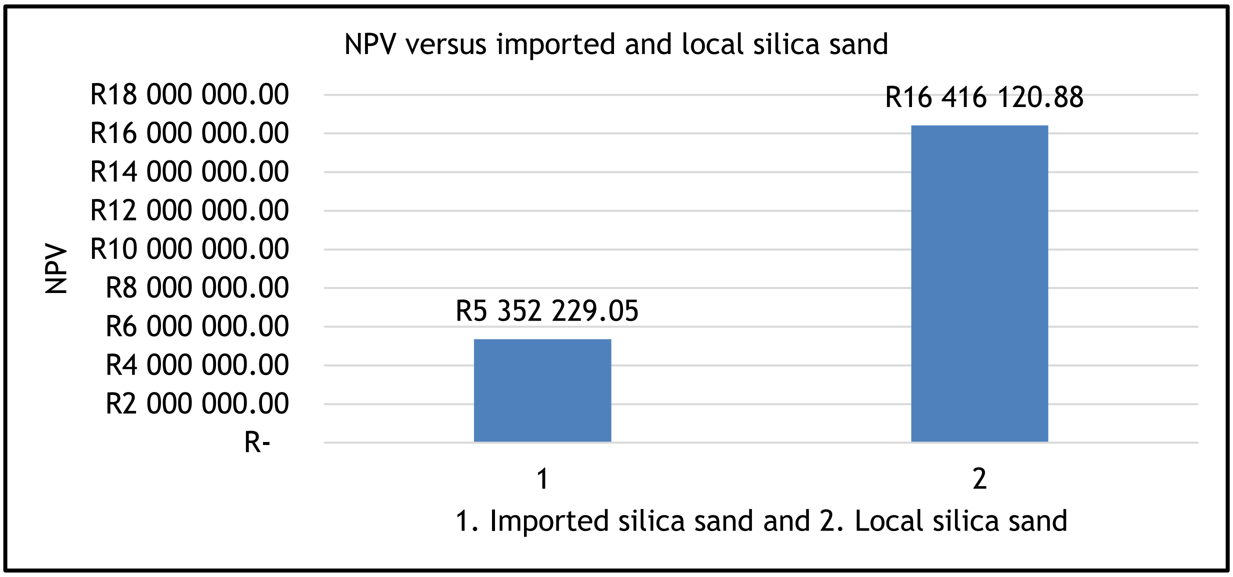

Figure 8: NPV of imported and local sand

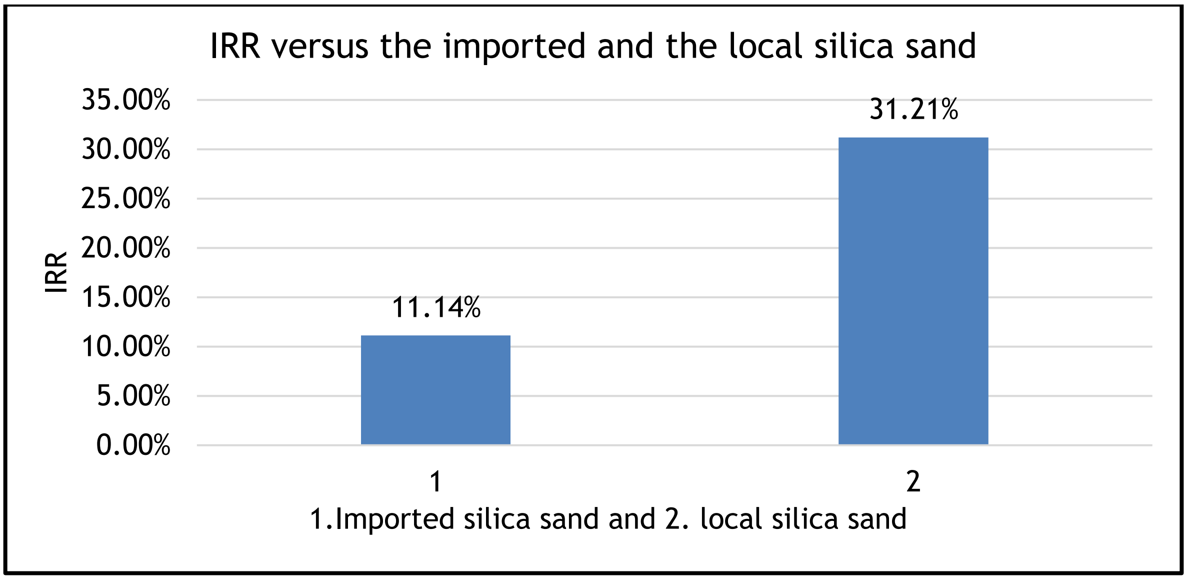

Figure 9: IRR of imported and local sand

The financial metric, the NPV and the IRR, confirms the reduced production costs when printing the impeller sand mould using the local sand. The increased NPV and the increased IRR due to sand localisation makes the binder jetting process more economically feasible for adoption by the local foundry. This is presented in Figure 8 and Figure 9 where the NPV and the IRR of the imported silica sand is R5 352 227.94 and 11.14%, respectively, while the NPV and the IRR for the localised sand is R16 416 119.76 and 31.21%, respectively. This means that localising the silica sand can increase the GP cash flows which means more profit on the direct cost of printing the sand moulds.

3.4 Cost contribution analysis

Figure 10 and Figure 11 show the sand mould cost contribution analysis when using the imported sand and the local sand for printing impeller sand moulds. The imported sand shows that the cost of the imported sand accounts for 39% of the total printing cost while the local sand contributes 9% of the total cost. This is due to the lower price of the local sand. The imported silica sand price per kg is 666.97% that of the price of the local silica sand, which significantly confirms that localising silica sand will lower the cost of printing sand moulds using the binder jetting process.

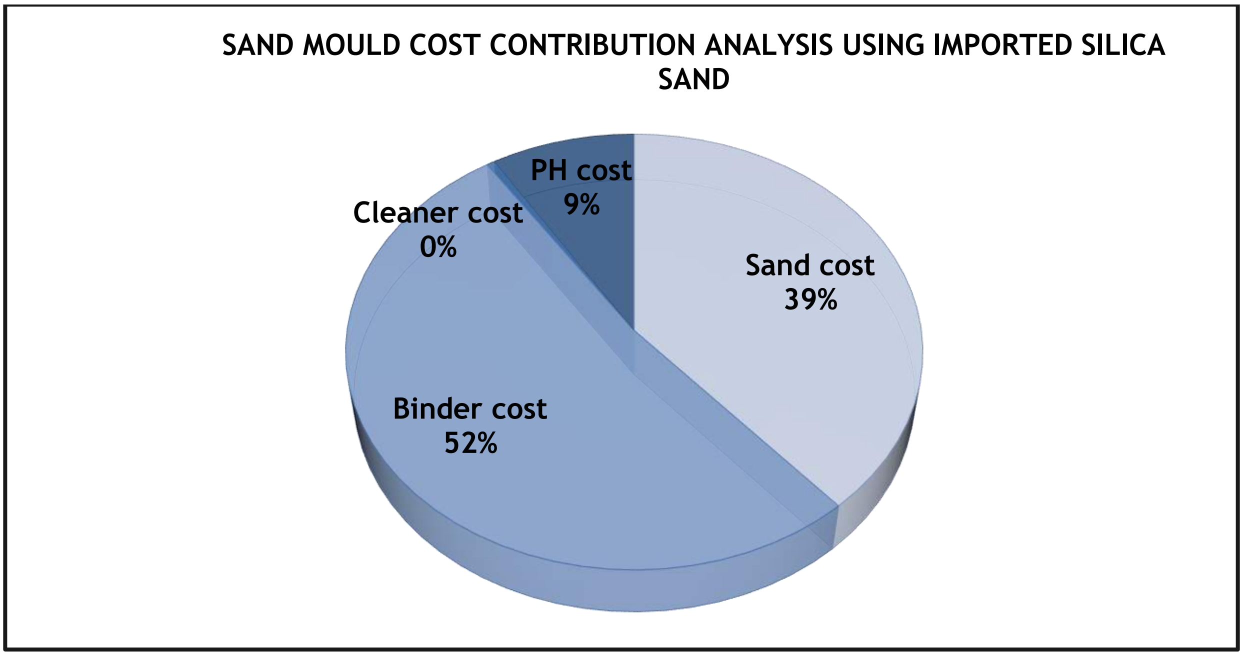

Figure 10: Cost contribution of imported silica sand

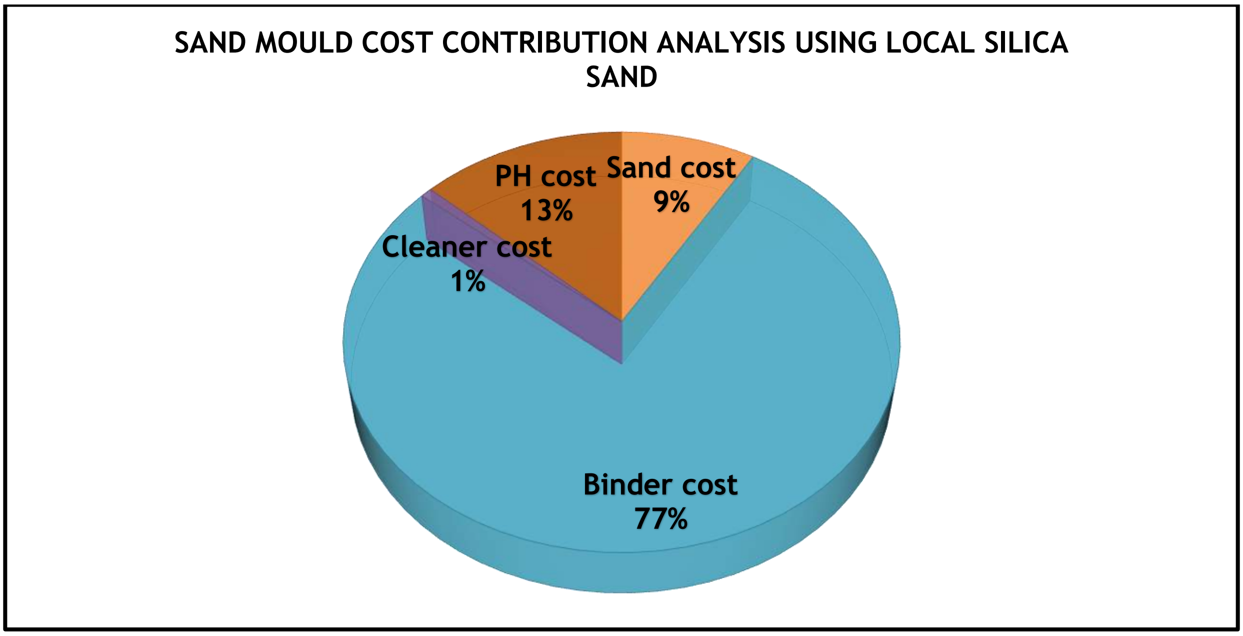

Figure 11: Cost contribution of local silica sand

4 CONCLUSION

The purpose of this investigation was to assess the financial feasibility of the binder jetting process using the Voxeljet VX1000 printer, based on a case study of an impeller sand mould. Both the imported silica sand and the local Cape Flats sand were assessed. The results showed that the direct cost of printing the impeller sand mould using binder jetting technology is economically feasible for the local foundry industry to adopt. Using the local silica sand, makes the process is even more feasible due to the increased NPV and the IRR, resulting from the lower sand price. The study also found that the imported silica sand is the second highest cost contributor to the cost of printing the sand mould. But localising the sand for the South African binder jetting process will reduce the production costs and make it the third highest cost contributor.

5 LIMITATIONS

The study's results were based only on the VX1000 printer, which uses the binder jetting process, and cannot be generalised to other machines and other AM processes. The findings were based on the printer operating 260 days per year, reducing or increasing the number of days will affect the results. Nevertheless, it is evident that localising the silica sand would reduce the binder jetting cost irrespective of sand mould or core printed or number of days that the printer is printing.

6 FUTURE WORK

Future work could consider analysing the cost of printing bigger and different moulds, to ascertain if the cost will decline even further or will remain the same.

7 GLOSARRY

Binder: An adhesive substance that is used to hold or stick things or particles together.

Binder jetting process: An additive manufacturing process that selectively creates objects by depositing a liquid binder into the powder bed layer by layer.

Casting: A manufacturing process in which a liquid metal is poured into a mould, allowed to solidify and removed from the mould to create an object.

Fedeer system: A component that is used to deliver materials or resources from one place or source to another.

Impeller: A component in a device that is used to increase the pressure and flow of liquid with a system.

Magix software: A software product that used for various purposes including the designing editing software material or components.

Printer head: A components that contains tiny nozzles and produce actual printable material in precise pattern to create the desired output.

Rapid sand casting: An innovative approach that combines the principle of traditional sand casting with modern rapid prototyping techniques, also known as rapid tooling sand casting.

Runner system: A gating system in a process of metal casting specifically processes like sand casting, investment casting and die casting.

Sand mould: A cavity created in sand to produce a shape that is used in metal casting process.

Silica sand: Industrial sand with high silicon oxide content of different specification and used for various manufacturing processes including manufacturing of foundry sand moulds, bricks, and tiles, plastering, etc.

Voxeljet VX1000 machine: A three-dimensional printer equipment that specialises in industrial three-dimensional printing and additive manufacturing technologies, specifically designed for sand printing which is used in foundry applications for creating moulds and cores used in metal casting processes.

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Appendix A: Costing of the impeller sand mould

Scost = Sand used (S*u*) × Sand cost per unit (Imported silica sand)

= Su × *Sand cost per kg*

= (((H*p* × L × W)/1 000 000) × Sd × Mr)) × Sand cost per kg
= (((310 mm × 1 100 mm × 637 mm)/1 000 000) × 1.6 kg/L × 80%)) × R20.00
= R5 560.76

Scost = Sand used (S*u*) × Sand cost per unit (Local silica sand)

= Su × *Sand cost per kg*

= (((H*p* × L × W)/1 000 000) × Sd × Mr)) × Sand cost per kg
= (((310 mm × 1 100 mm × 637 mm)/1 000 000) × 1.6 kg/L × 80%)) × R3.00
= R834.11

Bcost = (binder per mm^3 (l) × Vm × binder cost per litre) × (1 + safety factor)

= (2.516 669 620 348 19 × 10^{-8} L × 141 087 929.136 mm^3 × R1 923.24) × (1 + 10%)

= **R7 511.76**

Ccost = (Nl × cleaner per layer) × cleaner cost per litre

= (1 050 × 0.001 566 563 L) × R44.00

= R72.38

PHcost = printer head cost per hour × Tp,

where the printer head cost per hour = Printer head cost/Expected lifetime (in hours)

Printer head cost per hour = Printer head cost/Expected lifetime (in hours)

= R750 000.00/6 000 h

= R125.00

PHcost = R125.00 × 10.21 h

= **R1 276.04**

Appendix B: Income statements A and B

Income statement: A (imported silica sand at R20/kg)

Input variable of the income statement

Volume of the impeller sand mould	141 087 929.14 mm^3
Total cost of producing sand mould	R14 420.93
Price of the sand mould	R23 201.12
Sand moulds printed per day	2 per print
Total number of operational days per year	260 days
Total moulds produced per year	520 moulds (2 moulds per print × 260 days)
Average inflation rate (from 2019 to 2023)	5%
Discount rate	7%
Mark up	39.9%
Initial investment/Price of VX1000 printer	R 15 200 000.00

	0	1	2	3	4	5
Year	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Revenues		**R12 064 581.942**	**R12 667 811.041**	**R13 301 201.591**	**R13 966 261.671**	**R14 664 574.754**
Cost of goods sold		**R7 498 885.503**	**R7 873 829.789**	**R8 267 521.278**	**R8 680 897.331**	**R9 114 942.207**
Gross profit cash flows		**R4 565 696.439**	**R4 793 981.261**	**R5 033 680.324**	**R5 285 364.340**	**R5 549 632.567**
Discount factor	1.000	0.935	0.873	0.816	0.763	0.713
Present value of gross profit cash flows	**-R15 200 000.00**	**R4 267 006.018**	**R4 187 248.906**	**R4 108 982.561**	**R4 032 179.159**	**R3 956 811.314**
Net present value	**R5 352 227.948**					
Internal rate of return	**11.14%**					

Income statement: B (local silica sand at R3/kg)

Input variable of the income statement

Volume of the impeller sand mould	141 087 929.14 mm^3
Total cost of producing sand mould	R9 694.29
Price of the sand mould	R23 201.12
Sand moulds printed per day	2 per print
Total number of operational days per year	260 days
Total moulds produced per year	520 moulds (2 moulds per print × 260 days)
Average inflation rate (from 2019 to 2023)	5%
Discount rate	7%
Mark up	39.9%
Initial investment/Price of VX1000 printer	R 15 200 000.00

	0	1	2	3	4	5
Year	**2018**	**2019**	**2020**	**2021**	**2022**	**2023**
Revenues		**R12 064 581.942**	**R12 667 811.041**	**R13 301 201.591**	**R13 966 261.671**	**R14 664 574.754**
Cost of goods sold		**R5 041 031.705**	**R5 293 083.290**	**R5 557 737.455**	**R5 835 624.328**	**R6 127 405.544**
Gross profit cash flows		**R7 023 550.237**	**R7 374 727.749**	**R7 743 464.136**	**R8 130 637.343**	**R8 537 169.210**
Discount factor	1.000	0.935	0.873	0.816	0.763	0.713
Present value of gross profit cash flows	**-R15 200 000.00**	**R6 564 065.642**	**R6 441 372.826**	**R6 320 973.334**	**R6 202 824.300**	**R6 086 883.659**
Net present value	**R16 416 119.76**					
Internal rate of return	**31.21%**					

CHALLENGES AFFECTING THE ADOPTION OF ADDITIVE MANUFACTURING IN THE AUTOMOTIVE MANUFACTURING INDUSTRY: A LITERATURE REVIEW

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ABSTRACT

Additive manufacturing (AM), one of the nine technological trends of the fourth industrial revolution, commonly known as Industry 4.0, has been acknowledged as one of the technologies that will revolutionize different sectors. These techniques have the capacity to manufacture low-cost objects, leading to saving considerable amounts of time, labor, and material. However, the use of additive manufacturing and 3D technology in the automotive industry has been marred by several challenges. Therefore, when it comes to the adoption of additive manufacturing (AM) in various industries, including the automotive sector, several limitations and challenges need to be addressed to fully harness the benefits of this innovative technology. Some of the common issues include cost considerations, material limitations, process complexity, and regulatory compliance. Navigating these obstacles requires a comprehensive approach. Hence, this paper conducts an in-depth literature review, identifying the challenges affecting the adoption of additive manufacturing in the automotive manufacturing industry. The study also offers significant insights into the challenges and commercial considerations that affect this technology for automobile parts makers, which are of interest to both researchers and industry practitioners. Overall, this research contributes to filling a knowledge gap by increasing the level of awareness of the challenges that may arise when adopting AM technologies in the automotive industry.

Keywords: Additive Manufacturing, AM Technologies, Automotive industry, Parts Manufacturers

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1 INTRODUCTION

Additive manufacturing (AM) forms part of the nine technologies that are believed to have the potential to revolutionize multiple sectors in the era of the Fourth Industrial Revolution. Additive manufacturing is a layer-by-layer approach that joins materials using 3D model data to create objects. The three-dimensional object is created by joining or solidifying the material under a computer-controlled process [27]. These techniques have the capability to manufacture low-cost objects, leading to saving considerable amounts of time, labor, and material. Initially, AM technology was used only for prototyping purposes, but nowadays it is also to produce end-use products. Notably, the AM market has shown rapid growth in recent years due to advancements in quality, cost, and processing times, with the potential to affect not only the automotive industry but also other domains [5]. A number of industry areas, including medicine, construction, aerospace, architecture, food, and the arts and design, have seen AM's rapid expansion [4]. The automotive sector was one of the first to embrace AM techniques including laser powder bed fusion, fused filament fabrication, for the creation of prototypes, and more recently, inkjet printing and stereolithography for the creation of finished parts [9].

The South African Automotive Master Plan (SAAM), which was published by the Trade, Industry, and Competition department in 2018, states that South Africa needs an Energy-Efficient Vehicles technology roadmap focusing on likely changes to the domestic, regional, and global markets supplied by the local automotive part manufacturers. Securing up to 60% local content in vehicles built in South Africa must be a top priority for the SAAM. Thus, there is a need to prepare for and respond to emerging technology developments such as additive manufacturing in support of the automotive industry requirements of the 2035 SAAM vision. The automotive sector has to develop new products but doing so is frequently exceedingly expensive and a time-consuming process. The automotive sector has embraced the use of additive manufacturing (AM) technology as a crucial tool in the design and development of automobile components because it may help with the reduction of the development cycle and decrease in manufacturing and product costs. However, the adoption of AM technologies in the automotive industry is still in its early stages and there are several gaps and challenges that need to be addressed. Several major international automakers have their own additive manufacturing (AM) machines, but they are not utilizing the technology to its full potential. Most automakers are still using conventional manufacturing techniques, like subtractive ones, which have limited capabilities and are prone to waste material [10]. This paper aims to address the knowledge gap by conducting a literature review to identify the challenges affecting the adoption of additive manufacturing in the automotive manufacturing industry. Over the years, several studies have been conducted on challenges affecting the adoption of additive manufacturing. The focus of these studies has been on large companies or the use of mixed-sized samples without addressing a particular industry with its special traits. Only a few research papers such as [9, 13, and 14] covered the automotive industry. The approaches to adopting additive manufacturing often differ by industry [19].

The purpose of this paper is to review the challenges affecting the adoption of additive manufacturing and to recommend techniques to facilitate the adoption of additive manufacturing in the automotive industry. The following research objectives were defined to achieve the research aim:

- To review the state of additive manufacturing in the automotive industry.
- To review the benefits of additive manufacturing in the automotive industry.
- To review the challenges affecting the adoption of additive manufacturing in the automotive industry
- To present summary findings of the challenges affecting the adoption of additive manufacturing in the automotive industry.

- To recommend the techniques to facilitate the adoption of additive manufacturing in the automotive industry.

2 METHODOLOGY

This study adopted a critical literature review, which follows a deductive reasoning and non-systematic in approach. It allowed the researchers to comment on and analyse knowledge in conceptual and narrative manner. The scholarly writings were not based on a certain period, however latest studies were considered. A critical review is subjective and based on the relevance of the studies [16]. The scholarly writings were included on the relevance of the abstract title, abstract and if the aim, and key findings or key concepts were not coming out clearly, the paper was not considered. The study used only published materials such as peer-reviewed journals, books, conference papers and technical reports. Only papers that were written in English language formed part of the review.

The benefits of additive manufacturing (AM) and the barriers preventing its adoption in the automobile manufacturing sector were identified, assessed, and shortlisted after reviewing a number of scientific articles. Understanding the obstacles to the adoption of additive manufacturing (AM) technologies in the automotive sector is the first step in overcoming them. Therefore, it is necessary to assess the benefits and challenges of AM in the automotive sector. Thirty-two papers have been analysed, and the study uses a rigorous methodology to combine, assess, and clarify segments of the findings of several research studies, paying particular emphasis to the advantages of AM and the challenges impacting its adoption.

3 LITERATURE REVIEW

3.1 Additive Manufacturing

In comparison with the subtractive and formative manufacturing processes, additive manufacturing, which is executed through 3D printing, uses a variety of materials, including metals, polymers, and composites, to build parts layer by layer [29]. AM allows for the construction of complex geometries that are difficult to accomplish using traditional manufacturing processes. The materials used for the automotive component include plastics, metals, and composites. As stated in the ISO/ASTM 52900 standard [1], additive manufacturing is comprised of seven different process categories, as shown in Figure 1. These categories include binder jetting, material extrusion, powder bed fusion, vat polymerization, direct energy deposition, material jetting, and sheet lamination.

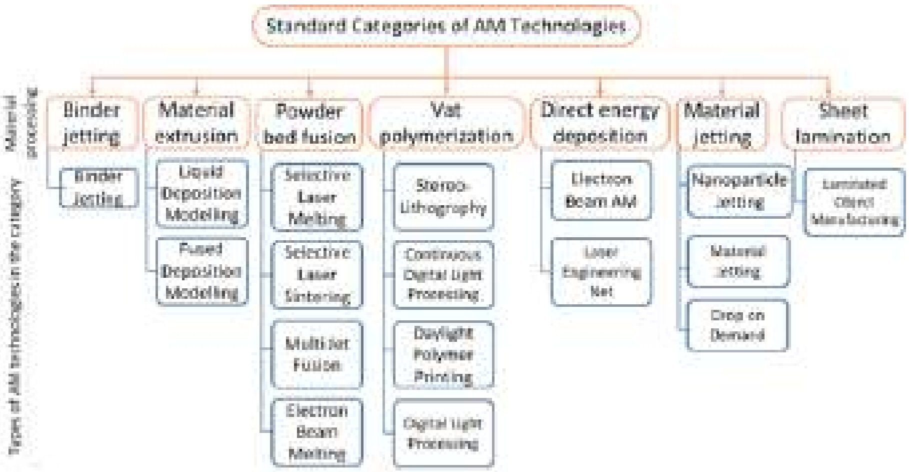

Figure 1. The seven standardized categories of additive manufacturing techniques [2]

Different layer building and consolidation techniques are used in AM processes. To melt or sinter (to form a homogenized mass without melting) metal or plastic powder, some approaches apply heat energy from laser or electron beams that are controlled by optics. Other procedures properly spray the binder or solvent onto powdered ceramic or polymer using inkjet-type printing heads [26]. The most used AM technologies include laminated object manufacturing (LOM), stereolithography (SLA), selective laser melting, fused deposition modeling (FDM), (SLM), and selective laser sintering (SLS) [25]. The key to expanding the range of materials handled as well as the applications for a given additive technology is the creation of parameters. Based on the condition of matter that is most crucial to the process, the processing processes can be categorized into five categories: melt, solid, powder, dispersion or solution, and vapor. To enable the understanding and application of common scientific and technical principles to a variety of materials, operations in each of the categories are used to create ceramics, polymers, and metals [3].

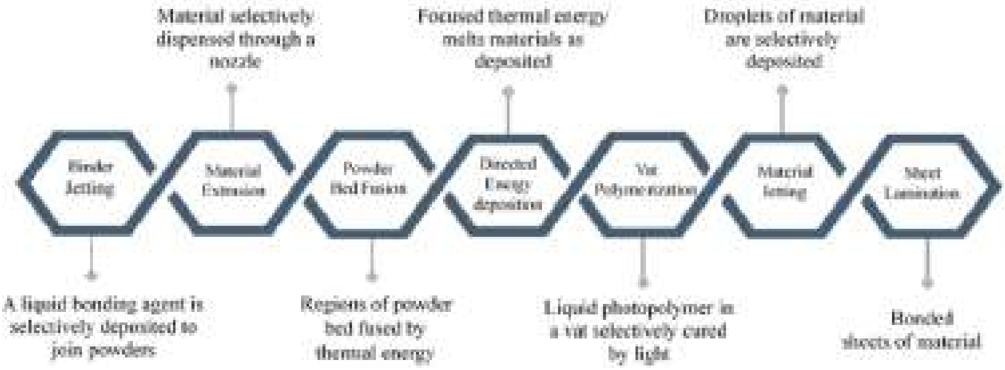

Figure 2. Methods of material processing in the standardized AM techniques [2]

The AM process in the automotive field involves different steps, as outlined in Figure 3. Using computer-aided design tools like Solid Works and CATIA, a 3D model of the vehicle component is first created. The design is then transformed into a 3D printer-compatible format. The 3D printer creates the part by adding layers of material on top of each other based on the design. The printer uses a laser or other heat source to melt the material and fuse it together to form the desired shape. Once the part is printed, it may require additional post-processing to improve its properties or appearance, which can include polishing, sanding, or coating the part with a protective layer. The final step in the process is to inspect the part to ensure it meets the required specifications. This can involve non-destructive testing techniques such as X-rays or ultrasounds to detect defects or flaws.

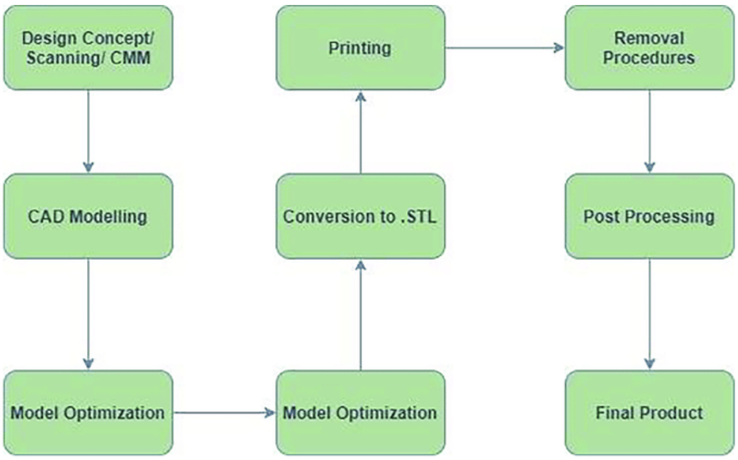

Figure 3. Key processing steps and application of AM in the automotive

3.2 Adoption Of Additive Manufacturing In The Automotive Industry

AM technologies have been used to manufacture tiny quantities of structural and functional parts like as drive shafts, brake systems, and engine exhausts for high-end, low-volume autos such as luxury cars. AM techniques have been effectively used by businesses and research institutions to produce useful components for racing vehicles [26]. This is due to the fact that racing vehicles, as opposed to passenger automobiles, typically use lightweight metals (such as titanium), have extremely complicated construction, and have low production volumes. Figure 4 illustrates the summary of the components that are presently manufactured using additive manufacturing and the components with the potential to be manufactured using AM in the future. The diagram illustrates the exterior parts in vehicles are currently manufactured through selective laser sintering AM technologies using polymer material. Fluid handling parts such as pumps and valves are manufactured through selective laser melting, and electron beam melting using aluminum alloy material. The exhaust and emission components are manufactured through selective laser melting using aluminum alloys. Interior and seating components can be manufactured through AM technologies such as selective laser sintering and stereo-lithography using polymers material. Wheels, tires, and suspension parts can be manufactured through selective laser sintering, inkjet, and selective laser melting using polymers and aluminum alloys material. Electronic parts can be manufactured through selective laser sintering using polymer material. Frame, body, and door components can be manufactured through selective laser melting using aluminum alloy material. Powertrain and drivetrain components can be manufactured through selective laser melting, and electron beam melting using aluminium and titanium alloy material.

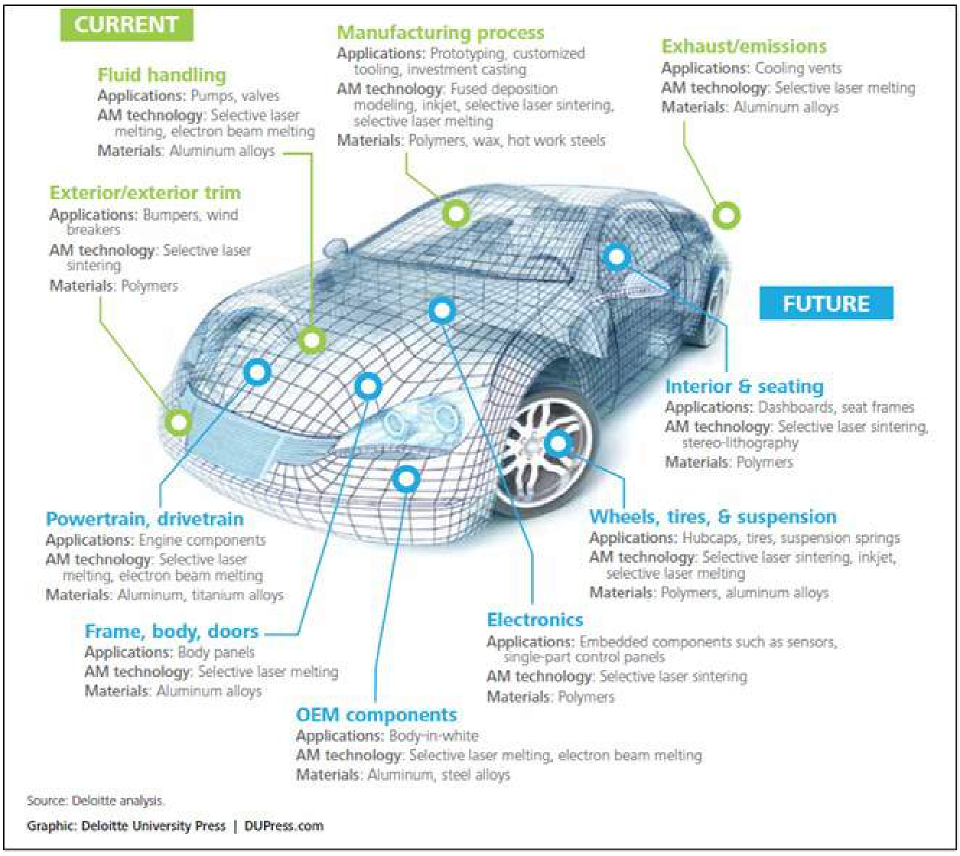

Figure 4. Application of AM in the automobile industry [10]

3.3 Benefits of additive manufacturing in the automotive industry

Various studies have been conducted to investigate the benefits of additive manufacturing in the automotive industry in terms of sustainability and its contribution to the economy [17]. All the additive manufacturing capabilities allow automotive manufacturers to drive significant change within the supply chain. A study conducted by Elakkad [14], in Egypt concluded that automotive manufacturers utilising AM technologies gain a major competitive advantage in the market as compared to their competitors. The technology has the potential to improve the efficiency of automobiles by increasing the capacity for designing optimised parts, which in turn contributes towards high fuel efficiencies [9]. A study by Gechev [15], revealed that AM can save companies up to 40% of material as compared to subtractive manufacturing where 96% of material can be removed to create a final component, and it does not require expensive punches, molds and tooling for injection molding. Unlike subtractive manufacturing, AM uses only the material that is necessary to produce a component which reduces scrap and cut down material usage (Deloitte university press). The use of AM has significantly saved the costs and expenses previously incurred by automotive manufacturers as it decreases the cost of manufacturing vehicle components, which in turn decreases the cost per unit of vehicles, thus increasing the net revenue and profitability of the automobile companies in the market [14]. Additive manufacturing technology does not only have the ability to create complex geometries and structures, but also it is currently one of the manufacturing technologies that guarantee the highest level of customization of parts [15]. AM is a rising technology with capabilities and the potential to limit environmental impacts in the automotive manufacturing industry by promoting sustainability. It minimises material waste, reduces energy consumption, and enables the use of lightweight materials, it contributes to the development of more fuel-efficient vehicles [20]. The ability to repair and replace specific components through 3D printing extends the lifespan of vehicles, reducing overall waste and environmental impact. The technology also fosters product innovation by enabling automotive manufacturers to experiment with prototypes at a much faster rate and produce a vast variety of prototypes, some of which are not entirely viable via traditional manufacturing methods [11]. With AM Automakers can quickly produce functional prototypes, test them, and make necessary design improvements in a significantly shorter timeframe compared to traditional manufacturing methods. This accelerated development cycle allows for faster time-to-market and enables automotive companies to stay ahead in a highly competitive industry [7]. The advantages of additive manufacturing compared to traditional production are shown in Table 1 for the automotive manufacturing sector.

Table 1: A comparison of the benefits of additive manufacturing vs traditional manufacturing

Additive Manufacturing	Traditional Manufacturing
Shorter production time	Longer production times
Reduced material waste	Increased material waste
Easily customized	Difficult to customize
Cheaper to make prototypes	Expensive to make prototypes
Reduced labor costs	Increased labor costs

Additive manufacturing has brought numerous benefits to the automotive industry. From enhanced design capabilities and cost savings to increased agility and sustainability, 3D printing has become a transformative technology, shaping the future of automotive manufacturing [23]. Despite the potential advantages of producing customized or complex shape parts on-demand and on-site, this innovative production method has not yet been widely used. According to research, there are still obstacles preventing automotive manufacturers from incorporating additive manufacturing technologies more generally into their manufacturing processes. These obstacles must be overcome before AM can adopted widely [30].

3.4 Challenges affecting the adoption of additive manufacturing in the automotive industry

When it comes to the adoption of additive manufacturing (AM) in various industries, including the automotive sector, several challenges need to be addressed to fully harness the benefits of this innovative technology. From cost considerations and material limitations to process complexity and regulatory compliance, navigating these obstacles requires a comprehensive approach. Thomas-Seale et al. [29], carried out a case study in the UK's heavy machinery, automotive, defense, aerospace, and medical device industries to identify and comprehend the existing industrial hurdles to the advancement of additive manufacturing for end-use products. The widespread adoption of additive manufacturing (AM) in industry has been hampered by a number of issues, including design, tolerances, education, software, cost, traceability, materials, scalability, machine limitations, in-process monitoring, repeatability, mechanical properties, scalability, finishing, validation, standards, inspection, quality, and sterilization. Understanding and overcoming the challenges associated with AM adoption is vital for automotive manufacturers to leverage its advantages and drive innovation [13].

Use full justification

3.4.1 Cost Considerations

According to Attaran [6], cost remains a significant factor hindering the widespread adoption of additive manufacturing in the automotive industry, particularly due to higher initial investment and per-unit production costs. Thomas and Gilbert [28], conducted a study on the cost and cost-effectiveness of additive manufacturing, the aim of the study was to examine the cost of implementing additive manufacturing and identify potential areas for cost reduction. The study revealed that when compared to conventional manufacturing techniques, additive manufacturing technologies are more expensive to produce a product. This could be as a result of the material costs, which account for a sizable amount of the cost of an AM-produced good. Increasing the adoption of AM may lead to a reduction in raw material costs through economies of scale. There is still a need for standardisation for those additive manufacturing materials that can currently be treated within the appropriate quality criteria [11]. A production cost analysis was conducted by Zhao et al. [32] based on two mainstream additive manufacturing systems for automotive applications. The outcome demonstrated that the expense of metal powder is what is preventing the automotive sector from using additive manufacturing more widely. The research by Thomas and Gilbert [28] also revealed that as the cost of producing goods using the technology falls as the use of additive manufacturing rises; between 2001 and 2011, the average price fell by 51% after accounting for inflation. As a result, it would be worthwhile to conduct further research in this area if additive manufacturing technology improves at the same rate as in the past because the price of making automobile components might decrease. A study conducted by Kulkarni et al., [21] concluded that Adoption of additive manufacturing technology in the manufacturing business is hindered by elements like machinery costs and higher levels of integration costs for metal components.

3.4.2 Technological Challenges

Technological barriers in terms of process implementation, materials, quality assurance, and post-processing; play a significant role in hindering the widespread adoption of additive manufacturing in the automotive industry [18]. AM is mainly for prototyping and the reason is that a lot of automotive organisations and their engineers are impeded by conventional design constraints. According to the Deloitte global report published in 2020, There are a number of technological issues that must be resolved, mostly in the fields of materials and processing, in order to advance AM use beyond the goal of prototyping. The development of materials for conventional manufacturing processes has already spanned years in terms of both processability and essential product characteristics. Through widely utilized and accepted norms, the industry has set traditional production material standards and specifications. Because additive manufacturing (AM) is a new technique, there is still a gap to be filled in terms of advances, standardisation, and material certification. Lack of information on long-term material properties has led to quality control challenges, and questions have been raised concerning the security of AM against counterfeiting [18]. The complex geometries of automotive components, combined with the requirement for precise and consistent printing, pose additional difficulties. Several studies have identified quality assurance as the biggest challenge of parts produced by additive manufacturing and that To increase the quality of the parts, inspection and monitoring procedures must be put in place. [8]. The limited material options with suitable properties for automotive applications restrict the range of parts that can be reliably produced using additive manufacturing. Furthermore, challenges related to post-processing, such as surface finishing and dimensional accuracy, need to be addressed to ensure the produced parts meet the industry's stringent quality standards [22]. Addressing these technological barriers is crucial to enable additive manufacturing to achieve the scalability necessary for automotive production. Advancements in hardware technology, materials research, process optimization, and post-processing techniques are key areas that require attention to overcome these barriers and unlock the full potential of additive manufacturing in the automotive industry [29].

3.4.3 Skilled Workforce Requirements

Another of the greatest challenges of additive manufacturing adoption is the lack of qualified and experienced technicians who are familiar with AM technology and can use 3D printing. It takes time to train individuals in the specialized design and manufacturing sectors needed for this fast-advancing industrial technology. AM requires qualified personnel trained in Computer-aided design (CAD), machine operation, material preparation and handling, maintenance, supply chain management, and quality assurance, in order to become a dependable and effective process [24]. Currently, most AM training is not standardised. The formalisation of training with specialised skill development programs is necessary for the technology to advance.

3.4.4 Process Scalability

The scalability challenge is emphasized as a crucial obstacle to overcome. To create object layers, AM methods frequently use liquid polymers, or a powder made of plaster or resin. These materials lack material strength, making AM impossible to build large-scale objects. Large-sized things are sometimes impracticable since they take a long time to manufacture and frequently have a rough, ribbed surface quality when made with AM techniques. This appearance results from the post-processing step of stacking huge powder particles or plastic beads on top of each other, which gives the product an unfinished appearance [26]. The widespread adoption of additive manufacturing in the automotive sector is being hampered by the lengthy production times involved in the technique. Some parts and components may be so large that they take a long time to print and post-process and files can be hard to scale for large orders. Robust investment in high-speed AM is a noted area of material scientists, research for academics, and commercial interests. Even though this has been a significant area of research in recent years, there has been limited progress on this front to date. The low-level production AM presently delivers is not practical for widespread commercial use in a sector driven by volumes [24].

3.4.5 Regulations and Intellectual Property Hurdle

Additive manufacturing is a cutting-edge manufacturing technology. According to Vogel [31], AM product designs cannot be copyrighted; they can only be patented. The possibility for manufacturing counterfeit components is significant because patent protection is unclear, and its enforcement is difficult. The process of additive manufacturing for automotive components is now being regulated and standardized, which is significant for businesses that make cars, since the safety of drivers and passengers is a concern. While 3D printing car parts is a great step in the manufacturing technology world, it is still in the development stage, particularly in terms of laws and regulation [24].

3.5 Summary of the challenges affecting the adoption of additive manufacturing in the automotive industry

The challenges are summarised and grouped in Figure 4 into six major categories (Machine, Method, Material, Man, Measurement, and Environment). By understanding and addressing these factors within the context of machine, method, material, manpower, measurements, and environment; stakeholders in the automotive industry can work towards overcoming challenges and promoting the wider adoption of AM in their operations.

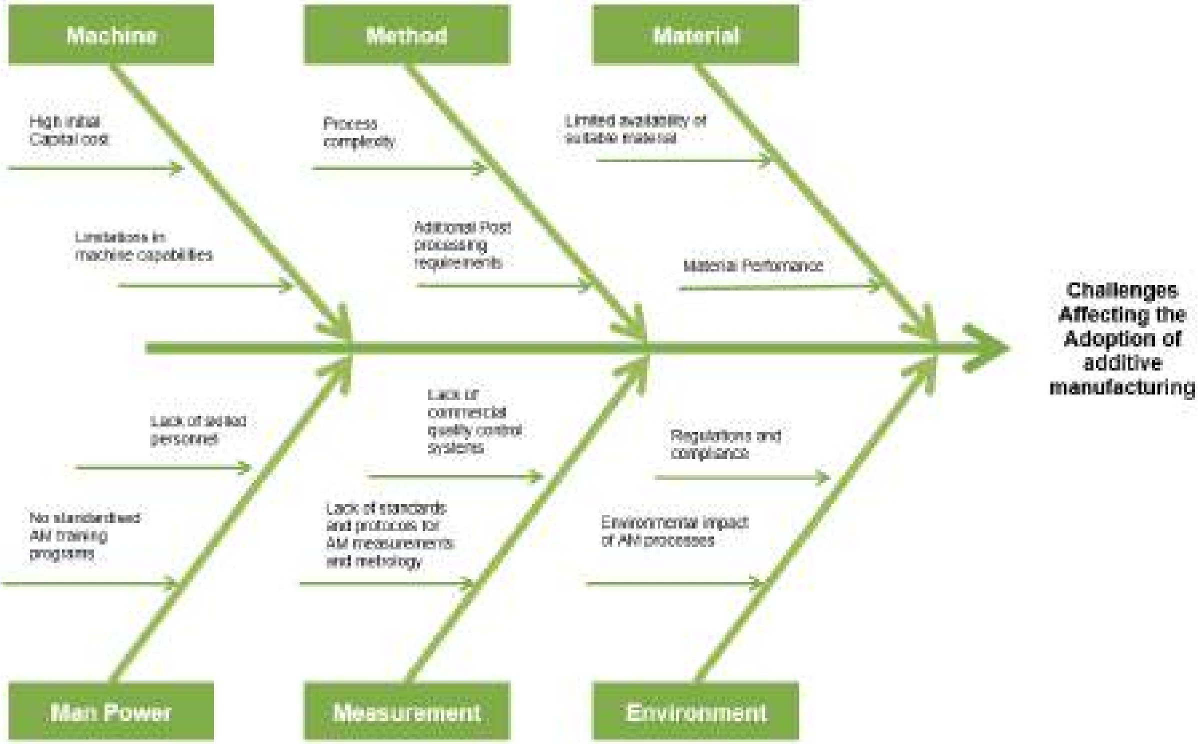

Figure 4. Challenges affecting the adoption of additive manufacturing in the automotive industry

In terms of machines, limitations in capabilities such as build size, speed, and accuracy can hinder widespread adoption, along with the high initial capital investment and maintenance costs associated with AM machines. The method aspect highlights the complexity of AM processes, requiring specialized knowledge and expertise, as well as additional post-processing steps that contribute to production time and costs. Material challenges arise from the limited availability of suitable automotive materials and the need for consistent performance in areas like strength and durability. Manpower concerns involve a skill gap in AM technologies and design expertise, requiring adequate training programs to develop a competent workforce. The measurements aspect emphasizes the importance of quality control and standardization to ensure dimensional accuracy and part integrity. Lastly, the environmental factors encompass the assessment of AM's sustainability, including energy consumption, waste generation, and compliance with environmental regulations. By addressing these factors comprehensively, the automotive industry can overcome challenges and foster the wider adoption of AM while maximizing its potential benefits.

4 RECOMMENDATIONS TO FACILITATE THE ADOPTION OF AM IN THE AUTOMOTIVE INDUSTRY BY DIFFERENT STAKEHOLDERS

Addressing the challenges facing the adoption of additive manufacturing technologies in the automotive industry will require a concerted effort from multiple stakeholders, including government, industry, and research organizations. By working together and putting strategies in place, it is possible to realize the benefits of additive manufacturing and create a more robust and innovative automotive manufacturing sector. The automotive industry needs to start using additive manufacturing on a significant scale in end-production in the following key areas where the most research and funding are needed.

Machine:

- Research and Development: Continuously invest in research and development to improve AM machine capabilities, such as larger build sizes, faster production speeds, and higher accuracy.
- Cost Optimization: Explore options for cost-effective AM machines, such as lower-cost models or leasing options, to reduce the initial investment burden.
- Collaboration: Partner with machine manufacturers and suppliers to develop customized machines tailored to automotive industry requirements.

Method:

- Knowledge Sharing and Training: Facilitate knowledge sharing and training programs to educate the workforce on AM processes, design optimization, and post-processing techniques.
- Process Optimization: Invest in process optimization to streamline AM workflows, reduce post-processing requirements, and improve overall efficiency.
- Standardization: Collaborate with industry organizations and stakeholders to establish standardized protocols and best practices for AM methods in automotive applications.

Material:

- Material Development: Invest in research and development of new materials specifically tailored for automotive AM applications, focusing on cost-effectiveness, performance, and availability.
- Material Certification: Collaborate with material suppliers and regulatory bodies to establish reliable certification processes that ensure the quality and performance of AM materials.

Manpower:

- Education and Training Initiatives: Establish partnerships with educational institutions and organizations to develop specialized training programs for AM technologies, design for AM, and process optimization.
- Workforce Development: Encourage existing employees to upskill through training programs, certifications, and knowledge-sharing platforms.

Measurements:

- Quality Control Systems: Implement robust quality control systems, including advanced inspection techniques, to ensure dimensional accuracy, surface finish, and part integrity.
- Standardization and Metrology: Participate in the development and adoption of industry-wide standards and protocols for AM measurements and metrology to ensure consistency and reliability.

Environment:

- Sustainable Practices: Embrace sustainability by optimizing AM processes to minimize energy consumption, reducing waste generation through recycling and efficient material usage, and adhering to environmentally friendly manufacturing practices.

5 CONCLUSION

An overview of the benefits of additive manufacturing and the factors affecting the adoption of additive manufacturing is presented in this paper. Additive manufacturing (AM) brings numerous benefits to the automotive industry, revolutionizing the way vehicles are designed, developed, and manufactured. One significant advantage is the ability to create highly complex and customized geometries that were previously impossible or impractical with traditional manufacturing methods. This enables lightweight designs, optimized part performance, and improved fuel efficiency. AM also offers faster prototyping and product development cycles, allowing for rapid iteration and reduced time to market. Moreover, AM enables the production of on-demand spare parts, reducing inventory costs and improving supply chain flexibility. With its ability to consolidate multiple components into a single part, AM reduces assembly complexity, enhances reliability, and minimizes the risk of component failure. Additionally, AM allows for design and production optimization, reducing material waste and energy consumption. Overall, additive manufacturing empowers the automotive industry with enhanced design freedom, accelerated innovation, cost efficiency, and sustainable manufacturing practices. However, there are still several challenges preventing its widespread adoption within the industry. The high cost of additive manufacturing equipment and materials remains a major hurdle. The initial investment required to set up and maintain additive manufacturing facilities is substantial, deterring many automotive companies from fully embracing this technology. The limited scalability of additive manufacturing poses a challenge. While AM printing offers great flexibility in producing complex parts, it currently falls short in terms of volume production compared to traditional manufacturing methods. The speed of additive manufacturing is another limiting factor, as it often takes longer to print a part compared to mass production methods. Furthermore, the quality and consistency of AM-produced parts need to match or exceed the standards set by conventional manufacturing processes. Strict regulatory requirements and certifications, especially in safety-critical automotive components, add complexity to the adoption of additive manufacturing. Overall, the challenges highlighted the importance of careful planning and evaluation when considering the adoption of additive manufacturing in the automotive industry. To overcome these challenges, ongoing research and development efforts are necessary to improve the cost-effectiveness, scalability, speed, and quality of additive manufacturing techniques in the automotive industry. Additionally, collaboration between automotive manufacturers, material suppliers, and regulatory bodies is vital to address the challenges and develop industry-wide standards for additive manufacturing. As these challenges are gradually overcome, additive manufacturing has the potential to revolutionize the automotive industry by enabling customizability, reducing lead times, and fostering innovation in design and production processes.

Regulatory Compliance: Stay updated on environmental regulations and proactively implement practices to ensure compliance with relevant standards.

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DEVELOPING AN INDUSTRIAL ENGINEERING INSPIRED ADOPTION FRAMEWORK FOR ELECTRIC VEHICLE MANUFACTURERS IN SOUTH AFRICA

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ABSTRACT

This paper explores the key marketing and implementation aspects involved in the phase-in of Electric Vehicles (EVs) in South Africa. The problem is that EV manufacturers are experiencing difficulties convincing potential customers to purchase and adopt an EV lifestyle. Therefore, this study aims to enhance the management of EV owners' lives by planning their lifestyles more efficiently by utilizing an Industrial Engineering (IE) adoption framework to help EV manufacturers convince potential customers to purchase and adopt an EV lifestyle. The DMADV methodology is the overarching methodology used in this paper. Furthermore, Kernel Theory, Lean Principles, Best Practice Principles, and Systems Thinking is utilized. All these components are used to design an adoption framework that promotes an improved EV lifestyle that any EV manufacturer can utilize. If more vehicle owners in SA adopt an EV lifestyle it will benefit the environment and also provide advantages to vehicle owners' daily lives.

Keywords: Electric Vehicles, Adoption Framework, Industrial Engineering, Change Management, Kernel Theory.

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1 INTRODUCTION

1.1 Background

A company's aftersales service could improve the firm's long-term brand image and brand loyalty. The aftersales department has the potential to produce 80% of a company's profit and improve its Operational Performance Indicators (OPIs) [1]. For the automotive industry, Internal Combustion Engine (ICE) Vehicles are phasing out worldwide with the phase-in of Electric Vehicles (EVs).

This research is focused on the aftersales of the automotive industry and will focus on the phase-in of EVs in South Africa (SA) and the difference in lifestyle of EV owners compared to conventional ICE vehicle owners. However, this will be done from an Industrial Engineering (IE) perspective. Which can result in more lean, more efficient, and more profitable business practices while increasing customer service and quality [2]. With EVs being quite new in SA, some logistical considerations are required in terms of daily planning. As infrastructure is still developing, it is imperative to recognize the challenges that may be faced when planning daily and long-distance travel [3].

In this paper, the advantages and challenges that EVs have to offer will be considered. Challenges may include, loadshedding, distance or location of charging stations, vehicle range, high buying cost, etc. Many vehicle owners in SA are still reluctant to make the shift to EVs since the benefits are not clearly marketed. It could be beneficial for customers to have a framework or roadmap of sorts on how to navigate this transition from ICEVs to EVs.

1.3 Examination of Core Problem

Even though our planet experiences climate change and greenhouse gas emissions must be lowered, EVs are not being mass adopted in SA as opposed to developed countries. Many reasons contribute to this fact, such as the challenges of owning an EV currently in SA. The cause-and-effect diagram in Figure 1 summarizes the challenges related to EVs in SA.

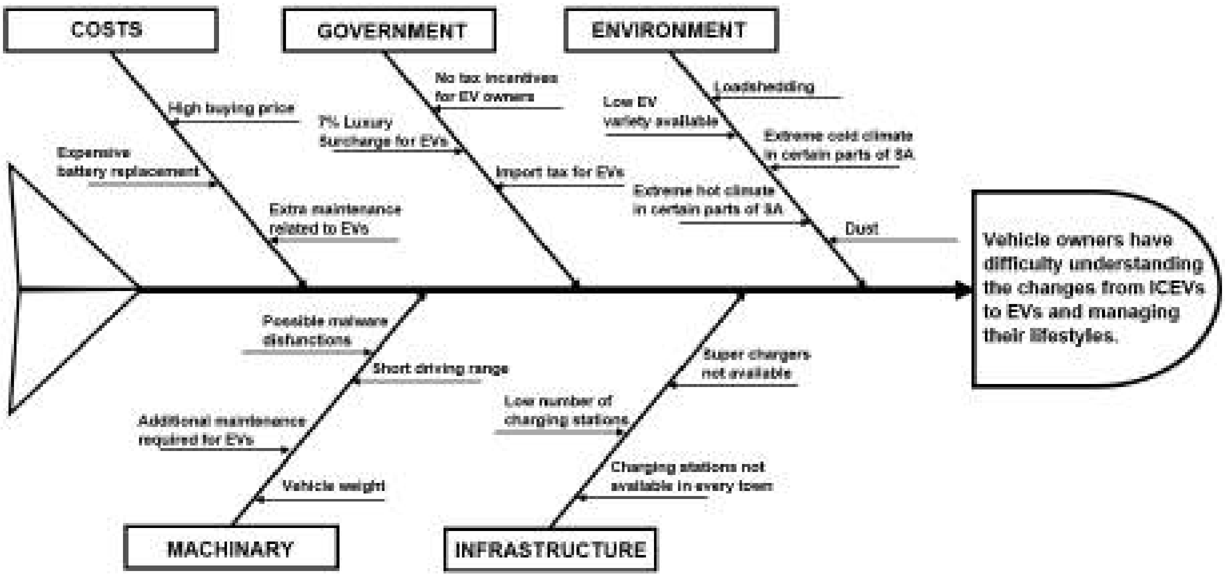

Figure 1: Cause-and-effect diagram – redrawn from Coccia.M. *[15]*

These challenges were identified through research and verified by employees of a German automotive association. Some of the factors shown in the cause-and-effect diagram have a larger effect on owners than others. The cost and government branches have a larger effect on the decision of whether an individual can afford to own an EV. However, the environment, machinery, and infrastructure branches influence the daily lives (management and planning) of EV owners and are therefore more relevant to this study.

1.4 Problem Statement

With the expected influx of Electric Vehicles in South Africa, Electric Vehicle manufacturers are experiencing difficulties convincing potential customers to purchase and adopt an Electric Vehicle lifestyle.

1.5 Aim

This study aims to help EV manufacturers convince potential customers to purchase and adopt an EV lifestyle utilizing an IE inspired adoption framework.

For this paper, an adoption framework for EVs is developed and verified through a small survey using lean, systems thinking and IE practices. In the subsequent sections, a literature review will be conducted to explain the key concepts of this paper, which will be followed by how these concepts were utilized in the methodology section. This is followed by the findings and results of the study as well as its verification and validation. Furthermore, the solution is discussed along with conclusions and recommendations.

2 LITERATURE REVIEW

2.1 EV framework requirements and considerations

From literature, four essential steps can guarantee the success of global decarbonization initiatives [4], namely:

1. Setting up a solid institutional and legal foundation for a low-carbon policy.
2. Converting low-carbon goals into a realistic roadmap for each economic sector.
3. Implementing the necessary policies and methods to carry out the roadmap.
4. Conducting public campaigns that address the socio-economic effects of the shift to a low-carbon economy.

Tongwane, M and Moeletsi, M (2021) [4] advocate that if EVs are to be effective and function more economically, changes in driving behaviour are necessary. The range covered, charging habits, and driving style all affect battery life. Additionally, policies that encourage EV charging during off-peak hours can enhance the amount of storage space available for renewable energy sources. They argue that EVs can store renewable energy, even though they will not have a significant impact on the nation's present energy balance [4].

Moreover, the current socio-economic conditions have a momentous impact on widespread car ownership, travel frequency, and occupancy patterns [4]. They believe that three major socio-economic factors affect the demand for EVs [4]:

1. Vehicle equipment – price and battery characteristics.
2. Social factors – lifestyle choices, income, household size, and literacy levels.
3. External factors – fuel prices and the accessibility and availability of infrastructure.

Presently, batteries account for 40% to 50% of the overall cost of EVs [4]. The intended CO^2 reduction targets cannot be met because of the low adoption of EVs due to their high total cost. In general, all technology becomes cheaper as it is developed further [5]. Fiscal incentives are therefore necessary, together with regulatory measures to close the parity gap [4], [6]. The South African government is exploring incentives for manufacturers to build affordable vehicles in response to this limitation brought about by low demand due to excessive pricing [4].

Long journeys are typical for many passengers, even though vehicles in SA only travel approximately 40 km on average per day [4]. For commercial needs, users have a range of battery options up to more than 300 km. Thus, they believe that effective marketing based on vehicle characteristics, price, and infrastructure availability becomes a beneficial strategy [4]. The minimal charging infrastructure that presently exists is considered a barrier to SAs rapid adoption of EVs [4]. However, there are new energy infrastructures in development. Fast-charging stations within certain charging infrastructures have been installed by the commercial sector in numerous public locations, including malls and office parks [4]. Additionally, since most EV users find it more convenient to recharge their batteries at home, it is crucial to include private charging in addition to recharging at public and commercial locations.

2.2 Habit Alteration Knowledge Base

Based mainly on the work of Chung, Lessard, Andreev & O'Reilly [7], the "habit alteration knowledge base" kernel theory aims to break established habits and promote preventive behaviours. It is centred around the correction of human behaviour. Thus, lifestyles can be adapted through the alteration of current routines. The aim is to repeat cue routines that favour more desirable alternative behaviour. There are four techniques (subsequently coded as 1K to 4K) that could be repeated throughout people's daily lifestyles. This could lead to the formation of "automatic behaviour".

Techniques targeting planning activities (1K) incorporate four methods concentrating on planning activities to alter ingrained habits:

1. Action planning: Goal-directed behaviours must be identified and linked to situational cues.
2. Coping planning: "If-then" statements are utilized as a self-control technique to consider obstacles that can obstruct action plans.
3. Decomposing the desired behaviour –The intended behaviour is broken down into a series of straightforward acts. Complicated behaviours are less likely to become automatic.
4. Stacking behaviours - Decomposed actions are placed after previously established behaviours (habits). People are more likely to undertake a desired behaviour when it is activated by another cue. Thus, the accomplishment of an established behaviour will cause the start of the desired action.

Action and coping planning assist people to predict how they will act in various circumstances and contexts. Therefore, these activities help change the cue-routine relations of a habit.

Techniques centred around self-monitoring (2K) focus on the target behaviour's self-monitoring. Strategies keeping track of how many times an individual avoided the undesirable behaviour or engaged in the desired behaviour, to break an established habit and encourage preventive behaviours, can be utilized. The results of these techniques will function as alerts when an individual has relapsed to undesirable behaviour. Self-monitoring enables people to recognize that they are carrying out the activity consistently, which promotes contextual stability and cue-routine linkages. Lastly, the outcomes can demonstrate the advancement achieved towards the ultimate objective and foster a sense of success.

Techniques aiming to use rewards (3K) create habits that begin with a cue that triggers predictable behaviour with the goal of receiving a reward. The brain is more likely to recognize future cues and replicate the pattern when the reward is deemed valuable. Duhigg popularized this loop as the habit loop in grey literature. Early on, behaviours that are deemed rewarding can support repeating the habit loop while those that cause negative effects are abandoned.

Therefore, it is essential to emphasize both the advantages of the desired behaviour and the repercussions of the undesired behaviour. However, it is critical to distinguish between extrinsic (like cash) and intrinsic (like pleasure) rewards. Extrinsic rewards may initially motivate behaviour, but when anticipation for the reward develops, they may lose their effectiveness. Finding intrinsic rewards that complement people's identities can help them internalize and repeat the desired behaviour.

Techniques focused on managing the context of the behaviour (4K) seek to control the context of the undesirable behaviour to prevent it while encouraging the desired behaviour. The ability to consistently connect the external cues with the routine behaviour is made possible by the repetition of a routine in a stable situation. Therefore, methods that concentrate on obstructing the social or environmental cues that cause undesirable behaviours can be utilized to change a habit. The interruption forces people to make conscious choices, which can be sufficient to cause them to deliberately change their behaviour in favour of the desired one. Alternatively, the development of cue-routine linkages can be supported by stabilizing the environment in which the desired behaviour is carried out.

2.3 Change management

Change management is a methodical strategy to deal with the transition or transformation of an organization's objectives, procedures, or technologies [8]. The goal of change management is to put strategies in place to bring about change, manage change, and assist individuals in the adaption to change [8], [9]. This includes approaches to prepare and support individuals, teams and organizations to manage lifestyle changes related to the shift to EVs.

2.4 Lean

The lean manufacturing methodology aids in the identification of waste in any production process and aids in its elimination or reduction [2]. Any activity that doesn't create value during the production process is considered waste. These non-value-adding operations merely raise costs and lengthen overall production time; they do not increase the value [10]. Non-value-adding activities, on the other hand, should be distinguished from both non-essential and essential value-contributing activities [10]. In this paper, the following lean tools will be considered (subsequently coded as 1L to 8L):

Table 1: Lean Tools

Code	Name
1L	Standardization
2L	FMECA - Failure mode, effects and criticality analysis
3L	LPS – The Last Planner Action
4L	Kaizen – Continuous Improvement
5L	TPM – Total Productive Maintenance
6L	TQM – Total Quality Management
7L	TVD – Target Value Design
8L	5 Whys

2.5 Systems Thinking

Systems thinking focuses on the interactions between the subject being researched and the other system constituents, which are a group of components that work together to produce behaviour.

This indicates that systems thinking works by widening its perspective to take into consideration bigger and larger numbers of interactions as an issue is being researched, as opposed to isolating smaller and smaller elements of the system being studied [11]. When anything that is dynamically complicated or has a lot of feedback from various sources (internal or external), it may lead to conclusions that are remarkably different from those produced by standard types of analysis [11]. Therefore, systems thinking is essential for this research topic.

3 METHODOLOGY

The overarching research methodology that will be used for this project is the DMADV (Define, Measure, Analise, Design, and Verify) method [12]. The DMADV process is an improvement system used to develop new processes or products [12]. Since this paper aims to develop a new framework that could improve EV owners' lifestyles, this methodology is very suitable. Table 2 outlines the method's various phases and applications.

Table 2: DMADV phases and applications

Phase	Steps
Define	• Examination of Core Problem • Project Aims and Objectives
Measure	• EV Advantages and Challenges • Porter's Five Forces model (measure the severity of all factors involved) • EV owner's needs (Maslow's hierarchy of needs)
Analyse	• Cause-and-effect diagram • Automotive Industry • Vehicle owner lifestyle • Problem scope • Conceptual Requirements
Design	• Conceptual Design • Final Design of EV lifestyle adoption framework
Verify (and Validate)	• Verification: Verification checklist • Validation: A survey was conducted combined with a video summary of the final design

The other research methodologies that are used are Kernel Theories and a Systematic Literature Review. These are incorporated in the analysing of the problem and the design of the solution.

4 FINDINGS AND RESULTS

This section is a combination of extensive research, brainstorming, IE thinking, and literature.

4.1 Define

The problem is that with the expected influx of EVs in South Africa, EV manufacturers are experiencing difficulties convincing potential customers to purchase and adopt an EV lifestyle.

The following objectives were defined and achieved for this research paper:

1. Conduct a literature review
2. Perform a root cause analysis
3. Construct at least three feasible designs
4. Validate design
5. Develop an IE framework or roadmap
6. Test IE framework or roadmap through validation and verification

4.2 Measure

The advantages and challenges of EVs are measured in this phase. Additionally, possible means to address these aspects are considered. This step aids in the identification and classification of the problem and its severity. Furthermore, a Porter's Five Forces model is used to measure the severity (low, medium, or high) of the factors involved.

Figure 2: Porter's Five Forces model - adapted from Rice.J. *[13]*

Figure 2 helped to identify why ICEVs currently possess a market advantage. Lastly, in Figure 3 Maslow's Hierarchy of Needs is used to measure the importance of specific human needs. It identifies the most important marketing aspects of EVs.

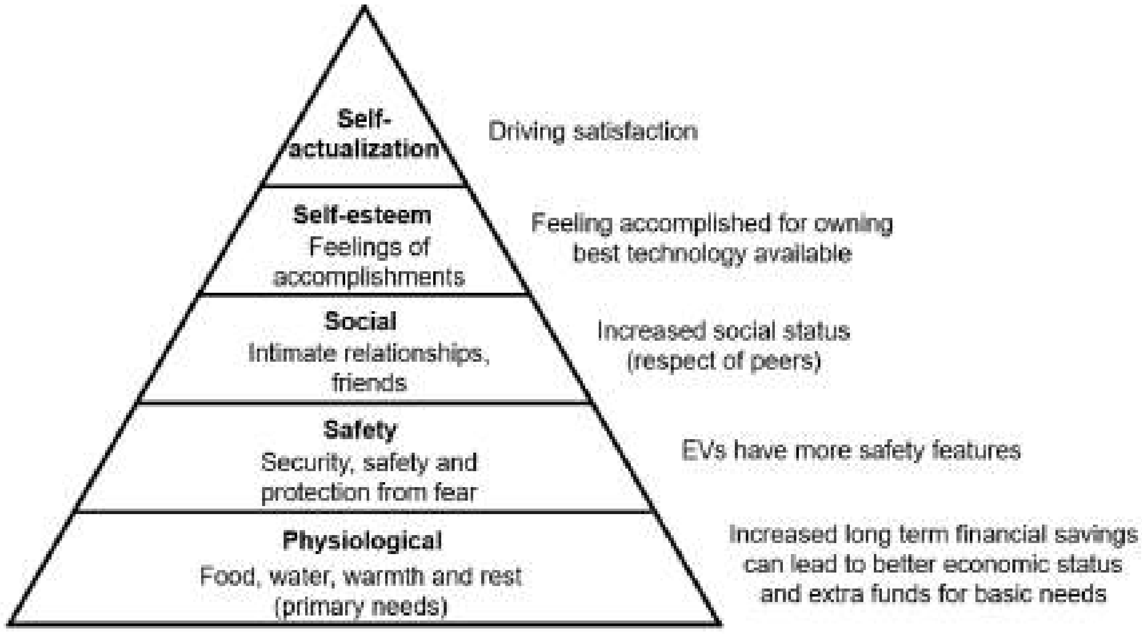

Figure 3: EV owner's needs - redrawn from Maslow.A.H. *[14]*

4.3 Analyse

A cause-and-effect diagram is used to analyse the problem in Figure 1. Many challenges were identified that contribute to this problem. Additionally, a literature review was done to analyse aspects of the problem and possible solutions. Furthermore, the design requirements were analysed for the solution. The design requirements dictated what the design should accomplish. Finally, the problem was re-examined and the problem scope was refined to only include the most relevant problem areas, as outlined in Figure 4.

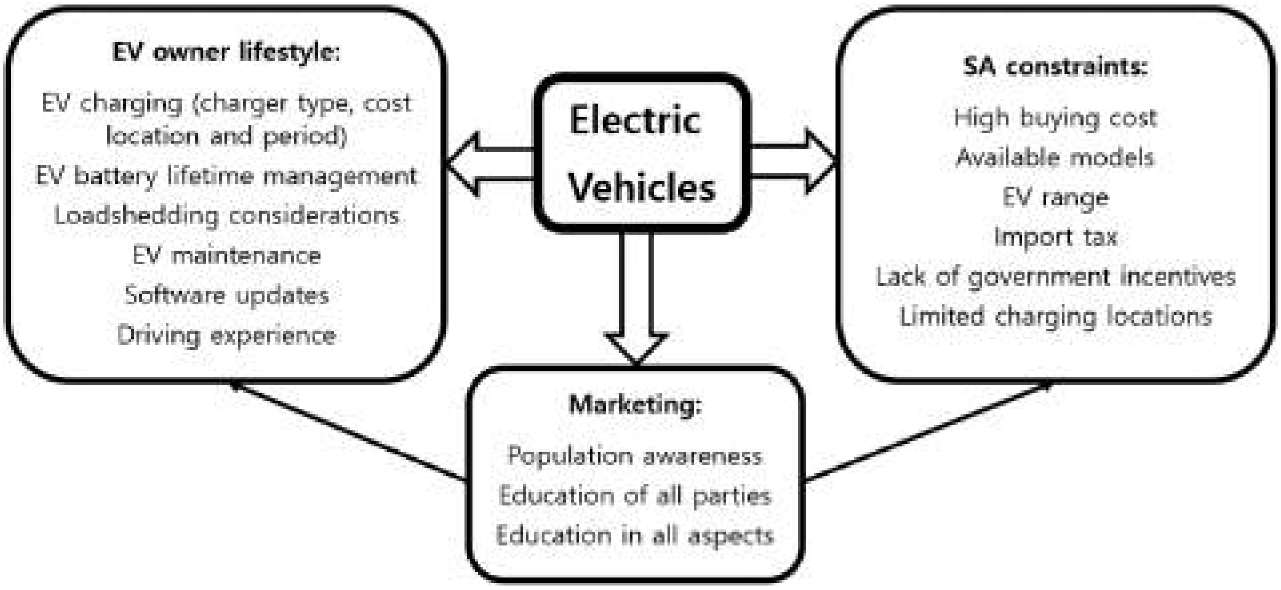

Figure 4: Problem scope

4.4 Design

Four different but viable alternative conceptual designs were considered for the solution to the problem. A visual depiction of each design was constructed. The conceptual designs were compared to each other to determine which one will provide the most effective solution. The design should solve the initial problem and meet the design requirements. Since the hybrid design was the best alternative solution, it is used as the final design.

4.4.1 Conceptual design

The design will follow a hybrid approach by incorporating the "habit alteration knowledge base" kernel theory with other complementary elements. Lean principles and systems thinking will be utilized as the Industrial Engineering element. The lean principles will be combined with best practice principles to ensure that the framework delivers an optimal EV lifestyle without eliminating any necessary components of the system. Best Practice Principles in this study refers to the best practices (according to literature studies) of each aspect of the EV lifestyle. Systems thinking will be used to analyse how the entire system's component pieces interact as well as how it functions through time and concerning other systems. This will help to ensure that the framework can successfully be incorporated into the larger society. Figure 5 illustrates the relationships between all the elements of the hybrid design.

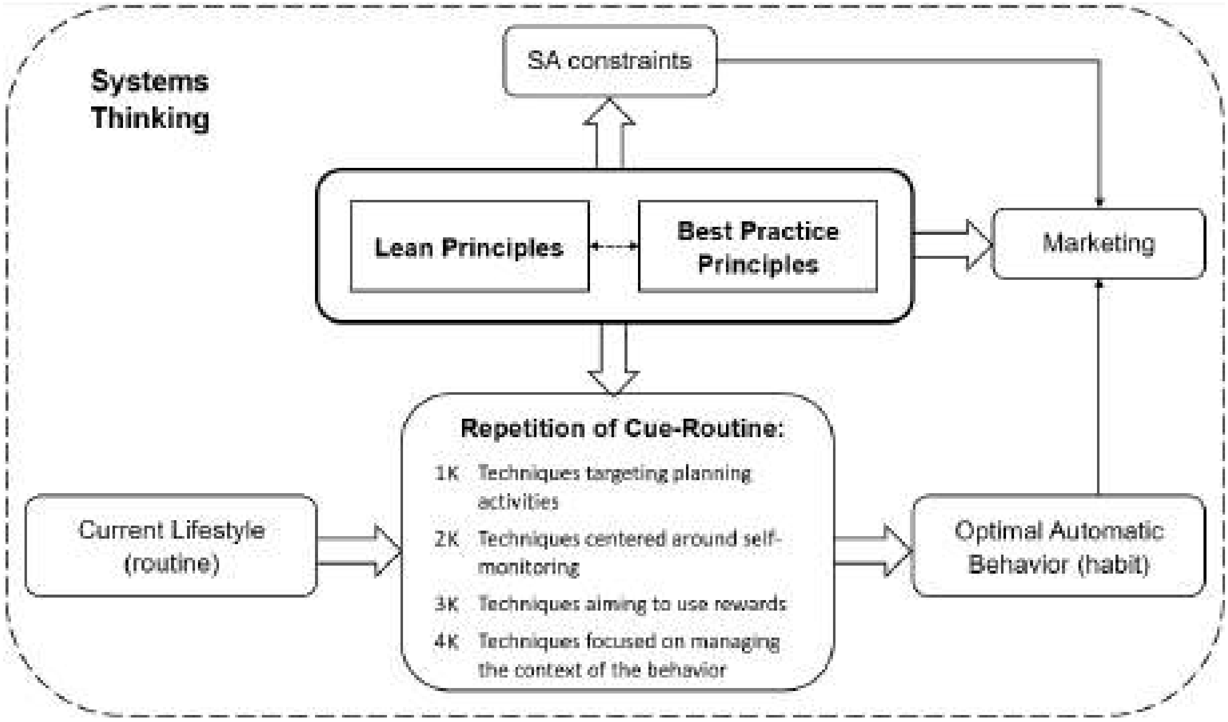

Figure 5: Hybrid concept design for IE inspired adoption framework

The objective is to repeat cue routines that favour more desirable alternative behaviour as depicted in the bottom part of Figure 5. However, during the repetition of cue routines that favour more desirable alternative behaviour, lean principles and best practice principles will also be incorporated. This can deliver the desirable automatic behaviour in EV owners' lifestyles. Furthermore, the combination of lean principles and best practice principles will also be incorporated into the handling of SA constraints and the marketing approach. This will be done while considering systems thinking for the entire framework.

4.4.2 Design logic

Since the design should help EV manufacturers convince potential customers to purchase and adopt an Electric Vehicle lifestyle, psychology is required. Psychology is part of Industrial Engineering [14]. Additionally, change management and other IE tools and techniques are utilized to help EV manufacturers convince potential customers to purchase and adopt an EV lifestyle.

The design is made to help potential EV customers see the benefits of EVs and mitigate the challenges that come with an EV lifestyle. Since many of the challenges stem from bad human habits (such as poor daily planning), the "Habit Alteration Knowledge Base" Kernel Theory is ideal. Additionally, lean principles and best practice principles are needed to cover other problem areas such as the constraints of South Africa that cannot be altered through psychology. Therefore, the hybrid design was essential to solve all aspects of the problem.

4.4.3 Design overview

The codes in Figure 6 indicate where certain tools can be used in the framework. However, for simplification purposes, only the most useful tools will be used in each situation. This will also make it easier to implement in owners' lives. Furthermore, 7L can also be used for SA constraints and the marketability of EVs.

Areas for potential tool usage:

B – Best Practice Principles
K – Kernel Theory
L – Lean Principles

EV charging:
- Charger type B 4K
- Cost B 3K
- Location B 1K 3K **1L**
- Period B 1K 2K 3K **1L 2L 4L**

EV battery lifetime management B 2K 3K 4K **1L 2L 7L**
Loadshedding considerations 1K 2K 3K **1L 2L 3L 6L 7L**
EV maintenance 1K **5L**
Software updates 1K 3K **1L**
Driving experience 2K 3K **1L 3L 4L**
SA Constraints **7L**
Marketing **7L**

Figure 6: Visual outline of codes used in the framework

Since EVs are still in the early adopter phase in SA there will constantly be changes to the current state. Owners will have to reassess the situation and newly available technologies. Furthermore, new EV technology is constantly being developed across the world, which includes new EV models, batteries, chargers, and additional charging locations. Additionally, policies will change over time that could provide more incentives for EVs or discourage ICEV sales. Therefore, this framework provides a supporting structure that vehicle owners can follow to help them adopt an EV lifestyle.

4.4.4 Practical components when implementing the framework

The first part of the framework requires potential EV owners to consider their own circumstances and requirements. Thus, they should determine their available budget and their vehicle requirements. This will differ for each person. Therefore, the lean tool of Target Value Design (TVD) can be utilized by vehicle owners. This strategy employs techniques such as "design-to-cost" or "design-to-targets" that allow the design to be developed in line with the restrictions, particularly cost. Furthermore, TVD takes the customer's vision into account when defining constraints and delivering the necessary goal value.

For this part of the framework, Best Practice Principles will be utilized since it will ensure that the best practices of each aspect of the EV are adhered to. Furthermore, it will help owners deal with the relevant constraints to be considered. Firstly, owners must consider the type of charging (AC or DC) and location (public or private) to optimize the cost of electricity. Owners could be constrained in this regard when their circumstances limit them to a specific option. Additionally, the lifetime – of the current Lithium-ion batteries that are generally used for EVs – can be improved by abiding by the ensuing guidelines.

It is best practice to maintain the battery's charge within 20-80%. However, the battery must be recharged as few times as possible. Therefore, owners must determine whether they have sufficient charge for their next drive before merely recharging their EVs. Additionally, extreme heat and cold have a negative effect on the EVs battery. For South Africa, this means that parking your EV in the sun for extended periods is unwise. It is important to note that new types of batteries are being developed that could improve these constraints or combine them with constraints of their own.

The lean tool of Total Productive Maintenance (TPM) can be utilized for the maintenance aspect. This tool is an integrated maintenance strategy that emphasizes proactive and preventative maintenance to extend equipment's operating life. The following maintenance should be done:

- Flush EV's brake system regularly to avoid corrosion
- Refrigerant (coolant) is required to maintain the correct temperature of the battery to prevent it from overheating and catching fire
- EVs require oil inside their gearboxes (must be changed during their lifespan)

Owners should always install the latest software updates as soon as possible. Over-the-air updates can improve the user interface and vehicle controls of EVs to ensure that they always have the latest software available. This also enables EVs to connect and communicate with each other on the road. This increases the personalization, safety, and user experience of the vehicle. Owners should also consider their driving habits to ensure they use their electricity as efficiently as possible. Even though EVs utilize friction braking and regenerative braking there is still some energy loss during the conversion of energy. Therefore, owners should use one-pedal driving of EVs more efficiently to ensure an optimal range.

All these Best Practice Principles add constraints to the lifestyles of EV owners. However, they can be accommodated through the lean tool of Target Value Design (TVD). It will allow the design to be developed in line with the restrictions. Furthermore, these BPP utilize the lean tool of continuous improvement (Kaizen) to constantly assess, examine, and improve the resources used. Moreover, the lean tool of Last Planner Action (LPA) can be utilized to make planning a collaborative effort and raise the dependability of the commitment. Loadshedding, general daily time constraints, and other disruptions can be controlled by the TQM and FMECA lean tools.

Total Quality Management (TQM):

1. Discover and assess the issue
2. Create and apply remedies
3. Evaluate and measure the outcomes

Failure mode, effects, and criticality analysis (FMECA):

1. Evaluation of failure (risks)
2. Consequences of failures
3. Core causes of failures

Owners should utilize these tools to evaluate, control, and resolve any time constraints that they might experience when planning their charging schedules. Once again, these lean tools can be combined with continuous improvement (Kaizen) and Last Planner Action (LPA) lean tools to improve the resources used (time) and raise the dependability of the commitment.

Figure 7: Standardization

Subsequently, standardization will be implemented into the planning of owner's lives as indicated in Figure 7.

Standardization focuses on the repetition of techniques or procedures to result in successful practices. The concept of the standardization lean tool is very similar to the "habit alteration knowledge base" kernel theory, and they can thus be implemented collectively.

Action planning, coping planning, decomposition of desired behaviours, and stacking behaviours are planning techniques of the "habit alteration knowledge base" kernel theory that EV owners can utilize to effectively plan their charging schedules.

1. Action planning: Goal-directed behaviours.
2. Coping planning: Utilize "if-then" statements.
3. Decomposing the desired behaviour: Breaking down the intended behaviour.
4. Stacking behaviours: The accomplishment of an established behaviour will cause the start of the desired action.

Furthermore, techniques like self-monitoring, reward systems and contextualization of undesirable behaviours can help to break established habits and promote preventive behaviours when used diligently. Self-monitoring can track how many times an individual avoided undesirable behaviour. In terms of reward systems, rewards can encourage repetition. Utilize methods that concentrate on obstructing the social or environmental cues that cause undesirable behaviours.

In comparison with ICEVs, EVs have many advantages that would delight and benefit any vehicle owner. The following are some of the best advantages of owning an EV rather than an ICEV:• Environmentally friendly

- No need to buy fuel (high prices)
- Less maintenance
- Lower overall ownership costs
- Can charge at home
- Easy software update (over Wi-Fi)
- Instant torque
- Regenerative braking
- Less noise while driving
- Safety aspects
- Owning the most advanced technology
- Status symbol
- Extra storage compartment: Frunk
- More space in the vehicle overall
- Fun driving experience
- Less carbon exportation tax for businesses

These advantages can be linked with Maslow's Hierarchy of Needs as depicted in Figure 3. This will help EV manufacturers explain that an EV can help fulfil human needs. Furthermore, EVs have many possible future advantages, namely:

- More environmental reasons
- Potential lower buying cost of EV
- Increased petrol/ diesel prices
- Increased charging locations in SA
- Increased range
- Shorter charging times
- Tax incentives for EVs
- Autonomous driving (self-driving cars)
- Built-in solar panels on EV

If these advantages are marketed correctly, then more vehicle owners will be interested in owning an EV. Therefore, they will be willing to educate themselves about all aspects relating to EVs. However, marketing must still be done on how to deal with the challenges of adopting an EV lifestyle.

Once vehicle owners are interested in buying an EV they must be made aware of all the changes involved with owning an EV. Furthermore, it must be marketed in an attractive way that will convince vehicle owners that it is worth the change. They must understand that even though there are some challenges, there are numerous methods to deal with those challenges. This will help to make it easier for EV manufacturers to convince potential customers to purchase and adopt an EV lifestyle.

4.5 Verification and Validation

To verify that the design incorporated all the elements and to validate whether it does fulfil what was promised, a verification and validation checklist was used by means of a Google Forms survey. The purpose of the checklist was to ensure that the framework accomplished the aims and objectives that were promised. The framework was validated by using statements from the design requirements as depicted in Table 3. The survey statements and results from the study can be used to validate the design [15].

The participants for this survey were split into three populations: Industrial Engineers, EV owners, and IEs with EV ownership experience. They were required to indicate their level of agreement with each statement on a Likert scale. The Likert scale uses a psychometric response scale in which responders specify their level of agreement to a statement typically in five points: (1) Strongly disagree; (2) Disagree; (3) Neither agree nor disagree; (4) Agree; (5) Strongly agree. The statements were derived from the aim of the study as well as the problem to be solved. The survey assessed the level of agreement that industrial engineers and EV owners have with the statements. Table 3 summarizes the number of times that a response was recorded for each number on the Likert scale.

Table 3: Survey results

The Framework:	**1**	**2**	**3**	**4**	**5**	**T**	$\bar{x}$	σ
Includes all aspects related to EV ownership in SA	0	0	0	5	8	**13**	**4.6**	**0.51**
Explains all differences in ownerships from ICEVs	0	0	0	8	5	**13**	**4.4**	**0.51**
Can improve SA vehicle owners' understanding of changes from ICEVs to EVs	0	0	0	4	9	**13**	**4.7**	**0.48**
Provides the means to handle or eliminate challenges to EVs	0	0	0	7	6	**13**	**4.5**	**0.52**
Can improve the management of EV owners' lifestyles	0	0	0	6	7	**13**	**4.5**	**0.52**
Provides the means to make EV owners' lifestyles more efficient	0	0	0	9	4	**13**	**4.3**	**0.48**
Aids EV owners to adopt a new lifestyle	0	0	0	3	10	**13**	**4.8**	**0.44**
Can manage the expected influx of EVs in SA	0	0	0	6	7	**13**	**4.5**	**0.52**
Includes Industrial Engineering principles	0	0	0	3	8	**11**	**4.7**	**0.47**
Can improve/simplify the marketability of EVs in SA	0	0	0	4	9	**13**	**4.7**	**0.48**

Can help owners that are experiencing difficulties understanding the changes from ICEVs to EVs and managing their new lifestyles	0	0	0	3	10	**13**	**4.8**	**0.44**
*EV owners struggle to manage their lifestyles	0	0	1	2	2	**5**	**4.2**	**0.84**
Total/Average:	**0**	**0**	**1**	**60**	**85**	**146**	**4.6**	**0.52**

The low standard deviation (σ) indicates that the data points are generally close to the mean ($\bar{x}$). Since the mean of each statement falls between 4,2 and 4,8 out of 5 it indicates that the participants largely agree with all the statements. Therefore, the design is validated.

5 DISCUSSION

5.1 Problem areas addressed by the framework

Given that the problem is that EV manufacturers are experiencing difficulties convincing potential customers to purchase and adopt an EV lifestyle, the solution focuses on explaining how vehicle owners can adopt an EV lifestyle. The following subsections will explain how the solution systematically solves the problem.

Since EV manufacturers are experiencing difficulties convincing potential customers to purchase and adopt an EV lifestyle the problem was first re-examined. It was found that many vehicle owners are struggling to understand the changes from ICEVs to EVs and adopt an EV lifestyle. Therefore, the problem was split into three parts: vehicle owner's lifestyle, SA constraints, and marketing of EVs.

5.1.1 EV owner's lifestyle

Since charging an EV is the largest challenge related to owning an EV, many tools are used to manage this aspect. Firstly, the best practices are identified. This helps to ensure that EV owners can utilize more ideal charging habits. However, the best practices also serve as constraints. Therefore, lean principles are implemented in conjunction with best practice principles. The lean principles allow the design to be developed in line with the restrictions, particularly cost. Furthermore, lean principles can be used to identify and eliminate non-value-adding activities. The combination results in the most ideal lifestyle management techniques.

However, humans are not perfect and will never be. This leads to deviations from the ideal planned lifestyle. Therefore, it is necessary to bring the psychological aspect into the framework. The "Habit Alteration Knowledge Base" Kernel Theory offers various methods to alter bad behaviour and promote preventative behaviour. This will help EV owners to improve the management of their lifestyles and use the best practice principles and lean principles to the best of their ability. Furthermore, they can use the Kernel Theory in other aspects of their daily lives. Therefore, they can potentially improve more than just their EV lifestyle.

The same procedure is followed for other parts of the EV owner's lifestyle part of the framework. Therefore, charging habits, battery lifetime, loadshedding, EV maintenance, software updates, and the owner's driving habits all first consider the best practices for each activity. Secondly, lean principles are added to work with the constraints and eliminate waste during activities. Lastly, the Kernel Theory is utilized to alter the human psyche. This combination results in an ideal lifestyle management plan. Furthermore, it can help EV manufacturers to convince potential customers to purchase and adopt an EV lifestyle.

5.1.2 SA constraints

Potential customers must be aware of all the challenges of owning an EV. Otherwise, they might have a negative experience with EVs. This could lead to misconceptions, bad reviews, and the loss of customers. Therefore, EV manufacturers must be transparent. However, all the challenges are manageable. Furthermore, the constraints will likely decrease in the future. Thus, more charging locations, EV models, government incentives, and longer ranges. Additionally, a decrease in loadshedding, import taxes, and lower buying costs are highly probable. Therefore, SA constraints should be paired with lean principles and correct marketing.

5.1.3 Marketing of EVs

This is the most crucial part of the framework. Since the EV lifestyle, SA constraints, EV advantages, and human needs should be marketed appropriately. Therefore, it plays a large part in every aspect of the framework. Furthermore, for the lifestyle management part of the framework, EV manufacturers, sales agents, and potential customers must be educated through marketing. Therefore, vehicle owners should be meticulously informed about all aspects and changes from ICEVs to EVs.

5.1.4 Systems thinking

EV manufacturers should consider the system as a whole when using marketing to convince potential customers to purchase and adopt an EV lifestyle. Thus, as mentioned they should market the lifestyle management techniques along with the challenges (constraints) and advantages of EVs. This will help EV manufacturers to convince potential customers to purchase and adopt an EV lifestyle.

6 CONCLUSIONS AND RECOMMENDATIONS

An adoption framework for EVs is developed and verified through a small survey using lean, systems thinking and IE practices. The combination of all the mentioned IE inspired tools and techniques used in the framework will help vehicle owners adopt an EV lifestyle and plan their lifestyles more efficiently. This will improve the marketability of EVs and help EV manufacturers convince potential customers to purchase and adopt an Electric Vehicle lifestyle.

To help EV manufacturers to convince potential customers to purchase and adopt an Electric Vehicle lifestyle, vehicle owners should better understand the changes from ICEVs to EVs. Therefore, they first need to foster the desire to own an EV. Otherwise, they will not be interested in educating themselves on how to own an EV. Therefore, the advantages of EVs must be marketed in such a way as to encourage and interest vehicle owners.

The model/framework emulates a puzzle in the way that it fits well together, and you can only solve the complete problem by fitting together all the pieces of the design. In addition, the results from “Atomic Habits” by James Clear can be merged with this framework since it has complementary ideologies.

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THE HUMAN COMPETENCIES (SOFT SKILLS) REQUIRED TO BE AN EFFECTIVE PROJECT MANAGER AND ENSURE PROJECT SUCCESS. A CASE STUDY IN SOUTH AFRICA

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ABSTRACT

Within the civil engineering consulting field, most engineers are expected to perform project management duties at some point. A literature review shows that a project manager's human competencies/soft skills are vital and contribute to project success. However, it appears that more emphasis is placed on technical skills in undergraduate engineering programmes, with soft skills not garnering enough focus. The literature review found that the following soft skills are the main soft skills required by a project manager for project success. Communication, Problem Solving, Leadership, Emotional Intelligence, Decision Making, Conflict Management, Team Building and Negotiation skills.

Surveys were used and the sample population included recent engineering graduates and senior engineering managers. The key conclusions of the study are that both groups agree that more emphasis should be placed on teaching soft skills in higher education institutes (HEI). Graduates believe that some critical soft skills such as team building, communication, decision making, problem solving, motivation, and Conflict Management skills are being taught at HEIs. However, managers believe that this is not the case, and these skills need to be adequately addressed in training, adding that graduates need to realise the importance of these skills in practise. Graduates believe that the top three soft skills required by project managers are communication skills, emotional intelligence, and leadership skills. Managers believe that the three soft skills required by project managers are communication skills, Decision-Making skills, and leadership skills. Suggestions are included on how these skills can be taught.

Keywords: Project Manager, Project Success, Civil Engineering Industry, Soft Skills

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1 INTRODUCTION

Within the field of civil engineering consulting, most engineers are expected to perform project management duties and execute projects from start to finish. As engineers develop in their careers, they are expected to evolve from a technical role to a management role, managing teams, clients, and other stakeholders. The field of civil engineering consulting is mainly operating through the execution of projects from the inception to the closing stages of the project. As a result, engineers need hard and soft skills to execute successful projects. However, according to academics [1], [2], [3], [4], [5], [6], [7], there is little emphasis is placed on the development of project management skills (human competencies) within the various undergraduate civil engineering programmes being offered.

[2], emphasised that educational institution's academic and training programmes should place more importance on the upskilling of "personal characteristics", and it was seen in their study that a project manager's attitude and personal characteristics had a high impact on achieving project success. However, they also mentioned that these personal characteristics must complement technical skills to be a well-rounded project manager.

A project manager who embodies soft skills in project management is vital because human interaction within the field of project management and in the completion of a successful project is crucial [8]. The success of a project is said to be obtained by how well the project team works and interacts (interaction between internal teams, external stakeholders, clients, licencing authorities, and other vital role players) [9]. Factors such as communication, leadership, and emotional intelligence are critical to ensure that a project team works well together to ensure project success. It is becoming more evident that more emphasis is needed on soft (interpersonal) skills to guarantee that a project manager will be effective in his job.

1.1 Problem Statement

There needs to be more emphasis on teaching the soft skills required to be an effective project manager. However, it is becoming more apparent, by the changing face of projects, regarding complexity and how they are executed, that soft skills are required to supplement the traditional project management and hard skills of a project manager [8].

An integral part of project management is the interaction between the project manager, the client, relevant stakeholders & authorities, the professional team, and the internal project team. Unfortunately, many organisations and recruiters appoint project managers purely on the basis of their technical skills without considering their human competencies and people skills [9].

Recent research indicates that soft skills are as critical, if not more important, than hard skills when hiring a potential candidate for a job position [8], [10], [11]. Furthermore, studies indicate that when new hires do not meet the employer’s required expectations in their new positions, the absence of soft critical skills is considered the cause.

The set of skills that an effective project manager must embody is still being debated by academics and researchers in the literature on this topic. It is also said that more emphasis should be placed on developing these soft skills within the various undergraduate engineering programmes offered by higher education institutes. This is seen as a stumbling block in the development of young engineers' careers, as managing projects and the need to possess soft skills when working within project teams is a vital key performance area in the development of engineering careers.

1.2 Objective

The objective of the research is first to understand the body of literature available on the related topics of the title and first to establish an understanding of the current research in the field. By understanding the existing body of literature, gaps in the literature are established, leading to the formulation of research questions. Regarding this study, the identified research perceived gap identified is that more emphasis should be placed on teaching soft skills within the various undergraduate engineering programmes offered by higher education institutes. Therefore, a survey is conducted to identify if this is the case by establishing the perceptions of two groups of research participants, one group being *recent engineering graduates* and the other *senior engineering managers* operating within the consulting engineering field in South Africa. The perceptions between the two groups of participants are then analysed to determine the critical perceptions of these two groups and how they relate to the themes identified in the literature review.

1.3 Research Questions

The following research questions were drawn from the literature review.

Research Question 1: *What are the top human competencies (soft skills) identified to be an effective project manager and ensure project success?*

Research Question 2: *Since engineers are required to execute projects, as this is the nature of business in consulting engineering firms, are these human competencies effectively taught within the various undergraduate engineering programmes at higher education institutes?*

Research Question 3: *Should more emphasis be placed on developing soft skills in undergraduate and postgraduate engineering programmes?*

Research Question 4: *How can these soft skills be further developed in undergraduate and postgraduate engineering programmes?*

2 LITERATURE REVIEW

2.1 Projects

In the last decade, academics have focused a lot on understanding the nature of projects [2]. In addition, consulting companies within fields such as engineering and architecture are project-orientated businesses that focus on implementing projects for various clients as their core business. Therefore, in this modern age, successful implementation of projects plays a vital role in the development of successful companies [1].

One of the most common definitions of a project is defined in the Project Management Body of Knowledge (PMBOK) guide as "a temporary effort undertaken to create a unique product, service, or result" [12].

Since projects are unique and often complex, even though much emphasis has been placed on advancing the implementation of projects, many projects to this day still fail [13], [2]. Therefore, there is an urgent growing need to further develop project management processes and project management competencies to provide excellence in the implementation of projects and ensure successful projects [14], [5].

2.2 Project Management

The field of project management is vital in the implementation of projects and governs the way projects are executed. Various project management organisations oversee the profession of project management, such as the Project Management Institute (PMI) and the International Project Management Association (IPMA).

PMBOK defines *project management* as "the application of knowledge, skills, tools, and technique to project activities to meet project requirements" and characterises "high-quality projects as those that deliver the required product, service, or result, within scope, on time, and within budget" [12].

It is evident from the PMBOK management areas and process groups that the field of project management is diverse and some aspects need to be managed with a more technical approach [8]. Previously, the field of project management was seen to pay more attention to the technical and hard skills of a project manager [10]. It has also been noted that previous editions should have emphasised the person skills of a project manager rather than focused more on the hard and technical skills [15].

As the field of project management is further researched and experience in project implementation develops, it has become more evident that a project manager has not only technical and hard skills, but also soft "people" skills, too [4]. A project is executed by a team that comprises a project manager, team members, and stakeholders, and at each stage of the project, there are people interactions. Therefore, [16] theorise that project management involves people management, which requires a different set of skills of project managers. These skills are known as soft skills and are often referred to as human competencies of a project manager.

2.3 Project Success

Projects are unique and can become complex endeavours, and as the implementation of successful projects becomes increasingly important, there are still many projects that fail [1]. [16] reported that the project success criterion is constantly evolving as more research and experience are gained in project management. Since projects can be complex endeavours, project success criteria can also become complex [2].

It has been stated that the initial literature on project management success focused on this traditional definition of success, as defined in the PMI and referenced as the "classic project triangle" of time, cost, and quality. However, the success criterion has moved away from this and expanded to include other aspects [2]. One of the main reasons for the failure of the projects, as reported by [17] was that the projects were initially assumed to be similar and that a similar set of tools and skills should be used in the implementation of each project. However, only some projects are the same and should be treated as such.

From the literature on project failure, it is evident that the skills and competencies of a project manager play a vital role in achieving project success, with [16] stating that project management frameworks alone cannot achieve project success.

2.4 The Role of the Project Manager in Project Success

The role of the project manager has gained significance over the years in ensuring project success and is a popular topic amongst the project management research community. Moreover, project success has been inexplicably linked to the project manager's competencies and skillset in the project management literature.

[8] links the success of the project with the ability of the project manager and the project team, considering that a project is executed as a set of efforts completed to achieve the goal of the project. Hard and soft skills play a vital role in project success, as these skills assist the project manager to better executing the project better. The skills identified by [10] include communication, team building, and problem-solving skills. [17] identified that the personality and behaviour have an impact on project success and therefore stressed that the personality of a project manager cannot be ignored when it comes to the positive outcome of a project and that honesty is a necessary trait to consider.

[18] states that the appointment to a project determines the success or failure of the project. [19] places great emphasis on the project manager's style, manner of leadership, interpersonal skills, and expertise to achieve project success. The research of [2], [20], [21], [6] and [5] all continues in the same vein by identifying a project manager’s competencies and interpersonal skills of a project manager, as influences the success of the project.

[5] and [8] agree that more than technical competencies are needed to ensure project success. Therefore, the balance of hard, technical, and soft skills influences the success of the project.

A study by [2] identified those project management traits that positively influence project success, including optimism, team building ability, motivational ability, trust building ability, emotional intelligence, and improvisation. All identified traits relate to the soft skills of a project manager. [10] indicated that a deficiency of soft skills in a project manager could lead to project failure.

The literature on this subject connects the human competencies of a project manager as one factor contributing to project success.

2.5 Effective Project Manager Skills and Competencies

Since the project manager's competency and skills have recently been linked to project success, a vast body of literature has sought to identify these critical competencies and skill sets.

[8] have alluded to the need for a successful project manager to possess a balance of hard and soft skills, as these skills, hard and soft, interact throughout the life cycle of the project. The authors conclude that "Hard skills reflect what you know, soft skills indicate who you are." They also emphasise the project manager's communication skills as one of the most critical skills to successfully manage each project stage. Communication is essential because the project manager spends a lot of time communicating at every stage of the project. Up to 85% of their time [8].

Although it is evident that a balance between hard and soft skills is required for the success of a project manager, [10] has brought attention to the fact that employers need to pay more attention to the soft skills required by a project manager, as project managers employed in the construction industry have been seen to possess strong technical skills, but they possess insufficient soft skills. The study concluded that soft skills play a vital role in helping the project manager solve project problems and planning and executing the project successfully.

2.6 Identifying key human competencies (soft skills) from the literature

Previous studies have emphasised the identification of the soft critical skills embodied by a project manager to balance technical/hard skills and ensure project success. As a result, various research articles have been identified in this field and each article has been analysed to determine the soft critical skills identified in the article. From the 16 research articles analysed in this study, the top ten soft skills that a project manager needs to achieve successful projects were identified and are recorded according to the ranking in the table below. The top soft skills were identified by the number of times a particular soft skill was mentioned in the total number of articles analysed. They are indicated in the table below.

Table 1: Top ten soft skills identified from the literature review

Rank	Soft Skill	Number of times mentioned in the reviewed research papers.
1	Communication Skills	12
2	Leadership Skills	10
3	Team Building Skills	9
4	Conflict Management Skills	8
5	Problem Solving Skills	7
6	Motivating Skills	7

Rank	Soft Skill	Number of times mentioned in the reviewed research papers.
7	Decision Making Skills	6
8	Negotiation Skills	5
9	Emotional Intelligence	4
10	Influencing Skills	3

2.7 Development of Soft Skills

[1] highlighted a disparity between what higher education institutes were teaching and the skills required by project managers to manage increasingly complex projects in increasingly difficult work settings. They argued that education institutions should offer more to better their students to prepare them for their careers and develop them into outstanding project managers. They established in their study that one way of doing this is that educational institutes give more attention to assisting students in developing "softer" skills to manage projects, especially "…interpersonal skills and leadership as opposed to just technical skills."

Similarly, [2] emphasised that educational institution's academic and training programmes should emphasise the upskilling of "personal characteristics." It was found in their study that attitude and personal characteristics had a high impact on the achievement of project success. However, they also mentioned that these personal characteristics must complement technical skills to be a well-rounded project manager.

Similarly, [3], [4], [5] and [6], also emphasised the need to pay more attention to the education of soft skills among students within the field of project management and engineering fields of study. [6] emphasises the gap between the teaching of soft/interpersonal skills and hard/technical skills.

The literature shows that the need to emphasise soft skills education is still a prevailing theme and relevant according to various researchers' studies, as demonstrated above.

2.8 The South African Context: Soft skills required in the current climate

Implementing a project in South Africa (SA) presents a unique set of challenges that can make a project complex and difficult to implement. SA is still a developing nation post the 1994 democratic elections which saw SA being freed from the previous apartheid government. In South Africa, challenges such as poverty, unemployment, corruption, and inequality are challenges people face daily. It has also been found that the diversity in SA between the various cultures plays a crucial role in the successful implementation of projects when analysing 'Mega Construction Projects' such as the Kusile and Medupi power station projects that are currently being implemented in SA [22]. Mega construction projects are characterised as projects that are large-scale, complex, have a duration of execution that exceeds four (4) years, have a total cost of implementation of more than $1 billion, and involve numerous stakeholders [23].

Executing projects in the South African context can often be challenging, especially in the public sector. South Africa is still a developing country with a developing economy that is currently grappling with mismanagement of funds, corruption, poor service delivery, incompetent public servants, lack of accountability, poor human resource practises, inadequate procurement practises, and lack of leadership [24].

Noting the unique challenges experienced in the South African industry [3] indicated that graduates must possess a unique set of interpersonal and technical skills to achieve project success within the climate of SA. Interpersonal skills are the most important, considering the unique challenges experienced with project implementation and delivery in SA.

3 RESEARCH METHODOLOGY

3.1 Literature Review Themes

The themes relating to the topic and problem statement field of research are drawn from the literature review.

The main themes identified from the literature review are:

- **Projects** are becoming increasingly complex to execute in the current global environment. Especially evident in the South African context due to the increasing number of challenges experienced locally.
- **Project Management**: As the developing field of project management is further researched and experience in implementing projects develops, it has become more evident that project management requires a project manager who possesses not only technical/hard skills but soft skills too.
- **Project Success**: In recent years, it has become more apparent that the project manager and his competencies are integral to ensuring project success.
- **The role of the Project Manager in Project Success**: It has become more apparent that the project manager's human competencies/soft skills are vitally important and contribute to project success. And not just technical skills.
- **Effective Project Management Skills and Competencies**: Much research has been done to determine the most important soft skills.
- **Identifying Critical Human Competencies (Soft Skills) from the Literature:** From the literature, the most vital soft skills possessed by a project manager were found to be, in order of importance, communication skills, leadership skills, team building skills, conflict management skills, problem solving skills, motivation skills, decision-making skills, negotiation skills, emotional intelligence, and influencing skills.
- **Education of Soft Skills**: There is a vast and ever-growing theme in the literature that more emphasis should be placed on teaching soft skills at higher education institutions.
- **The South African Context -** Soft skills required in the current climate: Taking into account the current challenges experienced in South Africa, project managers must have the soft skills to handle complex projects in SA, each with its unique set of challenges.

3.2 Study Design

Two sample groups were identified and targeted to gather information, address research questions, and determine how current perceptions within the civil engineering consulting field relate to the themes identified in the literature review:

1. Engineering Graduates (EG).
2. Senior Engineering Managers (SEM).

The method of research chosen to gather information from these two groups is the Mixed Research Method.

The chosen data collection instrument is the survey gathering tool and is explained further in the following sections. Two surveys were designed for each sample group on the SurveyMonkey® online survey platform, SurveyMonkey®. The survey questions are both qualitative and quantitative.

Prospective participants for each sample group were identified among colleagues and associates in the field. The link to the online survey and a letter explaining the study being carried out were sent to prospective participants. The raw data from the completed surveys were then analysed using quantitative and qualitative methods. The results of the analysis were discussed and compared with the themes identified in the literature review. Conclusions were drawn from the identified analysis to answer the research questions. Limitations of the study were highlighted. Finally, recommendations for future studies were identified.

3.3 Research Setting

The study was carried out within the consulting engineering sector, as data was collected from professionals in this field. The geographical location of the population group was limited to the Gauteng Province of South Africa.

3.4 Data Collection Instrument

Two surveys were designed and included questions to confirm whether the participants met the population group criteria required for the study. The remaining survey questions address the identified research questions, as well as to shed light on the themes identified in the literature, and were of a quantitative and qualitative nature.

3.5 Data Collection Process

Prospective participants were identified within the two sample groups. A letter was sent to each prospective participant by email. The letter addressed to each sample group contained the following:

1. An invitation to participate in the survey.
2. The title of the research study, details of the problem statement, and the purpose of the study.
3. Details of the researcher and the reason for the research (Qualification to be fulfilled).
4. The link to the online survey is for Engineering Graduates (EG) or Senior Engineering Managers (SEM).
5. The criteria the participant must meet to complete the survey.
6. The following vital statements about your participation in the survey are:
   - Participation in the research project is voluntary, and participants are not compelled to participate in the survey.
   - The option for the participant to decline to participate in the survey altogether or leave blank any questions that the participant does not wish to answer.
   - Confirmation that there are no known risks to participation in the survey and that participation in the survey will not harm the participant's reputation.
   - Confirmation that the responses will remain confidential and anonymous.
   - Confirmation that the collected data will remain confidential, safe, and reported only as a combined total.
   - Confirmation that no one other than the researcher will know the participant's answers to this questionnaire.
   - An indication that the survey may help participants in their careers to raise their awareness / curiosity about the soft skills required in project management.

3.6 Study Population and Sampling Method

The two identified sample populations are as follows.

1. Engineering Graduates (EG) and
2. Senior Engineering Managers (SEM).

Engineering Graduates (EG).

- Engineering graduates have graduated with an engineering qualification in the last five years and have at least one year of working experience in the engineering industry.

Senior Engineering Managers (SEM).

- Senior managers/directors/professionals within the engineering industry with five years or more experience, who work closely with recent engineering graduates and are involved in recruiting engineering graduates, and
- Engineering professionals who are registered and have five years or more experience.

Surveys were sent to prospective participants in May and June 2022. The participants/target sample was identified within the consulting engineering field (colleagues and members of other consulting firms identified).

3.7 Ethics

The survey questions considered ethical principles of autonomy, beneficence, non-maleficence, and justice when conducting this research study.

The survey questions were designed considering the *University of Johannesburg: Facility of Engineering and the Built Environment, Faculty of Ethics, and Plagiarism Committee, Standard Operating Procedures for Research Ethics*.

4 RESEARCH RESULTS

4.1 Methods of Analysis

4.1.1 Qualitative Analysis

A Mann-Whitney U test was performed on the qualitative questions of the survey due to the limitation of the small sample size for this study.

4.1.2 Quantitative Analysis

Most of the questions required qualitative analysis, as they were open-ended questions. Additionally, due to the limitation of the small sample size, a summative analysis approach was chosen for the analysis method.

4.2 Findings and Discussions of Analysis

4.2.1 Survey Responses Received

Survey 1 (EG) was sent to 32 prospective participants. Seventeen responses were received, thus a response rate of **53.13%**.

Survey 2 (SEM) was sent to 36 prospective participants and 19 were received. Therefore, the survey response rate was 52.78%.

4.2.2 Findings of the Participant Criteria

The first four questions of each survey focused on establishing if the survey participant met the required criteria to participate in the survey.

4.2.2.1 Engineering Graduates - Criteria

Of the seventeen participants, 15 participants graduated with an engineering qualification within the last five years and two did not. The two participants who did not meet this criterion graduated in 2016, this is only a year difference, and the difference proves to be insignificant within the study. Therefore, the responses of these two participants are included in the research analysis. The seventeen participants have work experience in the engineering industry, particularly in consulting, ranging from 1 to 5 years.

4.2.2.2 Senior Engineering Managers - Criteria

The 19 participants hold senior roles within the organisations they work for, with role descriptions including directors, managers, supervisors, and senior engineers. Seventeen of the 19 participants are professionally registered individuals with ECSA, and eight of them are registered mentors. The 19 have more than five years of work experience within the consulting engineering field.

4.2.3 Findings and Discussions of Engineering Graduate Survey Questions

Question 5 (EG & SEM): "Do you believe that the following soft skills are sufficiently developed in higher education institutes in engineering programmes? Decision Making Skills, Team Building Skills, Emotional Intelligence, Leadership Skills, Negotiation Skills, Communication Skills, Conflict ManagementSkills, Influencing Skills, Motivating Skills, Problem Solving Skills."

Findings: Among EGs, 76.47% agree that team building skills are sufficiently developed in higher education institutions. 64.71% agree that decision-making and communication skills are sufficiently developed, with 54.94% agreeing that problem solving skills and 43.75% agreeing that motivating skills are sufficiently developed. However, it appears that among EGs, there is a low confidence level in developing the following soft skills in higher education institutions, emotional intelligence, leadership skills, negotiation skills, conflict management skills and influence skills.

Among the SEMs, several participants agree that most of the soft skills listed are not taught at higher education institutions. However, there is agreement amongst SEMs that communication skills and problem-solving skills are being taught.

Discussion: From the findings, EG believes that some soft skills are being developed sufficiently. However, this contrasts with the conclusions of the SEM assessment, with SEM's having a much lower confidence level that these soft skills are being developed.

Question 6 (EG & SEM): "Following on from the previous question, do you have any further comments to substantiate your replies or general comments regarding the question?"

Discussion: The graduates identified specific skills that needed to be addressed. These included emotional intelligence, negotiation skills, influence skills, interpersonal skills, and communication skills. ***Negotiation skills were*** mentioned as a particular skill that is needed in practise. There was considerable support for the notion that technical skills and problem solving are the focus areas of training. Some mentioned that skills were developed through other subjects, such as humanities or participation in other activities, such as student societies.

Managers concurred that these skills are not adequately addressed in training and added that graduates do not realise this importance in practise. As such, they are not sufficiently prepared for the working environment. There was also agreement that the focus in training is mainly on technical skills.

Question 7 (EG & SEM): "Are there any other soft skills not mentioned above (**Question 5**) that you think are important for engineering graduates working in the engineering industry?"

Discussion: Regarding other soft skills needed, graduates mentioned skills related to interpersonal relationships much more frequently than managers. These included active listening, communication, team management, and delegation. All of these were mentioned only by graduates and not by management. Leadership was only referred to by management. The aspects mentioned by both parties were networking and stakeholder participation. Although both parties identified interpersonal relationships perse, it was much more frequent with graduates. Soft skills related to how one interacts with others were essential for both parties, but more so for graduates, and the focus of the two groups was slightly different.

Interestingly, quite a few (5) graduates mentioned a practical skill such as time management, while it was not noted by managers at all. Time management is, therefore, a skill that graduates feel they lack. Stress management was identified by both groups, while graduates also mentioned planning and creative thinking, while managers identified adaptability as necessary in the workplace.

It was noticeable that the work ethic was mentioned by several managers (3), while this was not identified by graduates. Additionally, the management referred to accountability, responsibility, and willingness to be mentored. These are skills that managers find lacking in the workplace.

Question 8 (EG & SEM): "Which of the following soft skills do you think are most important for engineering graduates working in the engineering industry? Rank the skills from 1 to 10, with one being the most important and ten the least important. Decision Making Skills, Team Building Skills, Emotional Intelligence, Leadership Skills, Negotiation Skills, Communication Skills, Conflict Management Skills, Influencing Skills, Motivating Skills, Problem Solving Skills."

<u>**Findings**</u>:

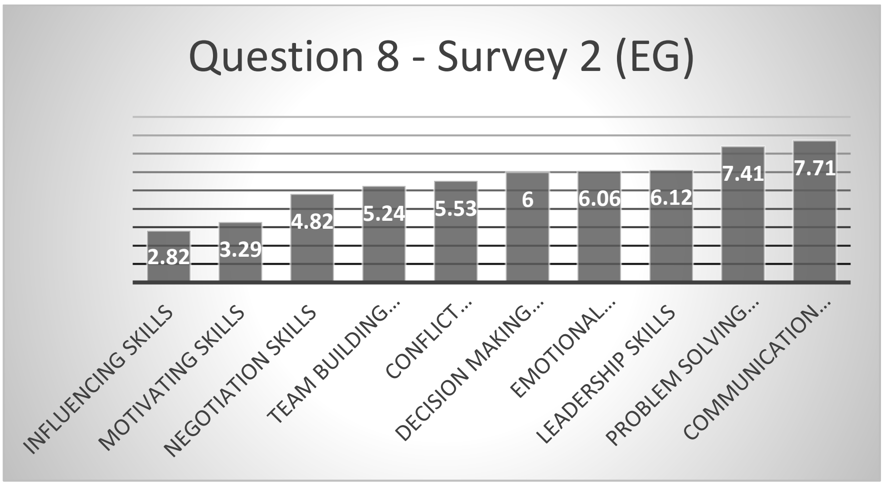

Figure 1: Survey 1 (EG) - Summary of the score Question 8

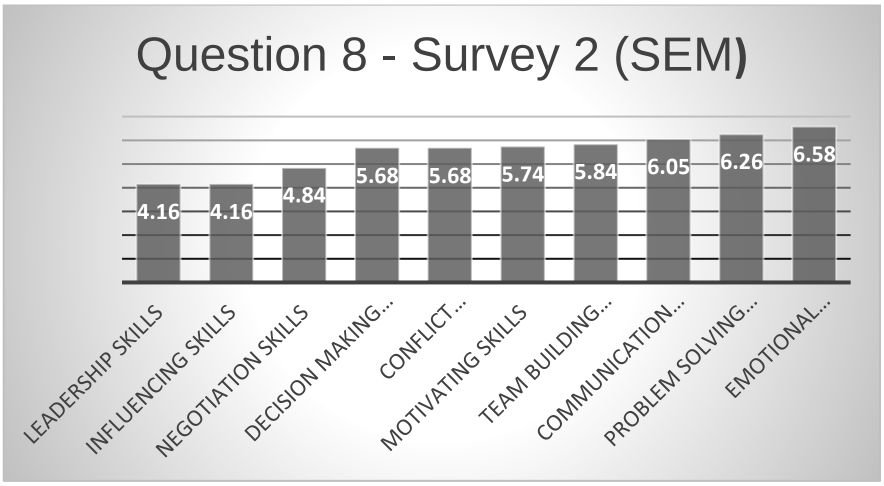

Figure 2: Survey 2 (SEM) - Summary of score Question 8

<u>Discussion</u>: EGs view communication skills as the most important soft skill, while SEMs view ***emotional intelligence*** as the most important. ***Influencing*** and ***Negotiating skills*** both rank low among both groups.

Question 9 (EG & SEM): "Following on from the previous question (**Question 8**), do you have any further comments to substantiate your replies or any further general comments regarding the question?"

Discussion: Although many respondents did not elaborate, graduates and managers mentioned emotional intelligence and communication as essential skills that graduates must possess when entering the workplace. Leadership and interpersonal skills were also highlighted in a similar way. Managers added negotiation skills and conflict management as of particular importance, while time management was once again *(referring to **Question 7**)* mentioned by graduates. The graduates also emphasised problem-solving skills.

Question 10 (EG & SEM): "Which of the above-mentioned soft skills do you think engineering graduates have the biggest problem with? Please substantiate your answer and provide examples where possible."

Discussion: Communication skills were identified by most of the graduates who commented (11 out of 14). One graduate explained that graduates are often scared to speak up because they are just grateful to have a job.

The fact that engineers need to be adequately prepared in their studies to work with people is clear from the comments. Engineers must be aware when entering the workplace that communication and negotiation are central to their role. Furthermore, engineers tend to be introverted, exacerbating the problem. As seniors sometimes overrule the decisions of junior engineers, they need to develop confidence and, as such, may also need more confidence to influence and motivate others.

Emotional intelligence is again emphasised, followed by decision-making and negotiation skills. Additionally, student life sometimes only promotes accountability, a crucial skill crucial in the workplace.

Regarding engineering managers, communication is also their top priority with regard to skills lacking in the workplace. This is followed by solid support for emotional intelligence. They agree with graduates that decision-making and negotiation skills are needed but add teamwork, leadership/influence, conflict management, and people management to the list, which graduates do not explicitly mention.

Question 11 (EG): "In your opinion, which of the above-mentioned soft skills were developed in the programme in which you graduated? Indicate specific modules/subjects, where possible."

Discussion: From the assessment of the responses, the problem solving skill was indicated to be the skill that graduates thought was the most developed, followed by the communication, conflict management, and team building **skills**. Other skills such as decision-making, motivation, and leadership were mentioned, but not significantly. Interestingly, emotional intelligence and influence skills were only mentioned once and negotiation skills were not mentioned.

Question 12 (EG) & Question 11 (SEM): "Do you have any suggestions on how these soft skills can be more effectively taught at higher education institute level?"

Discussion: Graduates and managers suggested that more practical projects or case studies could be introduced to better simulate those in the industry. These projects can develop communication, leadership, teamwork, and conflict management, to name a few. This option receives the most support from both groups. Both groups also suggested, but to a lesser extent, that specific modules/short courses/electives/summer schools could be introduced to develop soft skills. In addition, seminars and workshops could be held. More exposure to industry, on the one hand, and involvement of industry professionals, on the other, were also proposed.

Question 13 (EG) & Question 12 (SEM): "Do you feel that more emphasis needs to be placed on the education of soft skills in undergraduate engineering programmes to prepare graduates for working in the industry?"

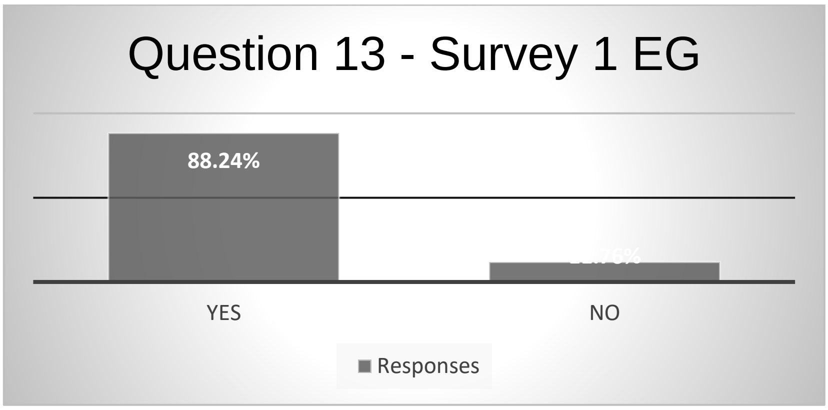

Figure 3: Summary of results – Question 13 - Survey 1 EM

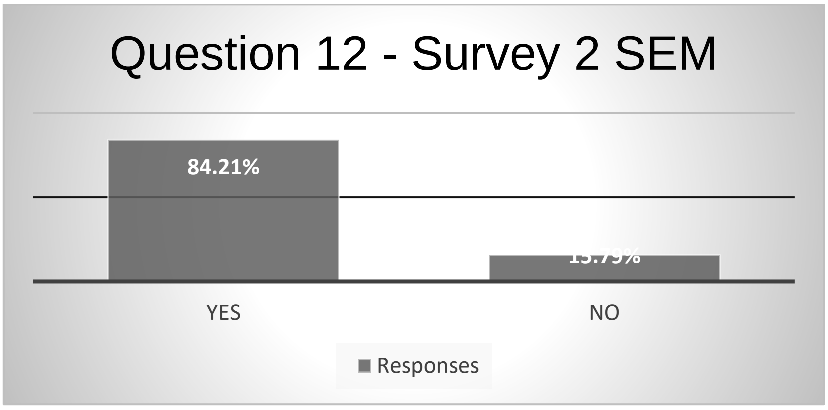

Figure 4: Summary of results – Question 12 - Survey 2 SEM

Findings: 88.24% of engineering graduates agree that more emphasis should be placed on the education of soft skills in undergraduate engineering programmes to prepare graduates for working in the industry.

84.21% of senior engineering managers agree that more emphasis should be placed on the education of soft skills in undergraduate engineering programmes to prepare graduates for working in the industry.

Discussion: The two sample groups strongly agree that teaching soft skills in undergraduate engineering programmes needs more attention. This relates to sentiments noted in the literature review, which commented that more attention should be paid to the education of soft skills among students.

Question 14 (EG) & Question 13 (SEM): "Please substantiate your previous answer."

Findings: Graduates agree that more emphasis should be placed on teaching soft skills in undergraduate engineering programmes, with the overall sentiment being that graduates are primarily unprepared for real engineering work environments. Environments where they are required to work in teams and manage human relations. However, some believe that focussing on soft skills in existing engineering programmes will dilute the learning of hard technical skills. There must be more space to teach soft skills in current engineering programmes.

Furthermore, soft skills can only be developed with experience in the work environment and through post-graduate studies and training.

Managers mostly agree that graduates need to prepare for the real-life engineering workplace and that soft skills development in undergraduate programmes will assist them in dealing with the pressure of the engineering profession. However, there are some views that undergraduate courses should focus on technical skills and that soft skills should be developed during primary and high school or postgraduate programmes.

Question 15 (EG) & Question 14 (SEM): "From the list of soft skills above, what soft skills do you feel are the three most important soft skills required as an engineer and project manager?"

Table 2: Responses to Survey 1 (EG) - Question 15

Soft Skill	Rank
Communication Skills	1
Emotional Intelligence	2
Leadership Skills	3

Table 3: Responses to Survey 2 (SEM) - Question 14

Soft Skill	Rank
Communication Skills	1
Decision Making	2
Leadership Skills	3

Discussion: The two sample groups rank communication and leadership skills amongst the top three soft skills required, including emotional intelligence and decision-making skills.

Question 16 (EG) & Question 15 (SEM): "In your opinion, do you feel that enough emphasis is being placed on the education of soft skills and the importance of possessing soft skills when entering the work environment?"

Findings: Eleven Engineering Graduates (64.7% of the sample population) agree that more emphasis should be placed

Seventeen senior engineering managers (89.5% of the sample population) agree that there is not enough emphasis being placed.

Question 17 (EG) & Question 16 (SEM): "In your opinion, do you feel that more emphasis is being placed on the education of hard skills and the possession of hard skills when entering the work environment?"

Findings: All seventeen Engineering Graduates (100% of the sample population) agree that more emphasis is being placed.

Sixteen Senior Engineering Managers (84.2% of the sample population) agree that more emphasis is being placed.

5 CONCLUSION & RECOMMENDATIONS

Research Question 1: What are the top human competencies (soft skills) identified to be an effective project manager and ensure project success?

The most critical human competencies that a project manager should possess for project success, as identified in the literature, are:

- Communication Skills
- Problem Solving Skills

- Leadership Skills
- Emotional Intelligence
- Decision Making Skills
- Conflict Management Skills
- Team Building Skills
- Negotiation Skills

A few other soft skills have been added to the list as identified in this study, and they are:

- Time management skills
- Stress management skills
- Planning skills
- Creative thinking skills
- Adaptability skills
- Accountability
- Responsibility
- Willingness to learn

Research Question 2: Since engineers are required to execute projects, as this is the nature of business in consulting engineering firms, are these human competencies effectively taught with the various undergraduate engineering programmes at higher education institutes?

The study graduates believe that some soft skills are being taught at HEI. However, managers were not as confident that these soft skills were adequately taught in the HEI. It should be noted that graduates do not realise the importance of having these soft skills when entering the work environment. The graduates also agreed that they did not know that these skills are required when entering the workplace.

Research Question 3: Should more emphasis be placed on developing soft skills in undergraduate and postgraduate engineering programmes?

Both sample groups, graduates, and managers strongly agree that HEIs should emphasise the education of soft/interpersonal skills in undergraduate engineering programmes. This view agrees with the literature and highlights the need to put more emphasis on soft skills, which remains a prevailing theme and concern.

Research Question 4: How can these soft skills be further developed in undergraduate and postgraduate engineering programmes?

The most prevalent suggestion of both groups is that more practical and real-life projects or case studies that simulate those in the industry should be introduced to the programmes studied.

5.1 Recommendations for future research study

Recommendations for future potential research have been identified:

1. Conduct a similar research study using a larger sample group, including managers and graduates, and increasing the sample group to include client bodies and HEI professors and lecturers.
2. Conduct a similar research study in a wider geographic area.
3. Conduct a study to fully explore the suggestions made in this study to teach the required soft skills more effectively.
4. Conduct a study to fully explore why engineering graduates have difficulty adjusting from student life to work life.
5. Some people believe that placing more emphasis on soft skills in existing engineering programmes will dilute the learning of hard technical skills or that there is no space to incorporate the teaching of soft skills in current engineering programmes.

Therefore, soft skills should be learnt and acquired postgraduate by attending training courses aimed at this, gaining experience in the field, and through postgraduate studies. This theme should be explored further to see if it is a viable alternative to emphasising soft skills during undergraduate programmes.

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RESEARCH PROPOSAL FOR THE DEVELOPMENT OF AN INTEGRATED SOLUTION FOR WHEEL MISALIGNMENT DETECTION IN THE ROAD TRANSPORT INDUSTRY IN SOUTH AFRICA

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ABSTRACT

One of the key contributing factors leading to road crashes in South Africa is associated with vehicle instability caused by wheel misalignment. Research conducted over the past 10 years shows that most vehicle accidents occur due to vehicle instability caused by wheel misalignment. Motorists currently check wheel alignment during periodic car service, which is a reactive approach posing a risk of motorists causing accidents on the road, which could result in loss of human life. However, wheel alignment requires real time monitoring and detection which should help to relay information on the degree of misalignment to make appropriate decisions. The solution from the integrated wheel misalignment detection system should provide information for decision making on the worst-case scenario where the misalignment is potentially dangerous to human life. This paper presents a desktop literature study that gives an overview of the current problem under investigation in the road transport industry. A gap analysis was conducted to identify further research questions associated with wheel misalignment detection in the road transport industry.

Keywords: Road Transport Industry, Wheel Misalignment, Systems Engineering

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1 INTRODUCTION

Most South Africans commute via the road transportation medium using either private or public commercial vehicles in a bid to meet up with their local-domestic responsibilities within the country. It is important to ensure that road worthiness of the commuting vehicles is ascertained[1]. There are many factors that can cause vehicle accidents on the road, one of factors is losing stability or control of the vehicle which can be caused by wheel misalignment[2]. There are various causes of misalignment, most of which are caused as a result of impacts such as bumping a pothole or driving too fast over a speedbump [2] can lead to wheel misalignment[2]. The misalignment of a vehicle’s wheels can result in a swift deterioration of the tyres. Considering the heavy goods vehicles (HGVs) for instance, wheel misalignment will result in a rapid and irregular wear of both the tyres and the roads which can be considered extremely harmful to safe operations, human life and the environment as a whole [3]. Hence, a regular wheel alignment examination should be carried out periodically to restore vehicle stability while commuting on the road for the purpose of safety amongst other road considerations[4].

Having a correct wheel alignment will not only avoid vehicle accidents on the road, it will increase the chances of sustained fuel efficiency of an automobile while also reducing vehicle tyre wear and bolt wear [5].

Many researchers have investigated and discovered that most of the road accidents may occur due to wheel misalignment and malfunctioning of the steering system[6]. According to Sulaiman et al.[7], motorists only check wheel alignment periodically during car service. This approach is reactive and can pose a huge risk for motorists which could potentially result in the loss of human life. However, wheel alignment requires a different approach, as it is an important element that must be monitored and detected in real time to ensure that wheel misalignment can be rectified urgently to avoid accidents on the road and minimise the number of lives lost on the road due to this problem.

In their research work,[2] identified wheel alignment as an important part of vehicle maintenance that involves adjusting the wheel angles to ensure that they are set to the specifications of the automotive manufacturer [2]. The main purpose making these adjustments is to reduce tyre wear and to ensure that the vehicle travel is straight and true[2]. The same authors argue that vehicle misalignment is also dangerous from a safety point of view as the vehicle is being pulled to the one side while the steering wheel is wobbling, and the car is vibrating [2]. Wheel alignment is closely related to driving comfort, tyre lifespan, and fuel efficiency[8]. According to D'Mello et al. [2] wheel misalignment can cause loss of fuel economy in a vehicle and also cause high carbon emissions associated with high rate of fuel consumption [9].

In this paper, a desktop study is presented in support of a research idea on the topic: Development of an integrated solution for wheel misalignment detection in the Road transport industry in South Africa.

1.1 Research problem, questions and objectives

Since the wheel alignment plays an important role in ensuring the safety of a car on the road and motorists only check wheel alignment during periodic car service, this is a reactive approach that puts motorists at a risk of causing road accidents that could result in loss of human life. However, wheel alignment requires a different approach as it is an important element that must be monitored and detected in real-time to ensure that wheel misalignment can be rectified timeously to avoid road accidents.

In support of the research problem the following questions can be stated:

- What technology currently exists in the literature to assist in building an integrated solution?
- How do you identify misalignment and what are the criteria to trigger realignment?
- What are the criteria to verify the correct alignment?
- What are the requirements that such a system should/shall fulfil and be verified against?
- What are the challenges related to wheel alignment and the detection of misalignment?
- To what extent have the proposed research recommendations been implemented to address the wheel misalignment detection problem?
- Can the proposed recommendations in the literature be implemented in South Africa?

These questions are answered in the rest of this paper using a desktop literature study to present an overview of this problem in the road transport industry as a gap analysis in identifying further research questions associated with wheel misalignment detection in the road transport industry.

1.2 Scope and Limitations

This study is going to focus on commercial vehicles doing their business activities in Gauteng Province in South Africa. Appropriate data will be solicited from Executives and Senior Management personnel within the automotive industry in the Gauteng Province. However, only those with at least 5 years' experience working in the industry at this level will be considered.

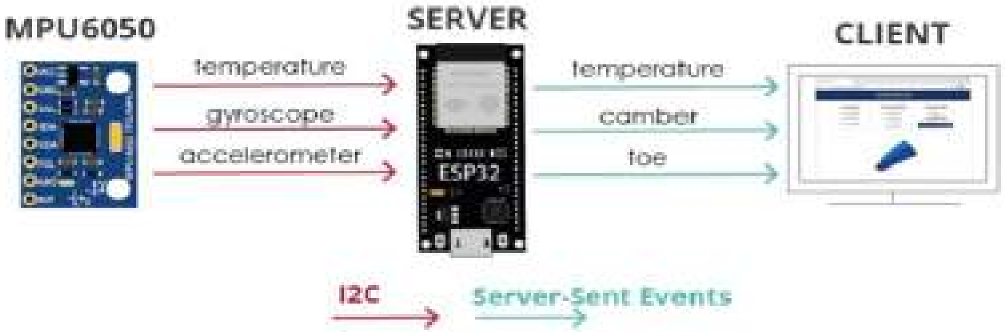
2 LITERATURE REVIEW

A literature study was conducted, it was obtained that there are about 86 700 scholarly work and 135 856 patents related to the search term "wheel-alignment detection system". Science Direct, IEEE Explore and Scopus scientific research databases were used to conduct the search and the following key words were used to search for literature:

- Wheel misalignment detection systems
- Integrated solution for wheel misalignment detection
- Integrated solution for wheel misalignment detection is South Africa
- Wheel misalignment detection systems from automotive manufacturers
- The importance of vehicle wheel alignment
- Risk associated with vehicle wheel misalignment
- Benefits of conducting wheel alignment

The literature review revealed the fact that research studies have been conducted in the road transport industry. The next section covers some details of research studies conducted across different countries relating to the topic.

In a study conducted by [2]in the automotive sector involves experimental research to investigate the feasibility of using an IoT embedded wheel alignment system, using an easily and user-friendly and low-cost method employing an MPU6050 sensor and an ESP32 microcontroller and a custom graphic user interface (GUI) has been developed. Figure 1 shows the proposed IoT wheel alignment system.



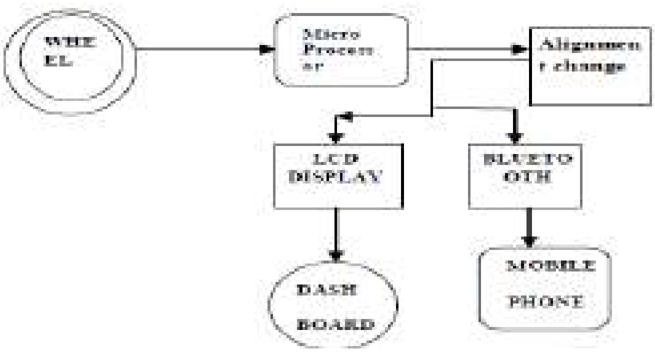
(Source: D'Mello, 2022)

Figure 1: IoT embedded wheel alignment system

The design of this device is relatively compact enough to be able to fit between the lug nuts of a wheel. The device can be mounted to a steel wheel using a flat magnet[2]. Alloy wheels require a suitable clamp that can be used to mount the device on a wheel[2]. This device consists of an MPU6050 sensor, as well as an ESP32 microcontroller that works together with a 9 V alkaline battery[2].

The proposed IoT based wheel alignment system has been tested on a vehicle, the results from this study shows that the system has a great potential to be a good alternative to existing wheel alignment inspection methods. However, this solution has not been implemented on a commercial scale nor adopted by automobile manufacturers to date to resolve the problem. Part of lesson learned from this study is that the system can Benefits associated with this system is that it can be adopted on any type of 4-wheeler where wheel misalignment detection is required and the system will still function as required.

In another study conducted in India by [1], the researchers took a different approach where they monitored the vehicle wheel alignment by using an accelerometer sensor which placed in a fixed position on the rear axle whereby the fixed value for the wheel alignment angle was sent to the microprocessor[1] . The change in wheel alignment angle is displayed on the LCD. The value of the vehicle wheel alignment is noted using the Bluetooth module, which is connected to the microprocessor unit[1]. Figure 2 shows the LCD/Bluetooth Wheel alignment alert system.

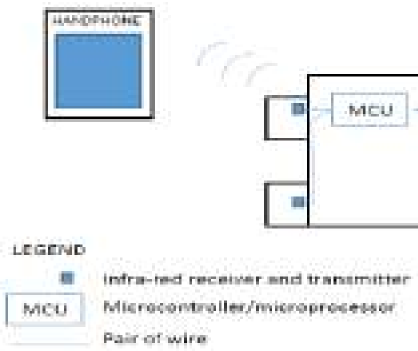


(Source: Balakrishnan, 2016)

Figure 2: LCD/Bluetooth Wheel alignment alert system.

The researchers claim that they have successfully been able to monitor wheel alignment by monitoring the alignment of the wheel continuously through the use of an accelerometer sensor[1]. The study consist of a computer-based vehicle wheel alignment measurement system using an accelerometer is presented in a different study by [4], this experiment has the advantages of using a simple circuit with high resolution and high working reliability. The causes and effects of improper wheel alignment by traditional methods are analysed in the model[4]. In this system wireless transmission techniques are adopted to transmit data between measuring unit and computer[4]. The hardware and software realisations are also explored in this paper. The system's practical applications show that its performance meets the design requirements. The results show that wheel misalignment can be detected in real time correction factors are also included in the calculations to get the actual angles from the angles with respect to the gravity[1]. The method adopted is the Wireless communication method to transmit the data between measuring unit and the actual computer which makes this system operation much easier which can be seen as one of the additional benefits of using this type of system[1].

An experiment was performed in the workshop with the help of the appointed mechanic [7]. In this work, smaller and portable wheel alignment monitoring system was introduced by using communication protocol between sensors, microcontroller and mobile phone application [7]. The GUI is utilised in the system via wireless communication technology using the TCP/IP communication protocol [7]. The system has been tested to suit the functioning architecture system for the wheel alignment to provide the user awareness on early detection of wheel misalignment [7]. In this experiment, the system is integrated with an Android mobile application via TCP/IP communication protocol and can view the results in real time on the smart phone [7]. Figure 3 shows the Wireless/Smartphone wheel alignment system.



(Source: Sulaiman 2021)

Figure 3: LCD/Bluetooth Wheel alignment alert system.

According to Sulaiman et al [7], the wheel alignment detection system generated favourable results in real time by using a smartphone to conduct the experiment. The application is consisting of a communication protocol that is placed between the sensors, microcontroller and also a mobile phone suitable for the system specification of this wheel alignment system. The this the wheel alignment monitoring system that uses the microcontroller application was successfully integrated with an Android mobile application through the TCP/IP communication channel and display producing results in real time. The experimental set up was conducted inside the workshop. There were no costs mentioned regarding the system, what has been mentioned is that the system can be able to measure the degree of misalignment on the vehicle in real time.

In addition, the literature reveals some great benefits associated with detecting wheel misalignment proactively,

According to Tang et al. [3] that can bring the following added benefits:

- Reduce the number of accidents and fatalities on the road caused by wheel misalignment.
- Fuel savings for motorists as a result of improved fuel consumption.
- Improved life of the tyres due to reduced wear and tear, subsequently reducing overall vehicle maintenance costs.
- Improved driver comfort and steering control.

3 SUMMARY OF LITERATURE OUTCOME

Based on the outcome on the literature

What technology currently exists in the literature to assist in building an integrated solution?

The reviewed literature shows that most of the studies have been conducted only by adopting the use of technology attempting to find a solution to monitor vehicle wheel alignment using certain instruments and sensors to monitor wheel alignment.

To what extent has the technology been implemented to solve the problem?

It is also noted that the researchers did not address how the results obtained from the above studies can be used in a meaningful way to solve the problem. No system architecture that integrates national or provincial regulations, organisational design, business processes, services, data flow and management with wheel misalignment detection technology could be found in this literature study.

To what extent have the proposed research recommendations been implemented to address the wheel misalignment detection problem?

In [2, 4, 7] it is mentioned how proposed solutions can be implemented per vehicle, whereby the information about the degree of wheel misalignment is not integrated to any system that can allow decision making by all stakeholders that can help avoid accidents on the road. Instead the technology only alerts the one driver per vehicle about the degree of wheel misalignment on the vehicle.

Can proposed recommendations in the literature be implemented in South Africa?

The studies in the literature above have been conducted outside South Africa.

There is a need to develop an integrated wheel misalignment detection system architecture to be used in the development of a specification for an integrated system solution in the South African context.

The following new questions result from above:

- Does an integrated system solution currently exist?
- Can systems engineering be applied to assist in the development of an integrated solution?
- What are the system and infrastructure requirements for developing an integrated solution to solve the problem in South Africa.
- How can the proposed solution from this research be implemented in the South African road transport industry?
- Who are the key stakeholders in South Africa that should be considered and included as part of an integrated solution to resolve the problem?
- Are operational procedures available in the literature that can help formulate an integrated solution?

- What technology currently exists in the literature to assist in building an integrated solution?
- What is the systems engineering design specification of an integrated system solution for South Africa?

4 PROPOSED RESEARCH METHODOLOGY

Design Science Research (DSR) approach will be use in formulating and understanding real world problems as compared to exploratory research [10]. The outcome of DSR is the rendering of knowledge that can be utilised in the design of practical solutions. The two primary activities of the DSR are [11]:

- The creation of new knowledge through design of novel or innovative artefacts or processes [11].
- The analysis of used artefacts or abstracting and reflecting on their performance [11].

DSR focuses on problem solving [12]. DSR facilitates mixed research methods. Some authors agree that DSR involve "systematic engineering" and an iterative approach to create artefacts [13, 14]. The main requirements on DSR are rigour and relevance [14]. The process is structured with three main interacting phases: Problem Identification, Solution Design, and Evaluation [14, 15].

The goal of a DSR research project is to extend the boundaries of human and organisational capabilities by designing new and innovative artefacts represented by constructs, models, methods, and instantiations [16, 17].

From the reviewed DSR literature above, the key benefit is a systematic approach to problem identification, solution design, evaluation and validation in an iterative and systematic manner.

It is proposed to use Design Science Research (DSR) to answer the above questions. It allows for knowing and understanding design problems in the development and operational deployment of solution artefacts [11, 18]. DSR solves important problems through the development and using of innovative artefacts and by evaluating and also predicting the benefits and associated risks of these artefacts [18].

It is further proposed to adopt a Systems Engineering approach combined with the systematic approach of DSR. DSR ensures scientific rigour in problem identification and artefact design by explicitly connecting to applicable knowledge consisting foundational and methodological knowledge that include theoretical knowledge, existing experiences and expertise, and existing artefacts and processes [19]. DSR also ensures practical relevance in problem identification and artefact design by explicitly addressing a business need requiring a solution involving people, organisations and technology [19]. DSR results in two deliverables [19]:

- New knowledge contribution to the knowledge base.
- Practical solution in an operational environment.

5 PROPOSED SYSTEMS CONTEXTS

Systems engineering process will be followed for this research study in conjunction with the Design Science Research process to design the solution for the problem identified in this research study. Systems engineering is "an interdisciplinary approach that can be adopted to enable the realisation of successful systems[20]. Systems engineering focuses on defining the needs of the customer and required system functionality early in a development cycle, and documenting these requirements, then preceding with design synthesis and system validation while taking into account the complete problem [20]. System engineering approach considers both the business and technical needs of all customers with the goal of providing a quality product that meets the user needs"[21]. Systems engineering function is to particularly guide the engineering of complex systems[20].

A popular departure point in Systems Engineering is the use of context diagram to determine the systems boundaries in its environment [20]. A first iteration for a systems context diagram for a South African Wheel Misalignment Detection and Management System (SAWMiDMaS) brainstormed by the authors is shown in Figure 4.

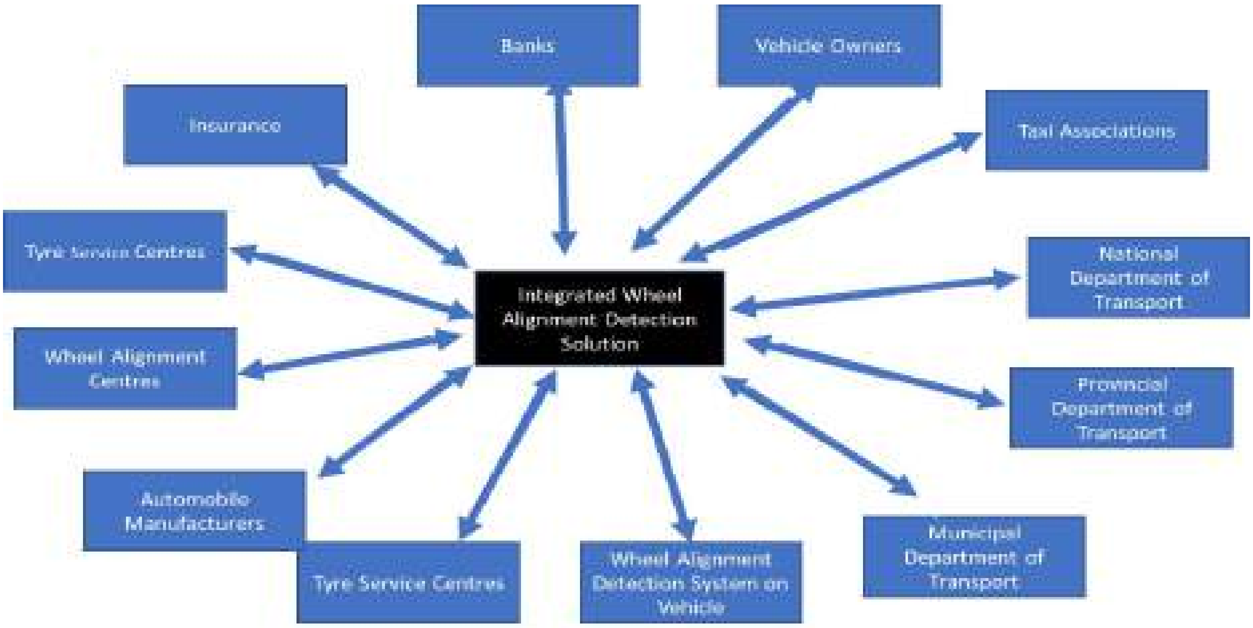


Figure 4: integrated solution for wheel misalignment detection

This context diagram can be evaluated and revised for its suitability during the implementation of accDSR activities proposed in Section 2.

6 CONCLUSION

Gaps have been identified and further questions identified in this paper. Further development of the proposed research idea can contribute to the body of knowledge on vehicle misalignment detection in the South African road transport industry. Technology that exist is implemented per vehicle, however to reduce the number of accidents and fatalities on the road the solution needs to be an integrated system focusing on actively managing wheel misalignment.

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SUITABLE LEAN MANUFACTURING TECHNIQUES FOR CONTINUOUS PROCESSES.

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ABSTRACT

In a changing economic environment, lean manufacturing techniques can improve productivity as commonly used in discrete manufacturing processes. However, continuous processes may also benefit from using lean tools and techniques but are not commonly researched from a South African perspective. This research explored lean techniques that are currently used in or may be introduced into continuous processes in South Africa. Two case studies which use continuous processes were used to conduct workplace observations and semi-structured qualitative interviews. According to the contingency theory, the environment and related circumstances will determine the type of action or intervention that is required. Overall, this study confirmed that continuous improvement initiatives and certain lean techniques can successfully be used in continuous process environments. Although some of the lean techniques and tools were used in the sample organisations, the staff did not know that they were using lean. Staff also deviated from standard operating procedures that were compiled by the leadership of the case study organisations.

Keywords: continuous process, lean manufacturing, 5S, Six Sigma, continuous improvement, total productive maintenance, total quality management, standard operating procedures, processes, waste

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1 INTRODUCTION

In a competitive economic environment, lean manufacturing principles are key for the survival of manufacturing organisations because they are mainly concerned with eliminating waste and removing non-value activities to improve performance, reducing costs, enhancing conformance to quality, improving productivity, reducing inventory levels and improving throughput times [1]. According to Deflorin and Scherrer-Rathje [1] as well as [2], lean manufacturing applications differ according to prevailing conditions within organisations. For example, industries differ according to the amount of product produced (volume) and according to the variety of products (different types of products). Lean manufacturing principles have various tools and techniques that have been commonly used in discrete manufacturing. Discrete manufacturing produces countable, distinguishable products and is associated with project-, jobbing-, batch- and mass process types [3]. However, [4] as well as [3] indicate a lack of the use of lean techniques in continuous process environments.

There is also a lack of research regarding the use of lean in continuous processes, particularly from a South African perspective. It is therefore not clear whether manufacturers who use continuous processes are using lean principles. The aim of the study was to identify lean techniques that are currently used or may be introduced into continuous processes from a South African perspective. The paper is organised as follows: a discussion of lean manufacturing application in continuous processes, research methodological procedures applied in the study, discussion and findings of the study, conclusions of the study, ethical considerations, acknowledgements, and references.

2 LEAN MANUFACTURING APPLICATION IN CONTINUOUS PROCESSES

Lean manufacturing was invented in Japan and rapidly spread to the USA and Europe because of their strong manufacturing infrastructures but lean has also been practised in developing countries, although to a much lesser degree [5]. Some examples of countries that are practicing lean manufacturing are Indonesia, India, Thailand and Malaysia [6]. Godinho et al. [5] confirmed that many manufacturing companies in Brazil apply lean manufacturing principles, but descriptions and evaluations of lean implementation are limited in continuous process organisations.

Lean manufacturing has three different levels namely lean manufacturing goals or philosophy, lean manufacturing principles, and lean manufacturing tools and techniques [3]. The importance of these stages is that they clarify the structure of how lean is observed and applied within organisations. Lean goals describe the main purpose of the lean manufacturing system, which is to create quality products that satisfy the customer, as well as meet demand with as little resources as is necessary by removing waste to decrease costs and improve quality. When lean is adopted as a philosophy in an organisation, processes throughout the organisation are restructured and streamlined using lean principles to improve productivity and create a more satisfied workforce, while enhancing the customer experience. In addition, staff members are trained to practice lean as a culture within the organisation. Bicheno and Holweg [7] state that lean manufacturing is driven by the behaviour of workers which is built through worker training, coaching and demonstration of how work should be done so that workers can gain self-confidence. According to Lyons et al. [3], lean philosophy is the theory that acts as the road map or a distillation of culture or core values that inform all aspects of business practices to improve organisational efficiencies.

Lean tools effectively cope with existing competitive challenges related to improving delivery reliability, delivery times, production quality, and productivity while reducing inventory and decreasing operating costs [8]. Piercy and Rich [9] as well as [10] found that the adoption of lean thinking can also result in improved sustainability, more stable operations, increased finance and better environmental performance through recycling and waste elimination.

Salonitis and Tsinopoulos [11] cite growth in market share, improvement of key performance indicators (contingency theory supports that every organisation can customise its improvement strategies based on their unique work environment or contextual factors), drive to focus on customers, and requirement or motivation by customers as benefits emanating from lean [6].

Lean principles are the guiding standards of the lean manufacturing system (which include the alignment of production demand; elimination of waste; integration of suppliers and creative involvement of the workforce). Lean manufacturing principles involve the implementation or integration of the lean principles into the daily activities of production processes and the supply chain. Lean tools and techniques that are most helpful in improving quality are: work standardisation, total quality management, statistical process control (SPC) and zero defects [12]. Abdulmalek et al. [13] mention that some lean manufacturing tools like 5S, total quality management (TPM), quality management programmes, value stream mapping (VSM), work standardisation, team–based problem-solving, and continuous improvements can be used in any manufacturing capability regardless of the type of manufacturing capability; however, these have not been recorded in literature for continuous processes from a South African perspective.

Lean manufacturing implementation is significant in some areas (not necessarily all areas may benefit from using lean principles), as different tools are used (based on the manufacturing environment) to benefit the company and its employees [14]. There is no unique roadmap to implement lean manufacturing principles and techniques and that it requires to be custom-made for different organisations to account for specific conditions [11]. This customised approach links in well with the contingency theory that was used as a theoretical underpinning for this study. According to this theory, the environment and related circumstances will determine the type of action or intervention that is required. Continuous processes have unique characteristics, which makes the adoption of lean manufacturing less simple to implement in continuous processes as it is in other process types [12, 15]. Panwar et al. [12] confirmed that not all lean principles are used in continuous processes.

Continuous processes have high volumes, low variety products, and inflexible machines whereas discrete manufacturing have lower volumes, high variety, flexible machines and are divided into four process types. Lean manufacturing principles are well established in most industries that follow discrete processing but should not be limited to discrete manufacturing only [17,1,11]. Continuous processes are usually highly automated and run continuously (24/7) with minimal human intervention. A continuous process environment employs different workers who are assigned to different shifts to ensure that production can continue around the clock. In continuous processes, machines and equipment need constant maintenance as they may be old and unable to be replaced easily due to high replacement costs and continuous use. Lean manufacturing is equally beneficial to continuous processes if it is properly adapted in the new environment according to the process, supply chain, market characteristics and other contingency factors [1].

Given the high cost of production and maintenance in continuous processes, the implementation of lean manufacturing techniques has numerous challenges that may not exist in other process types [18]. These challenges include a poor understanding of lean tools and techniques and the absence of knowledge regarding lean manufacturing principles and their various techniques [19,11]. The major challenges of implementing lean manufacturing techniques are related to the people: historical lack of employee education and training; absenteeism of workers (absenteeism can affect productivity); and carelessness of workers with organisational resources (for example, workers depend on recycling of defects and not making efforts to reduce defects to avoid recycling) [8].

Other challenges of implementing lean manufacturing include lack of labour resources, lack of implementation expertise, employee resistance to change, technical and financial resources [20,8]. Insufficient integration of lean principles and tools into the supply chain, lack of top management support, incorrect use of lean manufacturing tools due to poor understanding of lean tools and techniques and resistance to change by both shop floor employees and management [19,21]. Shop floor employees may be hesitant to offer recommendations for improvements to avoid becoming the culprit of errors and faults and take on more work than is necessary. Language barriers may restrict employees from articulating issues properly, and training may need to be offered on a multilingual platform for staff to grasp what they need to do more clearly. If the mentioned challenges are not managed well, production and staff morale may suffer, and the organisation may become less profitable.

3 RESEARCH METHODOLOGY

A qualitative methodology in the form of a case study design was chosen for this study that took place in the natural setting (took place in continuous process environments) of two businesses. A quantitative study would have been limiting for the researcher and a qualitative study provided more in-depth understandings and explanations around lean application within a continuous processing environment. The research used various methods that were interactive and humanistic (data were gathered through face-to-face interviews with participants and observations in the workplace); focuses on context (the researcher was able to observe the phenomena within the working environment, i.e. continuous processes); was developing (used follow up questions during interviews to probe); was primarily interpretive (transcripts were coded from which groups of codes were identified and translated into themes whereafter meaning was attached to the themes that were linked to workplace observations).

3.1 Research population

The population of this study consisted of organisations that follow continuous processes in South Africa.

3.2 Sampling and sampling techniques

This study used non-probability purposive sampling. Two plants whose operations use continuous processes were selected based on convenience, ease of access and willingness of the organisations to participate in the study. The participants consisted of four (4) shop floor supervisors, four (4) managers and four (4) workers that represented different work areas including quality assurance, maintenance, safety and operations management. It was a requirement that participants must have 3 years' working experience in the organisation. By choosing managers, supervisors and workers, the researcher was able to obtain both strategic and operational information. Due to the market that these two case study organisations service, the case study examples were significantly valid because their products are supplied nationally and used daily.

3.3 Data collection and analysis methods

Data were collected in three phases: literature review, qualitative workplace observations and qualitative interviews. A desktop study accessed peer reviewed published journal articles from credible journals, peer reviewed conference papers, books, and dissertations from various universities regarding lean manufacturing principles and techniques, particularly research that pertain to continuous processes. The researcher visited each of the two selected plants for a full week to observe the entire production process in the natural setting and to observe if any and how are lean techniques are used in the two case study environments. The researcher took notes during the observations. Open-ended questions were asked for participants to share their views. The researcher utilised a voice recorder to record the participants during the interviews to obtain an unbiased record of the data collected. The recorded interviews were transcribed verbatim coded through open coding, and analysed by means of content analysis. Three main themes, each with sub-themes, were identified.

3.4 Ethical considerations

The researcher obtained ethical clearance from the University of South Africa to ensure that the research adheres to the university's ethical guidelines. All the interviewees were requested to provide signed informed consent letters and no participants were forced to take part in the study. The participants were assigned pseudonyms and all identifying information were removed from the data. The rights of the participants to privacy, dignity, and confidentiality were upheld.

4 FINDINGS AND DISCUSSION

4.1 Company A

Operations run on a 5-shift system with 8-hourly shifts occurring daily. During the observations the researcher observed that the lean manufacturing techniques that were practiced are 5S (cleaning of equipment and collecting bottles on the floor, continuously wiping oil and water from the floor and continuous cleaning of machines and equipment), continuous improvement (ensuring that machines are set to the correct temperature to reduce defects and technicians are constantly monitoring the variables electronically) and TPM (maintenance of equipment through preventative and corrective maintenance) and TQM (the bottles go through inspection to ensure that they meet customer's specifications and after the bottles have been coated and annealed, they undergo quality assurance which is the last section in the manufacturing plant before the bottles are despatched for distribution).

4.2 Company B

The lean techniques that were identified are 5S, TPM, TQM and Continuous improvement (improvement (Six Sigma DMAIC, Fishbone analysis, 5 Whys and root cause analysis). The researcher observed that workers practiced 5S by doing ongoing housekeeping which included collecting bottles from the floor, continuously wiping oil and water from the floor to reduce accidents and cleaning machines. When machines are cleaned, these machines must be stopped for some time while other lines are used for production during that time. The workers also did continuous cleaning of the conveyor belt that transport input resources to remove foreign objects. TPM is applied by replacing worn parts through continuous maintenance because they are old and cannot be replaced easily due to their high costs and continuous use. Machines are not fixed immediately when they break down as breakdowns are prioritised according to its severity and fixed according to the level of priority assigned to the breakdown. The staff therefore appears to conduct reactive maintenance based on the urgency identified.

TQM is practised by monitoring variables throughout the process. Quality assurance is applied by removing waste such as the bottles with defects which do not conform to predetermined specifications that have been manually identified by staff and taken to the cullet plant where the bottles are broken to be reused. Continuous improvement is practiced when technicians who are constantly monitoring the variables electronically (control room operators monitor equipment, machines and other systems in the plant with a computer) and elimination of waste is applied by recycling defects (bottles with cracks) that are identified during or after the process of production.

4.3 Lean application in the case study environments

The researcher observed that teamwork takes place between workers, supervisors and managers while they manage operations and report defects through ongoing communication across different departments and shifts (reporting of defects and incidents among the team). Human errors are also recorded by the supervisors for training purposes as the errors may have detrimental impacts on production. Visual controls include cartoons, charts, light signals, lane marking on floor, safety instructions, warning signs and poka-yoke instructions that are displayed all over the workplace. There is a floor plan that indicates emergency evacuation areas as part of their safety and legal requirements.

In summary, companies A and B apply lean manufacturing techniques TPM (limited preventative and mostly corrective maintenance), continuous improvement (Six Sigma DMAIC, Fishbone analysis, 5 Whys and root cause analysis), 5S, recycling, visual controls and TQM in the continuous process environments of the case study examples, even though the workers are not aware that they are applying them.

Standards operating procedures (SOP) ensures that all workers are performing tasks in the same and correct way to ensure a consistent and uniform output [22]. SOPs assist to remove differences in understandings and execution among workers when completing activities in a working environment because the SOP process document specifies detailed aspects of all tasks pertaining to various processes to reduce mistakes, misunderstandings, miscommunications, procedural uncertainties, confusions and safety concerns. Manager-5 confirmed that the organisation has set waste management procedures in place:

> *we do we write strategies so on how to remove it from site and how to handle it to minimise, to eliminate all spillages and to ensure we comply on the procedure in terms of oil handling… they need to follow our waste management procedure.*

The interviews revealed that management have put standard operating procedures into place, but workers do not follow those standards operating procedures during production. Manager-3 said:

> *We just need to go back to basics, that's number one. For the last twelve years…we are no longer doing the basics… Like the SOP's are not being followed… We have them in place…I know if we can do them, we'll be able to get at least another five to ten percent into our efficiencies then.*

Manager 3 articulated: "We are not doing the basics, no-one is doing the basics, that's a pure, pure discipline issue." Although staff received area-specific training to teach them what is expected from them in their particular jobs, it is clear that they do not follow what they are taught. Management also do not seem to be hands-on involved in the production process to enforce the execution of standard operating procedures and ensuring the minimising of waste during the process. SOPs should be updated to accommodate changes that may have occurred in the manufacturing process. According to Manager-3, the quality assurance department is the only department that regularly review their SOPs: "Only the, the only department that I can say they are reviewing their processes is the QA".

The circular economy plays a significant role in enhancing sustainability. According to Goyal, Esposito and Kapoor (2016), the circular economy involves creating a closed-loop ecosystem (resource-product-waste-new resource) for the effective consumption and utilisation of resources as opposed to the traditional linear approach (resource-product-waste). Even during the observations, the researcher was shown where ash is kept for collection by external organisations that will reuse it again. Defective bottles were also broken to be reused in the manufacturing process. Therefore, the circular economy plays a significant role in reducing waste in the continuous process environments that formed part of this research.

*whatever we have produced, which is not in quality, we cannot just throw it away. We're able to go and recycle again from, from the production line. Then the other thing that we normally use again…there is a place where we put our general waste, where we put glass for recycling again (**Manager-1**)*

Quality assurance is a TQM lean technique that aids an organisation to develop standard operating procedures (specifications) that all organisational staff must observe.

we're dealing with glass bottles. In order to reduce waste, we need to produce quality bottles...our hourly inspection on our bottle sets, need to be done religiously. If not, then we're going to have webbing thrown away for unnecessary defects on the bottle…in that way we are reducing and optimising loss on our production end. (Supervisor 2)

During the observations the researcher witnessed that workers continuously define problems during production processes when they experience defects, workers measure the production output and compare it with previous day's production. Other workers monitor the production process from computers in the control room to ensure that the correct temperatures are used and that cameras that assist with quality control are working properly. The responses from participants show that different methods are used to solve different types of problems. Manager-2 mentioned:

*you would take the problem…things that could potentially lead to this failure and you list those two things or three, five things…Then the team would go out…when the, when the group comes back you normally find that, that you can eliminate three or four of those five things...then we start listing those things… Up to the point where you start eliminating the issues completely, but it's not an individual sitting…it's team based where the whole team gets involved…I think we're having a lot of waste that we can reduce by, by including people and you know, deeper investigations, proper downware analysis…so we do incident investigations…I want to see the root cause for this in, was this incident investigated?(**Manager-6**)*

*from operations to production to technical it might differ, where we would use either the fish bone, we would use things like the five whys, the five whys principles…We just introduced Six Sigma…we've introduced less green workers and we've just bought new machines that are with higher inspections. (**Manager-2**).*

*We're currently using Six SIGMA although it's not well established, but we're trying (**Worker-4**)*

Continuous improvement using Six Sigma DMAIC (Define, Measure, Analysis, Improve, and Control) is also practiced by continuously monitoring production processes electronically and reviewing reports to correct errors and reduce defects through introducing corrective action as required. Not all lean manufacturing techniques are applicable to the sample organisations. Cellular manufacturing, just in time and Single-Minute Exchange of Die for example did not feature.

5 LIMITATIONS AND DELIMITATIONS

This study focused on the application of lean techniques within continuous processes, and not on how lean techniques are used in discrete processes in South Africa. Another limitation relates to the data collection process whereby information attained during the interviews were dependent on what the participants were able and prepared to share. This study was conducted within two case study environments, and it cannot be transferred to other contexts in its entirety. However, components of the study may be applicable to other scenarios and organisations as well particularly because the two businesses serve consumers nationally and one has global operations.

6 CONCLUSION

This paper explored lean techniques that are currently used in or may be introduced in two continuous process organisations in South Africa. The researcher conducted workplace observations and semi-structured interviews that identified that the lean manufacturing techniques used in a continuous process environment are 5S, TPM, TQM, continuous improvement (Six sigma DMAIC, 5 Whys, root cause analysis and fishbone analysis) and recycling of resources. Based on the researcher's observations, standard operating procedures exist but are not fully practised in the case study environments. The interviews and observations further showed that not all workers are familiar with terminology related to lean manufacturing techniques even though they are using them. Proper maintenance execution through effective monitoring and control strategies can reduce the breakdown of machines and equipment but maintenance in the case study environments occur reactively.

This research contributes to the literature and knowledge that is available regarding the use of lean within continuous process environments from a South African perspective. The findings of this study will help continuous process manufacturers enhance productivity, decrease waste and improve efficiencies. It is recommended for management to ensure that policies and set standard operating procedures are adhered to and updated to reflect organisational and procedural changes that may have taken place. Continuous monitoring must ensure that workers adhere to organisational procedures and guidelines to improve quality and product consistency, protect workers from knowledge loss, save on training and maintenance costs and simplify performance management.

Management (leadership) and workers should work together as a team and constantly communicate about the challenges experienced during production processes for productivity to increase. Misunderstandings between workers and management must be reduced for creativity and innovation to increase, and for problems to be resolved quickly. In addition, it is recommended for a monthly forum to be established for workers and managers to exchange ideas as to how to solve pertinent issues and not to only rely on supervisors communicating worker issues and feedback in management forums.

Management, production staff and maintenance staff must ensure that proper maintenance (more preventative and less corrective maintenance) occurs to prevent the breakdown of machines and equipment. By adopting lean manufacturing as a philosophy, workers will be trained in lean manufacturing principles and techniques, which will make them more conscious about minimising waste and maximising overall value to the customer. This will however require restructuring of existing processes and functions to incorporate lean as part of the organisational structure. Value stream mapping (VSM) may be used to identify areas for improvement that is currently not being used in any of the two organisations.

This study explored how lean manufacturing principles can be applied in continuous processes within two case study examples. The sample can be enlarged for future studies to make the findings transferable. A future study can also conduct a comparative study of lean manufacturing in other countries.

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ENHANCING FOOD TRACEABILITY IN THE SOUTH AFRICAN FAST-MOVING CONSUMER GOODS INDUSTRY THROUGH THE USE OF BLOCKCHAIN TECHNOLOGY

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ABSTRACT

Food recalls are a common problem in the FMCG industry, however, technology to track and trace food products for fast and efficient recalls is limited. In this regard, farm-to-fork traceability is imperative to monitor the quality and safety of food in the supply chain, as well as manage religious and lifestyle preferences. To meet traceability requirements, multiple supply chain partners must participate so that food can be traced from its origin through its transformation process to the consumer. Current technologies used have shortcomings which are explored in this paper. In addition, blockchain technology is explored as a recordkeeping technology to share real-time information with supply chain partners in conjunction with the existing technologies that monitor conditions and movement of goods for better traceability of food products. Overall, the study confirms the importance of food traceability.

Keywords: Food traceability, Fast-moving consumer goods, Blockchain technology and Supply Chain

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1 INTRODUCTION

Food contamination and foodborne diseases are major problems for the Fast-Moving Consumer Goods (FMCG) industry which have resulted in many deaths and illnesses over the years [1, 2]. The World Health Organisation states that for 2010, illness from food contamination worldwide is comparable to that of malaria and tuberculosis [3]. As a result of food contamination and foodborne diseases, South African companies must conduct product recalls to deal with food contamination and foodborne diseases. South Africa experienced several Apple juice recalls by major food producers and retailers between 2019 and 2023. The recalls included the Coca-Cola Appletizer, Pioneer Foods Ceres Juice, Liqui Fruit and Woolworth's brand apple juice as a result of increased levels of patulin, a mould that is fruit-based called mycotoxin that can cause nausea, vomiting and gastrointestinal problems when consumed [4]. McCain recalled its green beans and Spar-branded frozen vegetables due to small glass fragments found in some food packaging. Nestle South Africa recalled Kit Kat chocolates because of the problem as McCain [4]. In 2019, Tiger Brands recalled 20 million Hugo’s and Koo canned vegetables due to defective cans that leak which have the potential to be contaminated with Clostridium botulinum, a life-threatening bacterium [5].

In South Africa, there was a listeriosis outbreak from 2017 to 2018 which caused more than 100 fatalities because of processed meat traced to a plant owned by Tiger Foods, the largest food processing firm in Africa [3, 6]. The source of the Listeriosis outbreak, which lasted over a year, was identified using DNA tracking, revealing that cold meat produced at a specific factory was responsible for the incident [7]. A product recall in March 2018 ended the outbreak [3, 8].

In contrast to DNA barcoding utilised by TigerBrands to trace the cause of listeriosis that lasted a year, Walmart has collaborated with IBM to enhance traceability within its supply chain by conducting two pilot tests utilising blockchain technology. The first pilot focused on tracing the pork supply chain in China, while the second pilot involved tracing the mango supply chain in South America [1, 9]. For these pilots, Walmart utilised the technology provided by Hyperledger Fabric, a modular blockchain framework [9]. The results of the pilots were significant, with the time required to trace mangoes reduced from seven days to a mere 2.2 seconds. Additionally, transparency across Walmart's supply chain was improved for more than 25 products from five different suppliers [2].

Risk mitigation strategies such as Quick Response Codes (QR Codes), Radio Frequency Identification (RFID), Wireless Sensor Networks (WSNs) and DNA Barcoding have not been able to deal with food traceability issues [10]. The outbreak in South Africa demonstrates the increasing food safety risks and the need to have an end-to-end food traceability system. Blockchain technology can improve food traceability and prevent fraud and counterfeiting [3, 11, 12]. The current technologies are unable to share information across the supply chain to facilitate and expedite food recalls as required.

The objectives of this study are to:

- To confirm the importance of food traceability in the South African Fast Moving Consumer Goods Industry
- To identify the challenges of current traceability technologies used in the FMCG industry
- To understand how blockchain technology can be used in the Fast-Moving Consumer Goods (FMCG) supply chain to improve the traceability of food products in South Africa

This paper discusses the food supply chain, traceability in South Africa, challenges of the current traceability technology in the FMCG industry and blockchain technology, and concluding remarks.

2 FOOD TRACEABILITY IN THE SOUTH AFRICAN FAST-MOVING CONSUMER GOODS INDUSTRY

2.1 Understanding the food supply chain

According to [13], the food supply chain refers to organisations that work to ensure the movement of agricultural food products in the supply chain. Food deteriorates in quality over time during manufacturing, storage and delivery due to factors such as climate change and transportation [13, 14]. Processed foods have a greater complexity due to the mixture of a wide variety of ingredients prone to risks such as bacteria causing foodborne diseases and poor-quality food products as a result of limited information on ingredients used during the production process [13].

Food supply chains are multifaceted and consist of a large number of customers and suppliers [13, 15]. The level of complexity and transparency within a food supply chain is large because of the number of partnerships and the movement of information among these partnerships [16]. Food supply chains are evaluated in terms of the life cycles of their products throughout-the end-to-end process [14]. A food supply chain comprises a retailer, suppliers, industrial producers, basic producers, wholesalers or distributors [13, 15]. (1) basic producers consist of farmers that produce raw materials and rely on climate and natural conditions; (2) industrial producers are manufacturers that are responsible for the packaging and processing of food products; (3) wholesalers are distributors that keep and move food products amongst basic and industrial producers; and (4) retailers retail food products to consumers [17, 18].

2.2 Traceability of food products

Food traceability refers to having access to recorded information on a food product in the supply chain [19]. Ensuring traceability is crucial to promptly identify and address potential risks associated with food, allowing for swift actions to prevent contaminated products from reaching consumers. The fast-moving consumer goods (FMCG) industry has become increasingly consumer-centric, necessitating timely feedback to effectively respond to instances of food contamination [33]. With the listeriosis outbreak in South Africa, it is evident that there are increasing food safety risks and food systems need to be modernised [3]. Contaminated food products pose a safety risk to the public and financial and reputational damage. In addition, many people have become more health conscious and religious requirements (halaal and kosher) also expect the reliability of the quality and origin of food to be intact. To track food from the source, sufficient systems need to be in place.

An effective traceability system possesses the capability to globally locate the origin of contaminated food, enabling the provision of data that identifies the source of the issue and facilitates the implementation of an appropriate corrective plan [19]. Traceability plays a vital role in reducing food safety risks and is considered a benchmark for quality within the food industry [19, 20]. The process of food traceability involves capturing, storing, and disseminating information about food across all stages of the supply chain, ensuring continuous quality and safety assessments in both upstream and downstream directions [20]. The application of technology-enabled traceability enhances accountability and traceability, leading to improved supply chain efficiency, as well as enhanced food quality and safety [21]. There are voluntary and mandatory traceability standards in the food supply chain to ensure traceability [22].

The mandatory traceability standards refer to legislation that manages food contaminations, controls traceability, labelling and the packaging of food products [23, 24]. Voluntary traceability is ISO standards that do not require legal conformity but provide benefits of improving traceability [24]. Food recalls are a method of removing food products at any stage of the process from the supply chain if that food threatens public health [25]. In South Africa, no legislation forces businesses to initiate food product recalls; all food recalls are conducted voluntarily in the interest of public safety [26]. However, all food businesses (manufacturers, distributors, wholesalers and retailers) have the responsibility and moral obligation to ascertain that consumers are protected from products that could cause a risk to their health [26]. Section 2(1) of the Foodstuffs Cosmetics and Disinfectants Act 1972 (Act 4 of 1972) prevents anyone from selling food products that are not safe to be consumed by humans [26, 31]. In addition, food safety alerts may be issued, requesting consumers to return implicated products to retailers and businesses or dispose of the food if it is not fit for human consumption [26].

2.3 Current traceability technology

Effective traceability technology enables continuous tracking of food products and provides a comprehensive history of each item [28]. Such systems are crucial for the supply chain, allowing for efficient recalls and ensuring quality and safety throughout the process [29]. To meet traceability requirements, supply chains rely on multiple partners to trace the journey of food products from the origin to the consumer [30]. It is essential for traceability systems to effectively interpret information, facilitating seamless sharing among supply chain partners. Despite the utilisation of traditional traceability systems like RFID, QR codes, DNA barcoding, and WSN, the FMCG industry still faces supply chain risks and increasing consumer concerns about food quality and sources [31]. Some authors argue that current systems fail to ensure the accuracy of the information or meet the traceability standards necessary for food safety [31, 32]. In addition, the communication of information from these existing technologies to supply chain partners is also problematic. Only the owners of the current technologies (RFID, QR codes, DNA barcoding, and WSN) receive information from the technologies [31, 32].

2.3.1 Existing traceability technology's ability to read information

It is crucial to utilise traceability systems that are capable of accurately identifying products. Various factors, such as metals and liquids, line of sight, read range, and durability, can impact how these systems gather and share information, potentially affecting its accuracy [33, 34]. While Radio Frequency Identification (RFID) is widely acknowledged for supply chain tracking, it is not extensively employed in the food and beverage industry due to its limitations. Metals reflect radio-frequency waves, while liquids absorb them, making it challenging to read tags placed on these surfaces [33, 35]. Consequently, the water content in food and the presence of metals like aluminium in packaging materials such as aluminium foil boxes, glass bottles, and jars pose obstacles to food traceability and impede information sharing [37]. Efforts have been made to position tags above the liquid level, attaching them to the bottleneck, cap, or cork. However, this approach is not consistently effective as beverage factories often use metallic tanks with liquids during the production phase, which can impact radio coverage, affecting the readability and tracking of food products within the supply chain [36, 37].

Unlike RFID, Quick Response Codes (QR codes) offer the advantage of being used at all stages of the supply chain since they can be placed on any type of food packaging, including metals and liquids [38]. DNA barcoding provides a reading method unaffected by metals and liquids. In India, this technology is employed to identify elevated levels of metals in traditional plant/herbal medication that may be harmful when consumed [40]. Similarly, in Taiwan, DNA barcoding has been utilised to detect excessive metal content in tuna preserved in olive oil or brine [41]. Wireless Sensor Network (WSN) technology also remains readable despite the presence of liquids and metals. It can effectively monitor water quality in agricultural irrigation systems and detect atmospheric gases [42].

Line-of-sight automatic identification (auto-ID) technology requires an unobstructed view between the data carrier and the reading device [34, 43]. QR codes face challenges in terms of readability as they rely on a direct line of sight to capture information from food products, resulting in the loss of historical data within the supply chain when visibility is compromised. Similar to barcodes, QR codes may become unreadable if they are facing the wrong direction, torn, or contaminated [34], which hampers effective product recalls and traceability capabilities. On the other hand, RFID does not rely on visual contact, but both passive RFID and QR codes are prone to human error since each product must be manually scanned [43]. Failure to identify a QR tag can lead to unaccounted products and create opportunities for inventory loss and theft [43].

However, harsh indoor environments can affect the accuracy of data captured by Wireless Sensor Networks (WSNs) for environmental sensing, as they may disrupt line-of-sight communication [44]. Such disruptions can lead to incorrect temperature and humidity readings, potentially impacting food freshness and quality by misrepresenting spoilage or expiry dates [45]. DNA barcoding, unlike other technologies, does not require line-of-sight for reading and capturing product information, as it utilises a different mechanism for species identification based on sequence variation within a genome However when it comes to readability, DNA barcoding relies on a web-based database called GenBank for reference sequences, which can introduce the risk of incorrect identification due to unreliable, incorrect, or missing DNA sequence data [45].

To ensure effective monitoring of product quality and safety, traceability systems need to be resilient in harsh environmental conditions such as sunlight and natural hazards, which can potentially impact the functionality of traceability technologies [33, 39]. According to Abenavoli, et al. [41], QR codes have faced challenges in terms of barcode readability due to their vulnerability to extreme environmental temperatures and external factors like dirt and humidity. These issues have resulted in reduced reading accuracy, disrupting the supply chain, and hindering the sharing of food product information [39]. Consequently, tropical regions characterised by high temperatures and humidity face limitations in using barcodes.

2.3.2 Information currently stored in traceability systems.

RFID technology employs waves to identify food products through a microchip attached to an antenna, which stores a unique serial number and additional information [46]. It is crucial to have comprehensive information not only about the transportation conditions but also about the entire journey of the food product, including details about farming practices (such as farmer information), growing conditions (such as pesticide and chemical usage), processing procedures, storage conditions, distribution channels, and retailers, ultimately reaching the consumers, which is commonly known as the farm-to-fork concept. However, RFID tags are primarily utilised for tracking food products during storage, distribution, and group packaging, leaving a gap in information regarding farming conditions [35]. RFID technology finds applications in various supply chain functions, such as transportation management, warehouse management, inventory management, and order management, for effective tracking of goods and services [47]. Nonetheless, a drawback of RFID is that it is mainly used for group packaging and does not provide individual product-level tracking [28].

QR codes are typically placed on product packaging, such as food labels, for identification, while the tracking codes themselves are not directly applied to the actual product [28]. This poses a challenge to information sharing because product packaging can be damaged or separated from the product, leading to the loss of information if the QR code cannot be scanned or if the QR code on the packaging is scanned when the product is no longer inside, resulting in the capture of incorrect information. On the other hand, DNA barcoding is a process used for verifying the authenticity of products, particularly in the traceability of seafood meat, raw milk, and edible plants [46, 48]. Unlike RFID and QR codes, DNA barcoding does not track the movement of products within the supply chain but rather ensures the authenticity of their contents to prevent fraud or counterfeiting. DNA barcoding focuses on taxonomic species identification and contributes to genetic traceability; however, it does not specifically track the movement of food products like RFID and QR codes [49].

In contrast to RFID, QR codes, and DNA barcoding, Wireless Sensor Networks (WSNs) employ sensing nodes to collect environmental information, such as temperature and humidity, which is then converted into a digital format and transmitted to a central base station for storage [29]. WSNs utilise wireless communication technology to transmit data openly [50]. Unlike RFID and QR codes, WSNs are not primarily used for the identification of food products, but rather for monitoring the environmental conditions in which the products are situated [46]. WSNs are commonly employed in the tracking and monitoring processes during transportation, as they can be attached to crates, pallets, or shipping containers as active monitoring devices to track the temperature and freshness of perishable goods and to detect any instances of damage or container tampering [51]. The use of WSNs in the food industry has seen a growing trend in environmental monitoring to ensure the safety and quality of perishable items delivered to consumers [29].

Supply chain managers express scepticism regarding the sharing of information with their trading partners due to concerns over perceived security risks and the complexities associated with information exchanges [52]. The potential risk of information leakage, which involves either the intentional disclosure of a company's confidential information to external parties or the unintentional revelation of information to unauthorised entities, has been identified [15]. According to [52], the level of security provided by supply chain information systems plays a significant role in determining the ability and confidence to share information. Several researchers suggest the adoption of blockchain technology in the food supply chain as it offers an efficient system for sharing information and ensuring traceability, enabling prompt identification of contamination sources and effective handling of food crises, thereby fostering consumer trust in food safety [53, 54].

RFID tags, with a storage capacity of up to 2KB, are ideal for disposable product packaging [46]. In comparison, QR codes can store more information with up to 7089 characters but have slower read rates and can only read one code at a time [28]. WSNs, unaffected by external conditions, can be set up anywhere and have a RAM size of 4KB [44]. However, their communication range is limited to 100m, requiring a large number of nodes to cover a large area [44]. DNA barcoding authenticates product contents but does not trace products within the supply chain. It offers great data storage but requires a large sample size for reliable genetic estimates. Blockchain, growing at a rate of 1MB per block every 10 minutes, stores vast amounts of data in each node [11]. With increasing transactions, participants in the agri-food supply chain constantly store data on the blockchain to validate transactions and track their sources [62].

2.4 Blockchain technology

Unlike RFID or QR codes that rely on scanners, blockchain technology relies on information to be entered into the system using computers, eliminating the need for physical contact with food [42]. Information is captured remotely, with every participant contributing to data capture and maintenance [21] and the captured information can be viewed by all authorised supply chain partners. Each computer serves as a node (representative of a supply chain partner) in the blockchain network, ensuring the accuracy of recorded data [21].

Blockchain technology, as a decentralised data collection, encompasses information, data, or transactions [55, 56]. Its implementation in the supply chain network ensures the distribution and simultaneous real-time viewing of transactions by participants to ensure the integrity of the food production process, traceability, food safety, and enhanced consumer trust [53, 60]. Each block in the blockchain contains transaction details from a specific timeframe and creates a verifiable digital footprint, establishing connections between preceding and subsequent blocks [59]. Modifying ledger information necessitates consensus from all network nodes, and since there is no single controlling entity, the information is visible to all network participants [57]. Food traceability facilitated by blockchain technology encompasses tracing the origin, source verification, faster and more accurate recalls, and improved food safety by reducing contamination incidents [61]. Although blockchain technology is relatively new, its use cases are evolving and advancing, it is recognised as a solution for achieving traceability in the food supply chain through decentralisation, enhanced security, transparency, and immutability [11, 13, 62, 63].

Security is a prominent feature of blockchains. Each block in the chain is timestamped and equipped with cryptographic hash values, ensuring the integrity and immutability of the information stored within the blockchain [62]. Blockchains function as open ledgers that can be shared among multiple participants, promoting transparency and traceability within the blockchain network [63]. Any node (supply chain partner) within the network can access and retrieve the blockchain stored in a folder, eliminating the need for a central verification system. This decentralised approach enables transactions to occur directly between two parties without requiring authentication from a central agency and participants' information is not stored centrally [64]. In a private blockchain, the identities will be known, or you will not know where to trace the issue for quick food recalls [62].

FMCG companies must have a formalised method of tracking the origin of food within the supply chain [65]. Blockchain technology offers a secure and immutable record of transactions that can replace traditional paper tracking systems and manual monitoring processes that are prone to inaccuracies [62, 66]. By leveraging blockchain, traceability in the food supply chain can be ensured at the individual level and communicated to the group at the batch level for quicker food recalls and better traceability [9]. For instance, Walmart conducted a blockchain pilot project for tracking mangoes and pigs, where they identified essential data points such as tagging pigs at the farm, details about fertilisers used in the pre-seedling stage of mangoes, tree quality, lot numbers for pig storage, packaging dates for pork and mangoes, temperature records during storage and distribution, quantity shipped, and purchase order numbers [9]. This approach enables Walmart to retrieve crucial information from a single source in the event of a consumer purchasing contaminated products [10, 67].

According to Sawtooth [68], seafood traceability in the supply chain suffers from various issues, including inaccurate and problematic paper-based record-keeping, inadequate storage conditions for food, illegal fishing practices, and mislabelling, which ultimately erode customer trust. In 2017, Intel demonstrated how the Hyperledger Sawtooth platform, which manages blockchains, could streamline traceability in the fish supply chain [69]. The objective was to establish a network that facilitates food storage, temperature control, and the tracking of fish from the sea to the consumer [66]. The use of a blockchain-powered fish supply chain offers the advantage of traceability, which fosters trust throughout the entire supply chain [68].

Multiple incidents in China in 2008 and 2018, involving baby formula and vaccines, resulted in the hospitalisation and deaths of numerous infants [70, 71]. In response, Danone introduced its Track and Connect service, a serialisation, aggregation and blockchain-based food traceability solution designed to enhance transparency and traceability of baby formula brands such as Aptamil, Karicare, and Laboratoire Gallia throughout the entire supply chain to provide post-sales support [72]. This service was launched in China, France, Germany, Australia, and New Zealand [70, 71]. The solution includes two barcodes: one on the outer packaging that, when scanned using the app, provides information about the production, processing, and transportation of the product until it reaches the store shelves [73]. The other barcode is laser printed on a tamper-resistant inner cover, and if the same code is scanned twice, it triggers an alert, ensuring the legitimacy of the product [70]. These barcodes guarantee transparency, and authenticity, and help establish trust between customers and suppliers, particularly considering the critical role that baby formula plays in an infant's nutrition [73].

Blockchain technology has the potential to enhance the manufacturing process by preventing the entry of counterfeit products into the supply chain by implementing scanning procedures at every stage [10]. By verifying the origin of the product and providing information on its journey from inception to the end consumer, blockchain ensures transparency and enables the creation of a comprehensive product history [10, 74]. Additionally, blockchain technology enables the tracing of various aspects related to a product, such as invoices, receipts, warranties, copyrights, licenses, and barcodes [74]. By mitigating challenges like manufacturing process issues, delivery delays, and unknown product sources, blockchain contributes to a more efficient and reliable supply chain [74].

2.5 Using Blockchain in the Fast-Moving Consumer Goods Market

Given the large volumes and high turnover of fast-moving consumer goods, it is important to have a proper system in place that can accurately track, and trace produce to ensure that products that are consumed are safe [20]. Food can be grown in a region, processed in another region or province, and distributed for consumption nationally or even internationally [19]. Food traceability systems must be able to still be effective despite the geographical distances involved [19]. Given the inability of existing systems to effectively track and trace food, it is necessary to consider a system that can enable real-time information sharing of each food parcel as it travels from farm to fork [31]. It is in this context that blockchain technology can be considered.

Blockchain, as a decentralised technology, does not have a line sight of the products and packages that must be traced and can therefore not replace existing technologies [31]. However, given the importance of being able to track and trace the origins of food from farm to fork, the technology can assist firstly in recording and secondly make the information accessible by all authorised parties [52]. Blockchain can use information that has been gathered from the existing technologies (RFID, QR codes, DNA barcoding and wireless sensors) to be made available in a centralised repository for access by all supply chain partners. In this way, current technologies that have problems storing a vast number of information can transmit the information to the centralised repository for storing before the information on the existing technology is edited or deleted. Blockchain usually stores information in blocks anonymously [57]. It is advisable for a private or hybrid blockchain to be configured so that the identity of the information capturer is made available. In this way, the origin of the contamination can be traced faster, and products can be recalled without delay to curb damaging risks to consumers [31].

All changes made to blockchain records are recorded in an audit trail, making the records secure. Counterfeit and replacement products can be curtailed and possibly eliminated using blockchain technologies [57]. Information placed on the blockchain is also available in real-time [53, 60]. Adhering to safety and quality standards is crucial and this information can also be managed in the blockchain. QR codes and RFID can continue to track the movement of goods, whereas DNA barcoding can verify the authenticity of products and may be used in conjunction with RFID and QR codes. Wireless sensors can assist in tracking environmental conditions that may be more useful for perishable goods. Blockchain as the recordkeeping capability can enhance records and tracing capabilities.

3 CONCLUSION

The FMCG industry is one of the world's biggest industries, providing consumers with lucrative goods and services. The inaccurate traceability of food can harm FMCGs and may result in the loss of income and brand reputation due to ill health or even the deaths of hundreds of consumers. The inability to implement food safety and traceability standards can limit exports of food products. Existing technologies cannot track the movement of food in certain mediums (water and metals), obstructions make it difficult for products to be scanned, some technologies cannot track environmental conditions, they sometimes cannot track itemised batches and may not have sufficient space to records vast amounts of information. In addition, information is not readily available across the supply chain and some food recalls have taken up to a year which has resulted in illnesses and many deaths.

International companies have already started to pilot blockchain technology into their supply chains to better manage food traceability. South African FMCGs may benefit from also revisiting their traceability systems to prevent loss of lives in future, be able to accommodate consumers changing needs, and sufficiently clamp down on counterfeit products and fraudulent activities that have been identified in the market. Real-time traceability systems will allow South African organisations and supply chains to effectively compete with international FMCGs. Product recalls will be efficient and easier to conduct when information is stored in an immutable, decentralised traceability system as supply chain participants will have access to information and can pinpoint where problems occurred in the supply chain. Although blockchain technology will enhance the real-time availability, authenticity and security of food information as it moves through the supply chain, it cannot replace existing traceability technologies. However, when used in combination with existing technologies, the information and traceability capabilities can be tremendously enhanced. Future research could explore how policies and legislation can be adapted to include blockchain adoption.

4 LIMITATIONS AND FUTURE WORK TO BE CONSIDERED

This study recommends that using a private or hybrid blockchain in addition to existing traceability technologies (RFID, QR codes, DNA coding and wireless sensors) will enhance information storing regarding traceability measures from farm to fork. Enhanced traceability capabilities will invoke more customer trust and loyalty.

To address privacy concerns, the researcher assumes that only authorised individuals (like validated supply chain partners who are involved with daily operations) will have access to view, capture, and update certain information while other parties (like consumers) may only have a view functionality of less information as they may for example not be interested in operational information. The design of the blockchain system includes configurations like the Public/Private Key Infrastructure, digital signatures, and encryption for transaction validation through the Merkle tree. A hybrid configuration will also combine decentralised and private functionalities that will accommodate customisation as required. However, all of these aspects mentioned do not form part of the focus of this paper, which centres on the tracking and tracing capabilities of FMCG technologies. This study is limited to fast-moving consumer goods.

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REFLECTION ON DEVELOPING A SUSTAINABLE INDUSTRIAL ENGINEERING HONOURS PROGRAMME TO SUPPORT STUDENT-CENTRED LEARNING AND TEACHING

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ABSTRACT

During the national re-curriculation process, the new Higher Education Qualification Standard Framework allowed comprehensive universities and universities of technology to review, revise and re-design engineering curricula. The re-curriculation process provided an opportunity to design programmes that focused on future sustainability within a developmental framework. As a result, the Bachelor of Engineering Technology (BET) Industrial Engineering commenced in 2018, and the new Bachelor of Engineering Technology Honours in Industrial Engineering commenced in 2022. A literature review on the proposed framework for developing an honours degree programme was done for this study. In addition, the literature study determined the critical elements for student-centred learning. Feedback was obtained from the first graduate cohort of students to assess their perceptions and experiences of the BET Honours programme. The results indicated specific opportunities for facilitating student-centred approaches. It is anticipated that institutions of higher learning can use the framework to ensure sustainability and student-centred approaches when designing new programmes, workshops and other curricular and co-curricular activities.

Keywords: Development framework, Industrial Engineering, Honours programme, Student-centred learning, Sustainability

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1 INTRODUCTION

The revised Higher Education Qualification Sub-Framework (HEQSF) presents a structure and criteria for qualification design and facilitates the comparability of qualifications while providing the basis for integrating all higher education qualifications into the National Qualifications Framework (NQF). Furthermore, the HEQSF provides a basis for standards development and quality assurance and a means for improving the coherence of the higher education system. It also suggests articulation routes between qualifications, enhancing the system's flexibility to enable students to move more efficiently from one programme to another should they pursue their academic or professional careers [1].

The Bachelor in Engineering Technology (BET) Honours Degree is a postgraduate specialisation qualification that prepares students for research-based postgraduate study. This qualification demands a high level of theoretical engagement and intellectual independence. The BET Honours Degree programme must include conducting and reporting research under supervision worth at least 30 credits as a discrete research component appropriate to the discipline or field of study. In some cases, a Bachelor's Honours Degree carries recognition by an appropriate professional or statutory body [1], as is the case for engineering programmes. South African engineering programmes must typically adhere to the Engineering Council South Africa (ECSA) prescriptions and requirements to ensure ECSA accreditation and professional registration of graduates.

According to ECSA, the South African BET Honours Degree is a postgraduate qualification that prepares students for Industry and research and demands a high level of theoretical engagement and intellectual independence [2]. This qualification typically follows a Bachelor's Degree, Advanced Diploma, or appropriate level 8 qualification. It aims to deepen the student's expertise in a particular engineering discipline while enhancing research capacity in the methodology and techniques of an engineering discipline. Furthermore, the BET Honours Degree enhances the application of research and development to meet the minimum entry requirement for admission to a cognate Master's Degree.

Engineering students completing this qualification should demonstrate competence as ECSA prescribes in all the graduate attributes contained in the standard. In addition, the content of the educational programme must also expose students to certain knowledge areas which adhere to ECSA prescriptions. Additionally, it should stay within the minimum credits in each knowledge area [2].

In the current South African landscape, the cabinet established the Presidential Infrastructure Coordinating Commission (PICC), which was mandated to coordinate a National Infrastructure Plan. Kgalema Motlanthe explains the need for the National Development Plan (NDP) to integrate and phase investment plans across eighteen Strategic Infrastructure Projects (SIPs) [3]. The SIPs aim to "unlock opportunities, transform the economic landscape, create new jobs, strengthen the delivery of essential services, and support the integration of African economies". The role of engineering in realising NDP objectives is undisputable; however, engineering is also one of the scarce skills identified by the government [3]. Owing to the focus of the BET Honours, which is strengthening and deepening knowledge and research, it can play a significant role in achieving NDP objectives. For instance, within the BET Honours in Industrial Engineering, research can be conducted in project management, healthcare and the identified industrial development areas of agro-processing, pharmaceutical processes and systems, localisation of freight and passenger rail components, other component manufacturing and mining, and processing.

Within the context of the NDP, the new HEQSF and ECSA requirements, comprehensive universities and Universities of Technology (UoTs) were allowed to renew, revise, re-design and recreate engineering programmes. Therefore, the re-curriculation process provided the opportunity to design programmes with the future in mind, ensuring that the programmes are sustainable and relevant not only in an international context but for local and national development and benefit. This situation meant that engineering faculty, typically not trained in course development, were faced with developing a Bachelor of Engineering Technology Honours in Industrial Engineering programme.

Accordingly, this research focuses on designing a Bachelor of Engineering Technology Honours in Industrial Engineering programme that will be sustainable and student-centred in South Africa while meeting national and international accreditation body requirements. A further study will extend this framework and describe the programme content that will be developed by applying the proposed framework.

2 DEVELOPING SUSTAINABILITY FRAMEWORK

Slavin [4] identifies that honours students are risk-takers and "are willing to take intellectual risks both inside their discipline and outside of it: they enjoy the challenge … revel in discussions of quantum mechanics and the outstanding engineers who cannot read enough history … they are willing to explore and often find themselves surprised at their interest". Ferguson [5] also proposed that the traditional value of an honours programme lies in the benefits for the individual student, such as obtaining and enhancing skills that are academic, social, leadership-orientated, personal and professional. Furthermore, although these outcomes can be achieved outside of an academic honours programme, an honours programme provides a place and resources for nourishing these outcomes in the company of like-minded high-achieving students who are typically undergoing the same transformations and share the same ambitions. An honours programme also exposes academics to a new pedagogy of student-centred learning (SCL), whereby they must now place more responsibility for academic success on the student to allow them to inquire, explore, discover, collaborate, create and take risks [5]. However, Ferguson [5] cautions against faculty short-circuiting the process by "injecting faculty control in the form of overt or implied correct answers or in directed assignments where the outcome follows from the direction". This type of faculty intervention could be disguised as the process of applying rigour or standards.

On the other hand, when faculty gave up the desire to control the learning process and outcome, the students responded far more enthusiastically when they were treated like mature self-directed students. An additional benefit of offering an honours programme is that it can attract other high-achieving students to the university. As a result, "leading with the honours program[me]" has been used as a strategy to increase admissions standards and numbers [5]. Therefore, an honours programme can potentially have a "catalytic impact" on the learning experiences of honours students and faculty, peers and administrators.

In addition, offering an honours degree holds many benefits for the university, students and academic staff and has the potential to contribute to the region's development. In the case of South Africa, it can also contribute to achieving aspects of the NDP. Designing, planning and managing such a programme successfully and sustainably would be essential for Higher Education Intuitions (HEIs). Although no standard explanation for sustainability appears to exist, sustainability can be defined as "effectively leveraging partnerships and resources to continue programmes, services or strategic activities that result in the improvements" [6] for Industry and the region. The concept of sustainability encapsulates the mission of the Industrial Engineering Department, which is to "work for the growth of stakeholders by providing excellent training, innovative research, scholarship and professional expertise" [7].

2.1 Building a framework for attaining sustainability

Wiek, Withycombe and Redman [8] suggest that the critical check for adequacy of competencies is how graduates can improve sustainability in the world. Cortese [9] paints a picture of sustainability with engineers designing technology and activities that sustain and do not degrade the natural environment whilst enhancing human health and well-being. As a result, future technology is inspired by biological models operating on renewable energy and where waste is limited because waste is the raw material or nutrient for other species or activities. So, human activities should be managed in a way that restores and increases biological diversity and the complexity of ecosystems. Flexibility is also required as sustainability challenges and provides insight into how to cope with these challenges, which change over time [8]. For this research, the primary goal was the process suggested for developing an honours programme that can be sustained over time. Owing to the graduate attributes prescribed by ECSA [2], the desired outcomes within the research context and more profound knowledge are already known and prescribed. Therefore, developing the modules and module content of the honours programme within a framework that will ensure that the programme is sustainable in the long term is the current focus of many UoTs, comprehensive universities, and this research.

In the literature review, reference was made to healthcare literature that revealed eight principles or elements that can provide a foundation on which to build sustainability plans and influence the sustainability of a programme over time [6]. Although the research of the Department of Adolescent Health [6] focused on creating sustainable health promotion and disease prevention programmes, a similar framework can be used for developing a sustainable academic honours programme for industrial engineering [6]. Accordingly, eight factors in developing a sustainable programme [6] were identified:

- Create an action strategy: Right from the start of the process, sustainability should be the main focus of the programme developers. As such, an orientation will chart the programme development's course. This implies that the programme developers must develop its content to anticipate the long-term environment in which it operates. Achieving sustainability requires careful planning and ongoing monitoring of policies and Industry needs as it evolves.
- Assess the environment: Developing an honours programme requires key stakeholder perceptions and perspectives. A comprehensive community or industry readiness assessment could lay the foundation of a viable and sustainable plan and, thus, the honours programme. Considering industry readiness, local demographics, existing postgraduate programmes, and industry niche markets can inform a sustainable postgraduate programme. It would also be essential to assess the internal and external environments in which the university operates.
- Adaptability: A meta-analysis of the literature indicated that a core domain of a programme's sustainability strategy could be the ability to adapt and improve effectiveness. As industry needs evolve, addressing the needs can be challenging, especially in a controlled, regulated and bureaucratic environment where universities operate. However, continually assessing the programme's effectiveness and being aware and responsive to changes as far as possible can contribute to the sustainability of the honours programme.
- Securing industry support: A deliberate and well-planned communication approach is critical for successful programme implementation. Industry support can take many forms and can provide support through various avenues. This could include funding, bursaries, guest lectures and workshops, sponsoring field and equipment, and providing internships.
- Integrate programme and services into industry infrastructure: It is important to explore opportunities to make the honours programmes an integral part of the Industry and consider partnering with industry members. Capitalising on the strength of local

Industry and their commitment to uplifting and developing the Industry can facilitate the sustainability of the honours programme.
- Building a leadership team: Dedicated and competent leadership often differentiates between sustainable programmes and those that are not sustainable. Sustainable programmes usually have leaders that "exercised considerable initiative, ingenuity and flexibility to keep programmes going" [6]. A leadership team comprising university and industry members, rather than one single leader, can bolster success, even during periods of staff turnover. This would also mean that the developers and management team of the honours programme must develop a clear vision to ensure continuous support for the programme as the team composition changes over time.
- Creating strategic partnerships: Effective partnerships can help the honours programme achieve sustainability. Partnerships can be strategic and build upon a commitment to shared goals or missions. Ongoing assessments of the strengths and challenges of existing and potential partners can lead to solid networks. Thus, long-term sustainability involving non-traditional partners will allow the university to draw upon a variety and new backgrounds, skill sets, knowledge bases and cultures.
- Securing financial opportunities: Lack of funds often inhibits student enrolment. It would be beneficial to programme sustainability to set funding goals apart from government funding.

Based on these factors and considerations, the framework depicted in Figure 1 was proposed to develop the honours degree programme in Industrial Engineering. One factor, securing financial opportunities, was left out of the initial framework. The factor is, however, added to the framework in Figure 2. Now that the programme is running, the focus will shift to identifying industry partners to secure funding opportunities.

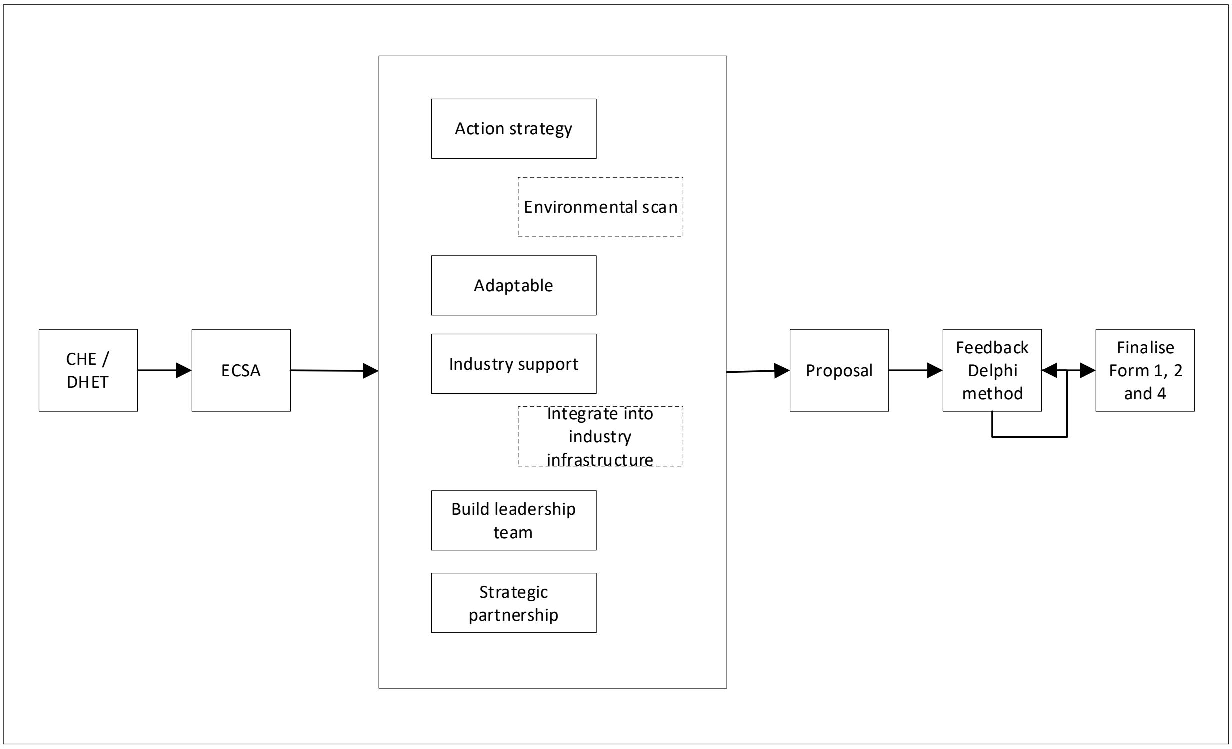

Figure 1: Proposed framework for developing a sustainable honours programme

Section 3 provides an overview of the process followed during the development of the honours degree in industrial engineering at the university of the study, highlighting the amendments made to the proposed framework.

3 FRAMEWORK FOR HONOURS DEGREE DEVELOPMENT

The BET Honours Degree in Industrial Engineering at the university where this study is situated was developed using the proposed framework illustrated in Figure 2. The first cohort of students that graduated at the end of 2022 was asked to provide feedback on their experience of being a student in the BET Honours programme and their perceptions of its student-centredness and sustainability. The feedback assisted in assessing the efficacy of the honours programme in promoting sustainable, student-centred learning. The research design is discussed in Section 3.1.

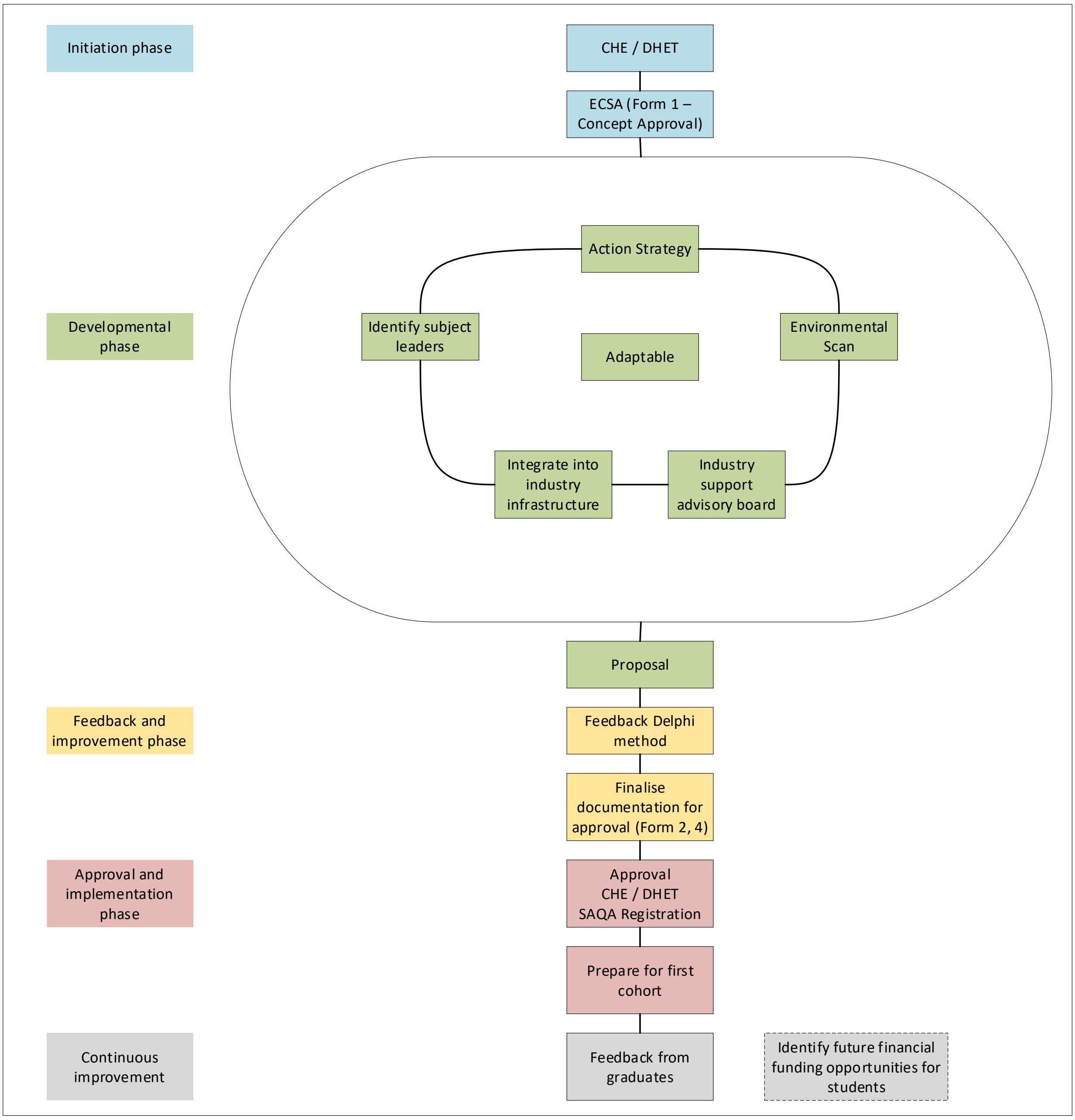

Figure 2: Framework used for developing a sustainable honours programme

3.1 Initiation Phase

The process was initiated when the Council for Higher Education (CHE) and the Department of Higher Education and Training (DHET) requested the HEQSF to re-design qualifications. With the re-design, ECSA introduced Graduate Attributes (GAs) into the engineering qualifications and minimum credit requirements in specific knowledge areas. The Department of Industrial Engineering approached an advisory board for input into the new honours degree concept. The concept for the honours degree was then formalised (Form 1) and submitted for approval to CHE/DHET and ECSA. CHE/DHET and ECSA approved the concept. The next phase could then commence.

3.2 Developmental Phase

Action strategy was a critical component of this developmental phase. Throughout this phase, an intentional and rational thought process focused on factors and variables influencing the sustainability of a student-centred honours qualification. Key stakeholders were consulted to give input in this phase, ensuring the qualification aligned with industry requirements. Subject leaders were identified that were tasked with the curriculation of modules and identifying future lecturers for the modules. Throughout the developmental phase, the team showed adaptability to changes required by the Industry with the introduction of Industry 4.0. The Covid-19 pandemic also significantly impacted the use of technology in Industry and academia. At the end of this phase, a draft proposal (Form 2) was ready to be shared with the advisory board for feedback.

3.3 Feedback and Improvement Phase

The Advisory Board, which included members of Industry, members of other universities and other departments in the study's university, was requested to give feedback on the draft proposal. Once feedback was received from the advisory board, the draft proposal was updated according to the received feedback. All the submission documentation was then updated (Forms 2 & 4). In January 2019, Forms 2 and 4 were submitted for internal and external approval.

3.4 Approval and Implementation Phase

The degree was approved in 2021 by CHE/DHET and ECSA, followed by the qualification registration with the South African Qualifications Authority (SAQA). The first cohort of students registered for the BET Honours Degree programme at the start of 2022, and six students graduated at the end of 2022 with the BET Honours Industrial Engineering degree.

3.5 Continuous Improvement

To assess the efficacy of the honours programme in promoting sustainable, student-centred learning, the first cohort of students was asked to provide feedback on their experience.

3.5.1 Participants and Data Collection

Graduating students were asked to give feedback on their experience of the programme to determine the effectiveness of the implemented framework. The students exhibited a 100% completion rate and were requested to provide feedback across four categories: Teaching and Course Content, Group Work, Personal Development, and Learning and Skill Development. The feedback obtained from the students was concluded by offering them the opportunity to provide closing remarks or make any additional comments about the qualification.

3.5.2 Data Analysis

The issue of future sustainability is a critical concern for Higher Education Institutions (HEIs). Based on the feedback provided by the students, a significant majority of 67% strongly agreed that they would recommend other qualifying students to pursue the honours degree programme, while 33% agreed that they would do the same (see Figure 3).

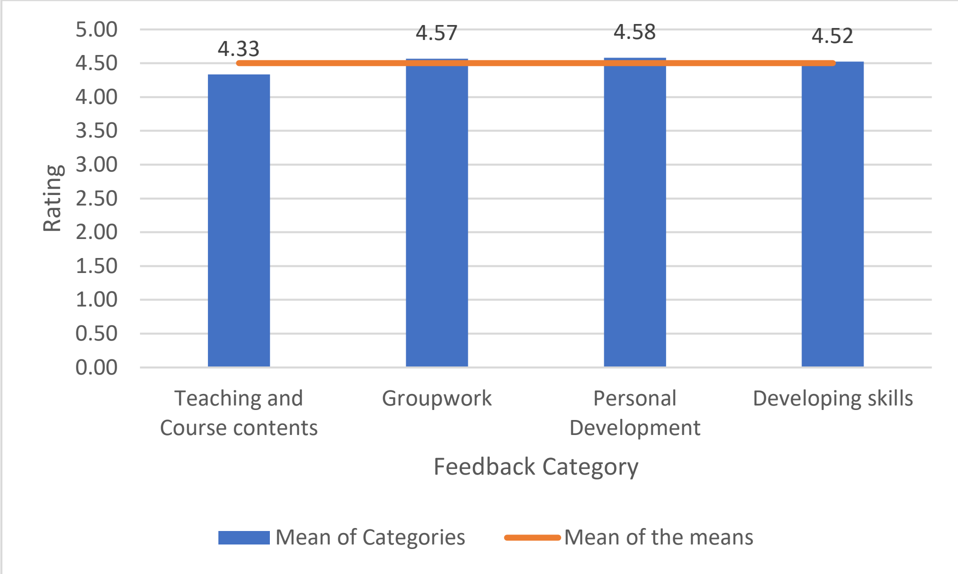

Figure 3: Average rating comparison per category

A rating scale of 1 to 5 was used for student feedback, where one will indicate a negative outcome, and five will indicate a positive outcome. The students' feedback was notably positive, with average ratings and standard deviations (see Figures 3 and 4) calculated for each category. The Teaching and Course Content category received an average rating of 4.33, with a standard deviation of 0.76. Similarly, the Developing Skills category received a slightly higher average rating of 4.52, with a standard deviation of 0.83. The Groupwork and Personal Development categories received nearly identical average ratings of 4.57 and 4.58, respectively, with corresponding standard deviations of 0.58 and 0.60 (see Figure 4).

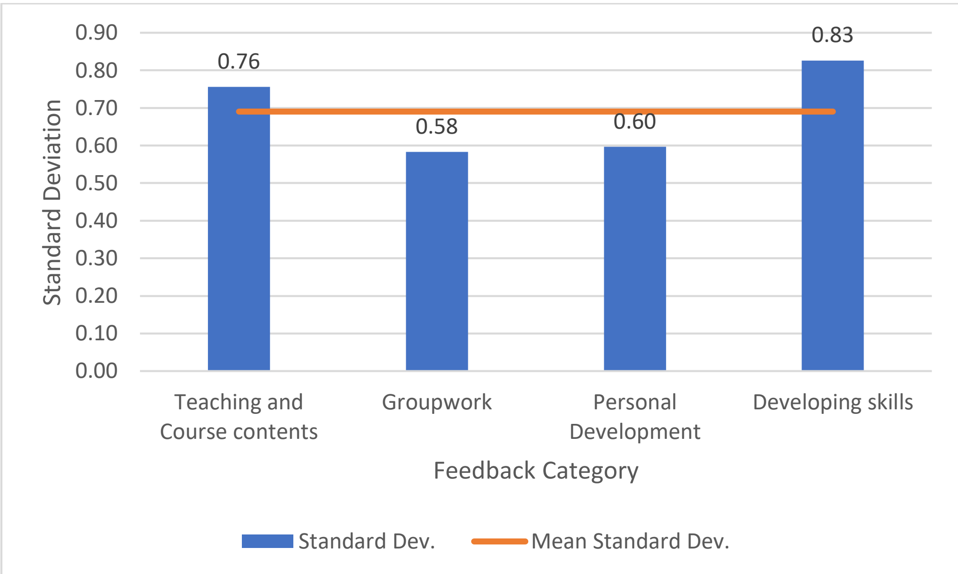

Figure 4: Standard deviation comparison per category

4 REFLECTION THROUGH STUDENT FEEDBACK

The feedback from the students was highly positive and encouraging, with most participants expressing a high degree of satisfaction with the BET Honours Degree programme.

Additionally, the closing remarks provided by the students contained several valuable suggestions and comments. Some of the noteworthy suggestions and comments included:

- Allowing students to select modules that are not part of their major coursework
- Demonstrating a greater capacity for independent learning and research and improved problem-solving, critical thinking, and communication skills, which boosted its appeal to potential employers
- Providing a robust foundation in problem-solving that is highly applicable in day-to-day work tasks

The qualification consists of eight modules. Figure 5 presents the average results of the students that graduated per module. Notably, in each module, at least one of the students achieved a mark close to 70% or higher, suggesting that the level of difficulty of the modules was reasonable and challenging simultaneously.

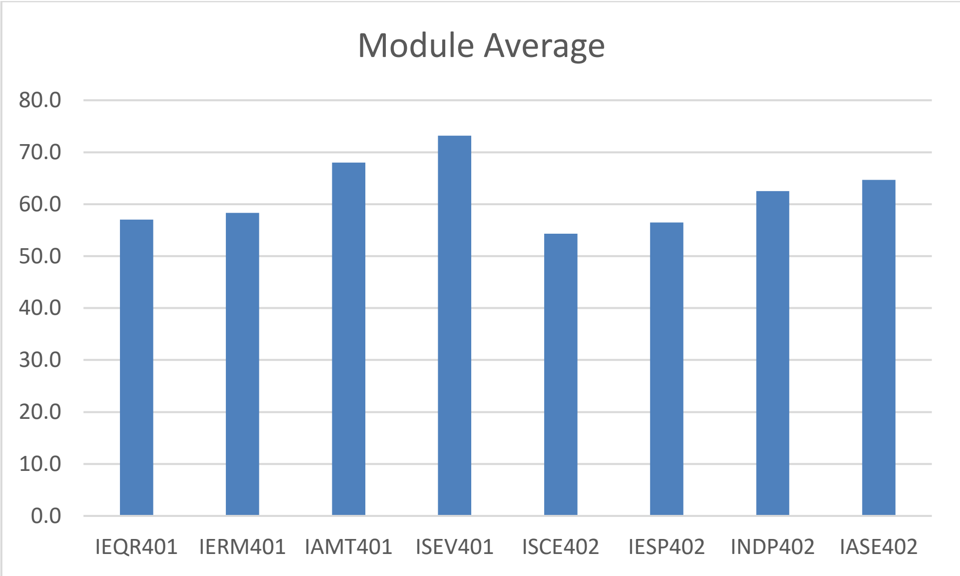

Figure 5: Average module results of graduates

During the first cohort of students, one of the primary challenges faced was the impact of the COVID-19 pandemic. With the new qualification, the lack of in-person student interaction posed a significant challenge. However, in response to these challenges, a hybrid approach was used, which entailed a combination of online and face-to-face lectures. While most lectures were face-to-face, this hybrid approach was designed to ensure that students could continue to receive a quality education regardless of any potential disruptions caused by the pandemic.

Currently, a significant challenge facing the future sustainability of the BET Honours Degree is its full-time nature, with lectures being presented during the day. This schedule makes it difficult for working students to balance their work and studies effectively. In the second cohort of students (2023), six approved students either cancelled their studies or did not register owing to work commitments. This challenge needs to be addressed to ensure the long-term viability of the BET Honours Degree programme. One potential solution could be to offer more flexible scheduling options, such as evening or weekend classes, to accommodate the needs of working students. Academic results demonstrated that in each module, at least one of the students achieved a score close to 70% or higher, suggesting that the level of difficulty of the modules was reasonable and challenging simultaneously. This could also indicate the success of presenting the programme full-time, allowing for more attention and deeper discussions into module content.

Feedback from the second cohort of students will be compared to feedback from the first cohort at the end of 2023.

5 CONCLUSION

Comparing feedback from multiple cohorts of students can provide valuable insights into the strengths and weaknesses of the BET Honours Degree programme, allowing for continuous improvement to better support student-centred learning and teaching. By addressing challenges such as the difficulty of balancing work and full-time studies, the programme can become more accessible and attractive to a broader range of students, further contributing to its long-term sustainability.

Based on the research presented in this section, it becomes evident that the design of a successful academic programme cannot be conducted in isolation. Partnerships and working with Industry are vital for success, as is a long-term view, which requires a well-thought-through strategic action plan. It would, therefore, be in the best interest of the academic department aiming to develop a sustainable honours programme to follow a structured process to identify the most relevant future knowledge required in modules as well as module content and to plan for any potential expenses related to resources such as staffing, software, equipment and buildings.

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THE EFFECT OF FOURTH INDUSTRIAL REVOLUTION TECHNOLOGY ON THE WORKPLACE

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ABSTRACT

Industry 4.0 has affected workplace diversity. Technology has removed mundane and repetitive tasks to simplify work and improve time of task completion in the workplace, however the integration of robots into the workplace has raised concerns of increased job losses. The increased use of technologies has brought about change in the traditional workplace This paper explored the impact of Industry 4.0 on the South African workplace using nineteen in-depth semi-structured face-to-face interviews and observations in the Gauteng province. Although there is much debate about job losses, the study confirmed that more jobs are being created. There is however a need for employees to be upskilled and there is a need for higher order thinking, conceptual skills, creativity and innovation to be developed within the workforce.

Keywords: Industry 4.0, workplace diversity, technology

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INTRODUCTION

Technology has impacted various facets including manufacturing, operations and livelihoods by interconnecting people and equipment regardless of geographical constraints or generational differences [1]. Technology is the driving force of globalisation [2] and has led to many improvements. The phenomenon of Industry 4.0 was first introduced in Germany in 2011 which shaped many industrialised countries [3] through cyber-physical systems (CPS), involving the arrangement of hardware, software and people to execute tasks [4] used to monitor and control the physical world [5]. The goal of Industry 4.0 is to increase productivity and attain mass production while using innovative technology [6].

Industry 4.0 enables automation and digitisation [7] using the Internet of Things, cloud computing, machine-to-machine communication, cognitive computing, big data and 3D printing, to name just a few. Machines capture and transfer data via machine-to-machine communications and to human operators [8], allowing the physical and digital worlds to converge which is changing the nature and landscape of work [9]. Therefore, there will be a need to recruit talent with the necessary skills to thrive in an automated workplace and concerns are raised regarding job losses of the workforce that do not possess the required skills [10]. Therefore, reskilling and upskilling employees to reduce skills shortages and to curb job losses are critical challenges that organisations and governments face [9].

Electricity outages, unskilled labour [11], unreliable internet connectivity, high data costs and inadequate infrastructure [12] may affect the rate at which technologies are adopted. Despite the high degree of automation, people are needed to manage the automation [6]. Therefore, understanding the impact of technology on the modern workplace is essential. People need to acquire and improve digital skills or change career paths to adapt to the new job market [14]. The purpose of this research was to investigate the effect that Industry 4.0 had on workplace diversity. The primary research question of this study is:

How has Industry 4.0 impacted the diversity traits of age, gender and education in the South African workplace? The research used a qualitative methodology to obtain thick and rich descriptions of the research focus area. The editors reserve the right to make minor editorial adjustments without consulting the author. The use of abbreviations should be avoided as far as possible.

INDUSTRY 4.0 IN THE WORKPLACE

Technology is at the forefront of our daily lives. As technology advances, it will alter the way in which people perform everyday tasks. As time lapses, old practices and the way humans previously carried out daily tasks change. Three other revolutions preceded the Fourth Industrial Revolution and shaped how the world is functioning and it created the world we live in presently. The First Industrial Revolution gave us the steam engine. The Second Industrial Revolution allowed for mass production and newfangled industries such as steel, electricity, oil and the use of the internal combustion engine. The Third Industrial Revolution (the digital revolution) introduced personal computers, the internet and semi-conductors. The Fourth Industrial Revolution has allowed for limitless possibilities by enabling digitalisation and allowing people to be connected by means of devices. Industry 4.0 is transforming production and how work is being performed (Stăncioiu, 2017).

Industry 4.0 allows for the integration of people, products and machinery, executing tasks swiftly, introducing products faster and expanding resource effectiveness through digitisation (Stăncioiu, 2017). Industry 4.0 allows for the real-time connection of physical and digital systems, enabling technologies to alter how work tasks are accomplished (Olsen and Tomlin, 2020). Information technology (IT) in Industry 4.0 comprises cyber-physical systems (CPS), cloud computing, the Internet of Things (IoT), 3D printing, big data, cognitive computing and cybersecurity.

Industry 4.0 affects work, lives, identities and the way in which society is governed. It does so by allowing for the acquisition of new knowledge and skills as well as the reconstruction of existing processes and methods (Savić, 2018). Industry 4.0 is made up of different technologies to modify isolated and optimised production into extensively unified, automated, and simple work processes and patterns (Vaidya, Ambad and Bhosle, 2018). This means that the production, integration, and acceptance of Industry 4.0 technologies will play a part in making life simpler, leading to improved efficiency and technologies.

Automation is our future. The ways in which we deal with, accept, and embrace the new technological world will allow us to work towards the change that is required. Manyika et al. (2017) reported on how Industry 4.0 would affect jobs and the possible new skills that will be required. The report indicated an increased demand for millions of jobs by the year 2030 in the face of an ageing society. In the workplace, the need for skilled and digitally abled workers will increase as the need for manual work will decrease. Maisiri, Darwish and van Dyk (2019) believed that some jobs have disappeared while others were created, and some skills became redundant while others became valuable. Mukwawaya, Emwanu and Mdakane (2018) added that, Industry 4.0 will result in the replacement of human labour in physical and repetitive tasks with robots and other digital technologies. With the economy predicted to grow over the coming years, the new developments in technology will increase productivity. This will lead to the creation of different types of jobs. According to Manyika et al. (2017), the expansion of digital and innovative technologies, as well as their implementation, have urged organisations around the world to continuously monitor developments and embrace modernisation and automation to remain competitive. Organisations and government need to look at the created opportunities, which will lead to job creation of different types of jobs. However, the creation of jobs may stem from current occupations and thereafter, as new technology changes work, the creation of jobs that currently do not yet exist (Manyika et al., 2017).

RESEARCH METHODOLOGY

The research followed a qualitative methodology in the interpretivist paradigm to explore the impact of Industry 4.0 on the South African workplace. The population comprised organisations in the Gauteng Province using Industry 4.0 technologies and three organisations from different industries in Gauteng were purposively sampled using the snowballing method. The first organisation offers training workshops to address skills gaps within organisations, the second organisation was from the automotive industry and finally, the third organisation specialise in freight logistics.

The participants included senior and middle managers as well as lower-level staff who were able to advise how Industry 4.0 had affected their workplace. The researcher initially aimed to interview eighteen employees but conducted nineteen interviews before data saturation was reached (no new information was forthcoming). The data collection occurred during the Covid-19 pandemic and securing willing participants were problematic. The data were collected using face-to-face and virtual semi-structured interviews using Microsoft Teams, a desktop literature review from annual reports, journal articles, conference papers, internet sources and textbooks, and observations during the interviews. Permission to conduct the study was requested from the organisations as well as the participants who individually signed consent forms to be interviewed.

The researcher had chosen to conduct semi-structured interviews to allow for in-depth descriptions in response to the questions. The questions were constructed to explore the participants' understanding of Industry 4.0 and the impact on workplace diversity, specifically for the traits of age, gender and education. The interview questions were open-ended to gain valuable qualitative insights into the study context [15]. The interview questions were made available to each participant beforehand to allow the participants to prepare for the interview. An audio recorder was used, and the researcher took notes during the interviews.

The interviews were transcribed verbatim, and the behaviour and reactions of the participants were recorded. Qualitative content analysis was used to analyse the transcripts [16]. Codes were allocated and clustered together to form themes and sub-themes. Common themes were identified and four main themes and sub-themes were distinguished: 1) understanding of the meaning behind Industry 4.0; 2) the impact of technology with two sub-themes: (i) the impact on staff and (ii) the impact on the workplace; 3) the challenges brought about by Industry 4.0 technologies in the workplace with two sub-themes: (i) the financial cost of implementing Industry 4.0 technologies in the workplace, and (ii the shortage of skilled employees who work with Industry 4.0 technologies; 4) the diversity traits of age, gender and education. Education was divided into two sub-themes: (i) formal education and (ii) informal learning. Member checking was conducted to increase the trustworthiness of the study whereby the transcript and coded documents were sent to all the participants to ensure that the correct interpretations were captured. The various themes were compared to each other, and findings were identified for the study.

TRUSTWORTHINESS

The researcher avoided bias by maintaining a neutral stance when collecting and interpreting the data. The procedures used to establish credibility encompass prolonged engagement with participants, persistent observation, member checking and reflective journaling [17]. The researcher checked and rechecked the data to ensure that the essence of the study was captured. Dependability involves participant evaluations of the findings, interpretations and recommendations of the study, such that all are reinforced by the data collected from the participants of this particular research study [18]. In this study, dependability was achieved through making sure that the data collected from all the participants occurred in a uniform manner. The purpose was to aid the researcher in obtaining rich data to interpret and from which to make recommendations and conclusions. Ethical clearance was obtained from the university before proceeding with the planned research.

DISCUSSION

Some of the technologies that were mentioned being utilised at some of the organisations were software development augmented reality, virtual reality technology, cloud technology, natural language processing for master data, and block chain. There were specific programmes used by some of the organisations however, due to the anonymity of the study the researcher could not reveal any further details as the programmes and software used in their workplace is unique to that organisation.

Technology affected the workplace in a variety of ways. Participant I mentioned ‘From the First Industrial Revolution and uh towards the Second Industrial Revolution […] people went from building things manually to having machines build them.’ Manual filing systems have been replaced by online storage, physical calculations migrated to computer-based programmes, and automation where machines or robots complete mundane and repetitive tasks. Face-to-face physical meetings were replaced with online meetings across geographical boundaries. Technologies are helping people to complete volumes of tasks at a better quality and faster through more streamlined processes [24] in-person or remotely at anytime and anywhere [25]. In fact, there is so much of information available that people may battle to make sense of it.

Industries are under constant pressure to integrate emerging technology into their operations and processes to remain competitive as confirmed by Participant A: Participant A was from Generation X. This generation had not particularly experienced the change and believed that the change in the workplace had been a gradual process that Participant A had not felt. The box provided the researcher's observation of Participant A during the interview whereby the participant's behaviour and body language during the face-to-face interview was noted.

> *It has been such a gradual process that I've not even feel it […] there used to be copious amounts of paperwork […] just laying around it was just so hard to get through the paperwork […] now everything is so streamlined and digitised. – Participant A*

Observation during the interview with Participant A: When Question 6 of the interview schedule was asked, Participant A had to ponder on the point. The moving of the head to one side, the look of thought in their eyes and the slight nod of the head indicated that the participant was thinking about the response. The participant further emphasised and paused while saying the word **'uhm'** also indicating the thought process. Thereafter, the participant mentioned that 'it has been a gradual process'. The tone of voice had a lowered register as the participant looked as if the change that technology brought was indeed gradually implemented so that participant A did not feel a difference. The word **'feel'** was at a slower tone of voice and the facial expression of slightly closed eyes indicated that there was not a major noticeable change that technology brought about. Furthermore, the participant used their hands to describe how the work has changed. They indicated that there used to be a copious amount of work by keeping their hands apart, indicating 'copious amounts', to placing their hands forward and closer together indicating a more 'streamlined approach'.

Other participants further added responses that reflected on workplace changes included the following:

> *Look at documents […] I can […] complete a document and sign it off and send it through for signatures […] Adobe allows you to sign a document it wasn't the case before and allows you also to add text to a PDF document so you find that there's less printing involved […] you don't have to waste time running from one office to the other office. – Participant O*

> *The nature of the work that I do it has gone from […] the hand calculations […] drawing by hand now everything is done on a laptop. – Participant P*

> *We went from using like hand calculations where we would literally calculate things by hand using an exam pad […] now we've got all of these […] structural modelling software, design software, drawing software […] really make our jobs a lot easier. – Participant N*

The participants expressed that workplace changes were brought about by technologies. These changes range from manual interventions to now using technologically enhanced programmes or software to help aid with work tasks and reducing time and effort required to complete work. Technological advances made it possible to move from tedious, time-consuming tasks to tasks that are completed quickly and digitally. Now an employee can spend time on other work tasks that can add further value to the organisation.

Industry 4.0 has significantly condensed manual interventions through computerised and interconnected technology [26] to enable improvements and efficiency gains using combined resources such as humans, materials, safety, capabilities and profitability within the business structure [27]. Digital systems have resulted in faster completion times, bigger storage facilities, improved reliability, and remote access from different locations. The backup of information is simplified, and knowledge management can be better coordinated within organisations and across supply chain partners as per interview excerpts:

> *The electronic stuff makes life so much easier for us and I'm sure we saving a lot of time […] production is better. - Participant D*

> *Industry 4.0 definitely reduces inefficiency […] it improves the overall way in which workplaces operate […] reduce lag times you have smooth operations where there's more transparency. – Participant N*

> *It's a smart way of […] doing things […] interacting with our equipment […] remotely […] we also be able to obtain […] much more data […] quicker […] and integration of […] systems […] making it easier for use to work. – Participant O*

> *Using technology […] in the workspace to improve […] the time how we deliver work – Participant P*

> *…automation and also help us to optimise our processes. – Participant S*

This study could continue during the Covid-19 lockdown because the researcher was able to connect with participants using online platforms. People have been learning to adapt to change since the earlier industrial revolutions. The difference in how we react to the change and how we choose to integrate changes remains an individual choice. Technology and the way we interact with programmes, software, and work systems inevitably help us to grow and improve ourselves and advances organisational objectives.

Finding 1: Technology has therefore enabled more interconnectedness in the workplace through modernised platforms and workflow processes that have reduced geographical and organisational distances and bureaucracy.

Industry 4.0 has enabled job creation and new opportunities but requires innovative sources of data, inventive approaches and specialised skills [28]. AI systems or programmes can assist with proofreading documents, transcribing or data capturing. A robot is therefore an autonomous machine (digital technology) with the competencies to make decisions and execute actions in the real world [29]. Pre-programmed robots, tele-operated robots, autonomous robots and augmenting robots, have already been incorporated into workplaces to save costs, decrease inefficiencies, increase innovations, and improve productivity [30], [32]. Automation is necessary and should not be feared [33].

Job tasks are changing and how we perform work is changing. Despite the use of robots and machinery, humans are still needed in the workplace. Organisations seek diverse people, with diverse interests and experiences, who add new insights to their teams and robots lack humanity, individual quirks and the rare and distinctive qualities that make people who they are [31]. There is a need for a human-robot collaboration, where humans perform cognitive or multifaceted tasks, while robots perform monotonous and easily automated tasks [34] as also observed by participants:

> *We still trying to bring electric vehicles into the country and we still struggling with that […] there are robots […] working in industries but it doesn't take away the jobs […] they (robots) also breakdown and […] stop working and you need to program you need to set them up. – Participant K*

> *So you've used your human-machine mix to optimise a better outcome for the company […] it's not like they decided I'm automating this line I'll retrench these humans […] because it would be impossible for their certain quality requirements a machine cannot tell the difference with […] only a human can so I think it's*

unreasonable to say the robots [...] they going to take our jobs I don't think so I think they need to be leveraged in a smarter way to free up humans to make these more high-ordered decision making things that human that robots can't. – Participant L

The relationship between a human and digital technology can aid in reaching organisational objectives, given that these two components (man and machine) work together. However, humans will always be needed to create and manage the new technology [35]. There are financial, legal and ethical obstacles involved should an employee be replaced by a robot [36]. Therefore, to contemplate that technology would replace the need for creative thinking, problem-solving, leadership, teamwork and initiative is unthinkable as people need to leverage technology to thrive in a better world [35].

Finding 2: Thus, integrating digital technology and robots into the workplace will require a change in organisational job functions, how work is performed and how people and machines will co-exist.

Some digital technologies simply automate mundane and repetitive tasks, while others can run factories via remote interventions from people. However, machinery can malfunction. As the possibility of digital technologies taking over jobs looms, some people may argue that digital technologies may add to unemployment, whereas the counter argument is that new jobs that are created [6]. Automation in the workplace may cause a displacement of lower job functions as digital technologies take over mundane tasks executed by humans [37]. Technologies have moved production towards a more automated process. Industrial robots can now autonomously weld, paint, handle and package materials [38]. According to the World Economic Forum's 'Future of Jobs Report 2020', it was expected that 85 million jobs may be displaced by the transformation in labour between humans and machines by 2025. However, there may be the emergence of 97 million new roles [39].

Technological trends drive the expansion of new job profiles, which requires upskilling of staff that training programmes should address [40]. Technological advancements may eliminate some jobs, cause changes to jobs or even cause the removal of certain current occupations although there is no consensus in literature on the extent to which digitisation and automation may affect jobs [41]. Every past technological wave eventually produced more jobs than it destroyed, delivered improvements, improved productivity and enhanced economic growth [28]. Job profiles are constantly changing as expressed by Participant I:

...my co-supervisors [...] said that he's almost worried for his kid in grade 1 [...] he said by the time he's at university [...] the jobs he might want to grow up to do [...] might no longer exist [...] but new things might exist. – Participant I

With the introduction of [...] Industry 4.0 [...] some of the jobs are being deemed unnecessary [...] it also made us [...] relook [...] what we call [...] a skill and [...] skills is being replaced by an introduction of some sort of technology [...] it has definitely changed the way we think and the way we look at jobs and [...] there's always gonna be new jobs created with the introduction of technology – Participant P

The robots are going to take over their jobs buts that's what they see as you say on TV [...] It's not what's in reality. –Participant K

I think people watch too many Hollywood movies and [...] dramatise that the robots are coming for us Industry 4.0 is about a human-machine [...] interfacing getting a machine to do rudimentary tasks that are inefficient when done by a human and where a human has a likelihood of making a mistake [...] it's going to change the way that humans are deployed on the shop floor there's going *different kinds of jobs that they need to do but I don't think its going to be a direct replacement. – Participant L*

From a macro-economic perspective, wherever there are sectoral job losses, other sectors are being developed and contribute to wage growth and overall employment [43]. People must change and adapt to remain competitive in the marketplace. When an organisation implements new technology, its work processes are affected, and a new balance must be established [44]. Should the change destruct job security, it is highly probable that there will be resistance to change [45]. When new technologies are introduced, there needs to be change management processes to manage the change. Employees have diverse education backgrounds and experiences which affects the way in which they accept change [44]. Some of the participants mentioned that change is not always accepted in their workplace.

there is sometimes a bit of resistance because people are used to doing things in a certain way and they don't necessarily want to change that. – Participant N

With a big company […] they are not always willing to change they not always willing to try out new things. – Participant D

Some participants believed that we need to adapt to this change that technology brings if we want to move forward. Also, that we humans need to have the right attitude to change, or we will be left behind.

You gotta change with the times otherwise you stay behind […] you will definitely be falling behind at a rapid pace. – Participant C

Part of humanity we adapt we change. – Participant I

The top skills required include critical thinking, innovation, complex problem solving, active learning, analytical thinking, and skills in self-management such as stress tolerance and flexibility [46]. The participants mentioned that technology has modernised society and helped people work more effectively, allowing for the upskilling of staff. Participant G mentioned that technology helps people work more effectively.

IT (technology) modernises us […] helps us work more effectively. – Participant G

They have allowed for the upskilling of staff to integrate and use these technologies […] allow companies to achieve new levels of efficiency, which creates the opportunity for growth, and thus employment and localisation. – Participant M

We need to now look at more skilled people or academically inclined individuals […] so we have to upskill and […] go out into the market and go and recruit […] that's why we bring a lot of expats into the country […] in multinational companies […] we borrow skills from other countries – Participant J

Integrating newer technologies into our daily lives allows companies and people to achieve better outputs and attain efficiency, as outlined by Participant M. However, there needs to be more skilled people employed and recruited in the organisation so that we in South Africa do not need to recruit from other countries as expressed by Participant J. The feedback all points to education and training that needs to happen in the workplace.

Finding 3: Digital technologies will not take over jobs but will assist in workplace-related tasks. Job roles will change and continue to change as technology is updated. This necessitates continuous upskilling of staff to stay relevant and be able to adapt to changes.

Industry 4.0 connects the real and virtual worlds [21] using people, intelligent machines, smart products, production processes and systems [22]. These collaborations may disrupt existing learning, behaviours, communication and relations [23].

CONCLUSION

This paper reviewed the effect that Industry 4.0 technologies had on workplace diversity with specific reference to age, gender and education. The introduction of technologies into the workplace did not only bring about many efficiencies and productivity gains but also introduced a lot of uncertainty about the future of work as well as insecurity regarding job availability. There are two opposing schools of thought that believe that Industry 4.0 technologies will create many job losses through automation and robotics, while other are of the view that many additional jobs will be created. Regardless, there is agreement that the skills needed to perform work will need to change and upskilling strategies must therefore be considered by organisations. Humans and digital technologies (machines and robots) will need to co-exist regardless of how work may change in the future.

The study identified numerous findings. Technology brought about more interconnectedness in the workplace through modernised platforms that reduced geographic boundaries and bureaucracy. However, the integration of digital technologies into the workplace will require a change in organisational processes and job functions. Also, job functions change when technology is introduced into an environment, but technology and humans can co-exist in organisations. To remain relevant, staff will need to upskill themselves as changes occur within the workplace.

The study may be of value to managers in various industries. It is recommended that managers heed the call for the upskilling of their staff. Organisations also need to work closer with universities to ensure that curricula produce the required skills for work of the future. In addition, policies and procedures must be adapted to accommodate a co-existence of technologies and humans within the workplace. Work procedures and processes must be adapted when new technologies are introduced into work environments. Change management strategies must accompany all major changes to facilitate proper implementation. Future studies could incorporate more organisations to further explore specific workforce impacts per industry.

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A METHOD OF DETERMINING THE LEVEL OF MODULARIZATION USING THE BALANCED SCORECARD AND THE ANALYTIC HIERARCHICAL PROCESS

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ABSTRACT

The level of modularisation is determined by the product structure. A modular product structure can also have an impact on the supplier-buyer relationship. This study developed a tool for determining the level of modularisation by integrating the method for determining product interface constraints and the supplier-buyer collaborative method. this research used the "balanced scorecard" BSC and Analytic hierarchy process AHP to determine the supplier-buyer "collaboration index" of a firm . A furniture manufacturing company was used as a case study, and a modular furniture desk was used as a vehicle for our study. The developed method is a practical tool that can be used by the practitioners in the manufacturing industry.

Keywords: Furniture, modularization, supplier

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1 INTRODUCTION

There is growing pressure on manufacturing companies to reduce new product design lead time and to deliver customised products to a heterogeneous market quickly and cheaply (Mikkola, 2006). Manufacturing companies are also seeking better ways to simultaneously match product architecture (PA) design with supply chain (SC) capabilities. The significance of PA design to SC architecture is more important than ever [1].

Many manufacturers are faced with a great challenge to find options and ways to enhance their supply chains (SC) metrics to be competitive [2]. A competitive supply chain must be able to satisfy a heterogenous market with diverse products. Mass customisation (MC) has been proven to be a very important strategy to provide diverse customer needs at a price equivalent to "mass-produced" products [3]. Mass Customisation is made possible through product modularisation (PM), PM is achieved through supplier-buyer collaboration.

Many researchers have found alliance and collaboration of suppliers and customers in a supply chain to be a competitive approach [4]. Scholars have recommended early participation of the customers in modular product designing [5]

The product modularisation approach has gained much attention from researchers [6], Nevertheless, most research papers in this field are qualitative Hsuan (1999), therefore this research seeks to introduce a quantitative method that measures the supplier-buyer collaboration to determine the level of modularisation.

This research seeks to apply an integrated "balanced scorecard" BSC and the "analytic hierarchy process" (AHP) framework for "supplier-buyer" collaboration performance analysis. A BSC has been considered the most appropriate tool in determining the SC performance. Balance scorecard perspectives have different importance and offer a multi-criteria environment. AHP is a "multiple criteria decision-making" (MCDM) tool that has been applied in practice and many academic research papers [7].

One of the objectives of this research is to determine the Supplier-Buyer "collaboration index" (λ); this index is used in this research to determine the level of SC partnership. The criteria were developed from "balanced scorecard" BSC perspectives that influence partnership in SCs and the monitoring and controlling information essential to attain preferred benefits from the partnership. This information or factor indicators define the nature of transactions, supplier-manufacturer relationships, and the characteristics of the supplier. Therefore, this research will use the "balanced scorecard" BSC and AHP to measure the supplier-buyer "collaboration index" (CI).

Using the CI, the level of modularisation at different levels of the "product architecture" are analysed, the levels are: "Component, Module, Sub-System, and System levels" [8]. Every level of the "modular product architecture" has an associated "interface constraints" factor, φ. The "interface constraints", φ is determined by the number of elements in consideration and the sum of interfaces [8].

The "level of customisation" is rooted in the "product architecture" and to be more precise "modular product design" architectures [9]. Product modularisation architecture can also have an impact on the supplier-buyer relationship; an open architecture can result in a close relationship between the buyer and the supplier.

This research proposes a proactive approach to product architecture design, its influence on SC allowing early detection of the adverse impacts of product architecture design and how they can be rectified early and economically before the commencement of full production.

2 LITERATURE REVIEW

2.1 Modularise Components to Customise End Products.

Creating "modular components" that may be combined to create a variety of end products is the greatest way to achieve "mass customization," which reduces costs while enhancing individual customization [8]. According to Sosa, Eppinger and Rowles [11] and Abdallah and Matsui (2008), "Economies of scale" are achieved through the use of components rather than products, "Economies of scope" are achieved by using various combinations of modules and components repeatedly in a variety of products, and "Personalization" is achieved by having a large number of configurable products. Manufacturing firms who employ “mass customisation” strategy spend a great amount of time with individual customers, making sure the customers get exactly the product that suits them, these companies have been known to spend so much application engineering time with a customer that they virtually realise all their profit on one sale (Abdallah and Matsui, 2008). These companies gain not only a delighted customer but also new ideas to extend their products with a new variety.

There are numerous methods to profit from modular components that may be combined and matched to create bespoke "end products" [12]. The foundation for a typology that can be expanded to indicate the MC of your products is laid out by [13], who focuses on discrete product modularity. The type is evolving from straightforward modular forms that enable a wide variation to those that enable customization of the product and cater to basic differences in each customer without actually changing its nature [14]. Five types of modularity are discussed below:

2.1.1 Component sharing Modularity (CSM)

To achieve economies of scope, component-sharing modularity (CSM) uses the component across different products [15] This type of modularity is crucial for restoring "mass" to rapidly expanding product lines whose costs are rising at a rate that is at least as rapid as the rate at which the number of goods is increasing [16]. Except when combined with other types of modularity, this type of modularity does not actually lead to "individual customization," but it does enable "low-cost production" of a wide range of goods [17].According to Ripperda and Krause [18], CSM is mostly used to lower the "number of parts" and, consequently, the expenses of an existing product line with a high degree of variability.

2.1.2 Component Swapping Modularity (CSM)

The goal of this strategy is to complement CSM by combining as many different components with the same "basic product" as possible to produce as many different products as.The distinction between "component sharing" and "component swapping" is frequently a question of level [19].

The use of a different textile material to cover chairs or sofas with the same basic frame is a simple example of component switching.The majority of "point of delivery customisation" also involves "component swapping" [20].An office desk, for instance, is made at a factory, b ut the finishing touch, such as a chest of drawers, is added after the product has been delive red.

2.1.3 Cut-to-fit Modularity

The difference between this approach and the first two is that in "cut-to-fit" modularity, a component or components are continuously changed within pre-set or practical limits [21]. Customization is accomplished in the "kitchen cupboard manufacturing industry" by precisely cutting the wood or furniture board to meet the rooms' measurements.

2.1.4 Mix Modularity

With the sole exception that the components are so "mixed" that they change, this sort of modularity can utilize any of the types mentioned above [19]. The varied paint colours won't show up in the finished product when certain colours are blended, as when painting furniture, for example..

2.1.5 Bus Modularity

The "standard structure" used in this sort of modularity allows for the attachment of a variety of components [22]. The main characteristic of "bus modularity" is that a "standardised structure" allows for change in the placement, quantity, and kind of modules that can be attached to it [22]

2.2 Mass Customisation of Wood Furniture

In the furniture business, [23] developed a digital design process for mass customisation. This study produced a technique that enables furniture buyers to take part in the product creation process. The study looked into how the product engineer might use "computer-aided design" (CAD) technologies to generate other designs while taking production process challenges into account. The product was designed, the chairs were manufactured, and they could be "mass customized" thanks to a CAD system. A vast range of opportunities that can be garnered through the use of the "mass customisation" paradigm were made possible by the CAD system.

MC is seen as a competitive strategy for small-medium companies (SME) for a variety of benefits [24]. Customized furniture gives producers that are close to the customers a durable economic edge, whereas low-cost mass-produced furniture gives international furniture manufacturing enterprises a competitive advantage [24]. Therefore, to meet the issue, local South African furniture companies should use aggressive "mass customization" techniques and leverage their proximity to clients.

To properly implement MC, furniture companies should standardize their components and modularize their products [24]. According to Torsten Buehlmann and Beauregard [24]), retailers stand between furniture companies and their clients, preventing direct contact. Furniture companies rely on skewed data from retailers which is crucial in putting "mass customization" into practice. Customers and furniture makers must establish direct communication; the internet can obfuscate boundaries in the SC by facilitating direct contact between the two parties.

2.3 Product modularisation (PM) and supply chain (SC) integration

The study conducted by. Ülkü andnSchmidt [25] whose research focused on the relationship between product architecture (taking into account how modular a product is) and SC integration (taking into account the "product development" process, either internally by the manufacturer or in "collaboration with suppliers"), is also helpful to this research. Partnerships and information exchange help to develop supply chain integration [26].

[27] concentrated on buyer collaboration in a SC. Their efforts were concentrated on early-design SC integration and "product modularization." There is disagreement on the impact of "product modularisation" on SC integration at the early stages of design, according to Caridi, Margherita and Sianesi [28].

According to Doran and Giannakis [29], "product modularization" tends to reduce the level of collaboration between suppliers and buyers because a corporation can produce the "modules" independently and assemble them in a factory. The significance of coordination and ongoing information communication between suppliers and purchasers was emphasized by [30].

2.4 Modular Product Architecture

To calculate the advantages of a modularization on different levels of the product architecture, taking into account the "component level," "module level," "subsystem level," and "system level" as the four various levels of the product structure [9]. The "modularization function" takes into account "interface constraints" (IC) at the levels of "components," "modules," "subsystems," and "systems." The IC depend on how many components there are and how many interfaces there are between them. A partnership index of 1 indicates an "arm's length" relationship, while a partnership index of 0 shows a "strategic partnership" [31]. The partnership index, or, indicates the degree of "supplier-buyer" relationship. The "flexibility in a trade-off with the interface constraints" is determined by the degree of interrelationship. The interface constraints and the partnership index have an impact on the chances for modularization because companies offering competitive systems frequently adhere to completely distinct sets of interface limitations.

$$f(\varphi) = e^{-\lambda\varphi^2} \qquad ; \qquad 0 \leq \varphi \leq 1 \qquad (1)$$

Where

$f(\varphi)$: Mathematical modularisation function (The derivation of the formula is in Appendix F)

φ: “Interface constraint”

λ: supplier-buyer collaboration index.

The goal of this study is to evaluate the degree of customization at the component, module, sub-system, and system levels of the "product architecture" [9].

There is a IC element, that is related to each level of the "modular product architecture". According to Hsuan [9], the IC are based on the total number of interfaces and the number of elements being taken into account. The value of the "interface constraints" in the system (final product) is expressed as the sum of all the "interface constraints" at various levels of the product design.

2.5 Balanced Scorecard-Based (BSC) Supplier-Buyer Collaboration (SBC) index (λ)

The CI denotes the strength of supplier-buyer relations. This might affect interface limitations, and as a result, the "opportunity" for modularization. An "arm's length" relationship is indicated by a CI of 1, while a "strategic partnership" is indicated by a CI of 0 [31]. Many manufacturing companies actually operate between the 0 and 1 -index levels [9]. The "flexibility in a trade-off with the constraints" is determined by the degree of interrelationship between the provider and the buyer. The "interface constraints" are typically completely different for each set of "offering competitive systems" firms, and they have an effect on the prospects for modularization.

In this study, "supplier-buyer" collaboration performance is analysed using an integrated "balanced scorecard" (BSC) and "analytic hierarchy process" (AHP) methodology [33]. [33] claim that BSC has been regarded as the most useful technique for evaluating SC performance. Perspectives on balance scorecards vary in relevance and provide a multi-criteria environment. AHP is used in the research to create priorities, combine performance measures, and make difficult decisions [32]. The "multiple criteria decision-making" (MCDM) method known as AHP has been used in numerous academic research publications as well as in real-world settings [32]. AHP has been regarded as the greatest MCDM tool out of many [32].

Finding the Supplier-Buyer "collaboration index", which is utilized in this research to gauge the degree of "supply chain" cooperation, is one of the goals of the study. The criteria were created using "balanced scorecard" (BSC) views that have an impact on partnerships in SCs and the monitoring and controlling data required to achieve the desired partnership advantages.

The type of transactions, the relationships between suppliers and manufacturers, and the qualities of the supplier are all defined by this data or factor indicators.

2.6 Level of Customisation or Modularisation ($f(\varphi)$)

Product modularization, according to Hsuan [9], can be carried out at four stages: “Component Level, Module Level, Sub-System Level, and System Level”.

2.6.1 *Component Level*

The lowest of the four degrees of modularization, this level can be reflected in furniture goods by using common parts like hinges, slides, and drawer knobs. The furniture industry commonly accepts and uses these "standard components" [34]. Hardware stores provide these "off-the-shelf" items, which come in a range of options for various sectors. Low component customization, low-value inputs, and a low degree of supplier-buyer interdependency are frequently seen in supplier-buyer partnerships at this level, according to Hsuan [9].

2.6.2 Module Level

Systems created by numerous diverse standard components are called modules. So a drawer may be seen as a module in the furniture sector. "The design and manufacturing of modules must keep up with the demands of technological innovation and specification compliance of a particular system" [9]. A module is a collection of several parts put together, like a drawer on a desk at work, that are built or intended to fulfill a certain need of the overall system.

2.6.3 Sub-System Level

Sub-systems are assemblies of various modules that are frequently highly customized. Many different vendors produce subsystems, and some of them are also made in-house, particularly the subsystems for wood furniture. A pedestal can be made domestically in the furniture industry, but metal pedestals are purchased from outside sources. To put it another way, "interface and protocol compatibility between modules and sub-systems are essential for a system to function" [9]. The degree of customization is smaller at this level than at the module level, and the supplier-buyer relationship is also considerably stronger [9].

2.6.4 System Level

A system, in the words of Hsuan [9] is a "closed assembled system" when its interfaced subsystems, which have boundaries that are well defined, are linked together to function as a system. An object like an office desk, cabinet, or chair is a full product that is made up of "components, modules, and sub-systems." According to Hsuan [9], "Modularization at the System Level becomes more restricted as new components are created at each level." The LC and the MC are influenced by interfaces between the pieces. Designers of modules and components should be able to "predict how modules will evolve" and should have a thorough understanding of the product they are designing. Because "modularisation" improves MC, a good "module design" lets the company to compete.

Since "modularization" paves the way for the realization of the MC approach, a deeper comprehension of the variables influencing its execution is required. From "Component Level to System Level," several chances for "modularization," "product architecture," "interface compatibility effects," "component customization," value inputs, and "supplier-buyer interdependence" exist [9].

3 METHODOLOGY

For model validation in this chapter, a furniture manufacturing business in Johannesburg, South Africa, was utilized. This business specializes in producing office desks and chairs that satisfy consumers looking for modern wooden office furniture. The business is an inventive, market-driven manufacturer of products of unrivalled quality. Partners in the business are knowledgeable and capable. The business is committed to creating office furniture of the highest calibre through the utilization of trained personnel and investments in cutting-edge techniques. The business can create and produce in association with well-known designers. The corporation was selected for this research because it has had long-standing commercial partnerships with several global businesses and brands. The business employs more than fifty people and has a 5,500 square metres manufacturing facility.

The vehicle for the analysis was a modular office desk. Manufacturers of office desk furniture can be challenging to categorize because they frequently use "mass production" or "mass customisation" tactics, depending on the order placed. The manufacturer is required to create a set of office desks with a mix of colors, sizes, and modules for specific orders. The business also manufactures office desks for large corporations and academic institutions when hundreds or thousands of identical office desks are needed. The furniture manufacturer creates customized goods by combining and adding value to existing modules after receiving an order. As a result, this business falls under the category of MC also known as a build-to-order system.

A modular office desk was selected as a vehicle for the analysis. Office desk furniture manufacturers are sometimes difficult to classify sometimes they employ “mass production” strategies or “mass customisation”, it depends on the order received. For certain orders, the manufacturer must produce a set of custom-designed office desks with a mix of colours, sizes, and modules. For other orders, the company produces office desks for universities and large companies, where hundreds or thousands of identical office desks are required. After receiving an order, the furniture producer, mixes and adds or matches value to existing modules, to design customised products. Therefore, this company can be considered as a mass customizer or build-to-order system, which is under the category of “mass customisation”. The purpose of the research in this part is to determine the degree of customization of a "product architecture" and its effects on "supply chain" metrics rather than to categorize the companies.

Information was gathered from the senior management, including the sales, marketing, and production departments, in coordination with the wooden furniture desk department. The department of manufacturing and operations management was consulted for technical details on the office desk architecture. Data were gathered using structured interviews and questionnaires to determine the "collaboration index" , "interface constraints," and "level of customization," which were then utilized to create the "system dynamics" model.

3.1 Data collection

This case study focuses on the production of hardwood office furniture. There were several trips to the furniture factory. Interviews with the production manager, buying manager, sales manager, and other officials helped collect the necessary data. The company produces a variety of furniture items, such as office desks, chests of drawers, and chairs. However, because the office desk accounts for 70% of all sales, we chose it for our study. Since board furniture accounts for 80% of the office desk's material, the study concentrated on one supplier who is a producer of furniture boards. To collect data, a number of interviews were done utilizing standardized questionnaires.

The biggest obstacle was management's resistance to sharing information, particularly financial information, and to working together. The management chose to present statistics in the form of ratios, nevertheless.

In addition to giving the management the questionnaire to complete, further questioning was conducted to gain a better grasp of the issue at hand. The major goal of the interview was to get the interviewee thinking creatively while learning more about the manufacturing company's philosophy. In order to comprehend the degree of partnership between the buyer and the supplier, which greatly influences the "level of customization," important questions regarding the various viewpoints in the BSC and the product structure were posed. The management of the company stated that allowing the customer to customize their office desk is a key element in the success of this furniture manufacturing company.

4 RESULTS

Using mathematics, [9] suggested a modularization paradigm. The amount of components, modules, and sub-systems has an impact on how modularization is portrayed in the model as a function of "interface constraints" (φ). The function also takes into account how modularization may be impacted by supplier-buyer cooperation. The Balance Score Card (BSC) "supplier collaborative index" (CI) ((λ) that was proposed by [33] is used to estimate the "supplier-buyer index" (λ) in the current study. The dynamics of the "supply chain" system are then determined using the modularization level function.

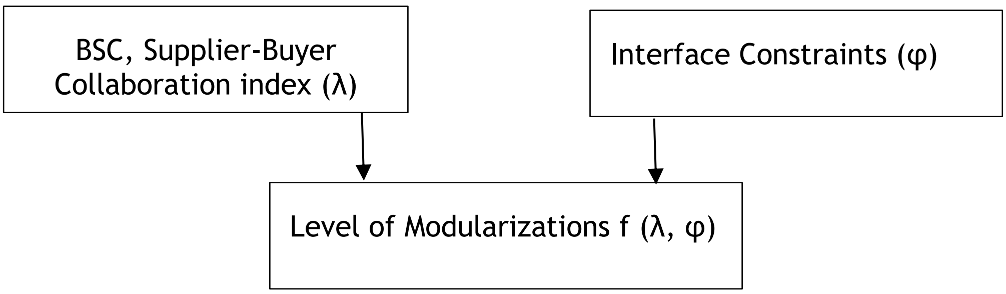

Figure 1

4.1 Collaboration Index calculation (λ)

In this section to calculate the degree of collaboration between the provider and the customer. The calculations adhere to the eleven-step process below:

Step 1: Identify the supplier

To measure the degree of cooperation between the supplier of wood and furniture boards and the manufacturer of furniture, the partnership index (λ) was established.

Step 2: A score was given to each perspective from the "Balance Score Card" BSC after the furniture manufacturing company was asked to identify significant perspectives. The "analytic hierarchy process" (AHP) was used to order the Balance Score Card perspective scores. The management of the furniture manufacturing company assigned the following Saaty scale scores (Saaty, 2008) to gauge the relative weight of each viewpoint. The partnership was added as an addition to the "pure" four BSC viewpoints since it is a special driver of "supplier-customer" collaboration [33].

"Analytic hierarchy process" The criteria weights are calculated using the AHP technique. in Table 1.

Table 1: Selected perspective and weights

Balance Score Card Perspective	Score	PIN
Customer	4	0.25
Finance	4	0.25

Internal business process	4	0.25
Learning and growth	4	0.25
Partnership	4	0.25

Step 3: The furniture management company was asked to identify factors under each perspective from Table 2 using the criteria chosen in Step 2 as a guide. The furniture company was asked to rate each factor using the Saaty's scale of relative importance. The "analytic hierarchy process" AHP approach was used to determine the factor weights based on the scores assigned in Table 2.

Table 2: Factor Weight

BSC Perspective	Factors	Score	Factor Weight (FIN)
Customer	Supplier performance (SP)	1	1
Finance	Payment terms (PT)	1	1
Internal business process	Innovation (IN)	1	1
Learning and growth	Ethics (ET)	1	0.3333
	Technology and technical competency (TC)		0.3333
	Audits (AU)		0.3333
Partnership	Long-term business commitments (LB)	1	1

Step 4: "Factor indicators" (FI) were given to each factor at this point. Based on their "suitability and applicability" to the furniture manufacturing firm from Table 5.3, the firm was asked to select the suitable factor indicators. In Table 3, the identified factor indicators were input. The importance of each factor indication to the firm was then relatively graded for each indicator. The factor indicators in Table 3 were given weights using the "analytic hierarchy process" (AHP), and the weights are denoted as FIIN.

Step 5: The attained performance number (APN) for each "factor indicator" (FI) is now calculated. The APN value (Table 3) represents the example company's evaluation of its performance in relation to the benchmark value for the furniture sector, where one is the maximum ratio.

Step 6: Equation 2 is used to determine the "performance value" PV, which is the sum of the FIIN and APN for all factor indicators.

$$(PV_j)_i = ((APN)_j \times (FIIN)_j)_i \quad (2)$$

Step 7: At this point, Equation 3 is used to compute the "performance index" values for each factor, and the results are shown in Table 4.

$$(PerI)_i = (\textstyle\sum_1^m (PV_j))_i \quad (3)$$

Step 8: Equation 4 states that the "factor performance value" FPV (in Table 5) is the product of the performance index (PerI) and the "Factor indicator number" (FIN).

$$(FPV)_i = (PerI)_i \times (FIN)_i \quad (4)$$

Table 3: Selected FIs and their relative weights

Perspectives	Factors	Factor Indicator	FIIN	APN	PV
Customer perspective	Supplier performance	Quality, Quantity, and Price	0.25	0.40	0.1
		Delivery commitment	0.25	0.00	0.000
		Past troubles	0.25	0.600	0.150
		Environmental, health hygiene and safety audits	0.25	0.10	0.025
Financial perspective	Payment terms	Adherence to industry standards	0.25	0.60	0.15
		Adherence to agreed terms	0.25	0.50	0.125
		Advance payment	0.25	0.45	0.113
		The criticality of part and volume of supply	0.25	0.60	0.15
Innovation and learning perspective	Innovation	Value-added to product or process	0.50	0.25	0.125
		Markert pressure for innovation	0.50	0.30	0.150
Internal business perspectives	Ethics	Code of conduct	0.33	0.4	0.132
		Ethical practice	0.33	0.60	0.198
		Wrong information	0.33	0.60	0.198
	Technology and technical competency	Skilled human resource	0.25	0.40	0.100
		Technical standards	0.25	0.60	0.150
	Audits	Qualityaudits	0.25	0.60	0.150
		Process audit	0.25	0.60	0.150
Partnership perspective	Long-term business commitment	Committed to quality, payment terms, and price	0.5	0.4	0.200
		Demand fulfilment	0.5	0.5	0.250

Table 4: Performance index (PerI)

Factors	PerI
Supplier performance	0.275
Payment terms	0.5375
Innovation	0.275
Ethics	0.528
Technology and technical competency	0.25

Audits	0.3
Long-term business commitment	0.45

Step 9: For all BSC viewpoints, the "Factor Index" FacI is currently calculated. The FacI illustrates how each BSC perspective affects supplier-buyer cooperation. According to Equation 5, FacI is the total of all the FPVs for each perspective. The sum of the FPV values for the three components (ethics, technology, technological competence, and audits) in Table 5's learning and growth viewpoint, for instance, equals 0.358974. As a result, the learning and audit performance is 35.9%. Of all the views, the partnership perspective performs the best.

$$(FI)_i = \sum_1^m (FPV_j)_i \quad (5)$$

Table 5: Calculation of factor index

BSC Perspective	Factors	PerI	FIN	FPV	FacI
Customer perspective	Supplier performance	0.275	1	0.275	0.275
Finance perspective	Payment terms	0.5375	1	0.5375	0.5375
Internal business process	Innovation	0.275	1	0.275	0.275
Learning and growth	Ethics	0.528	0.333	0.175824	0.358974
	Technology and technical competency	0.25	0.333	0.08325	
	Audits	0.3	0.333	0.0999	
Partnership perspective	Long-term business commitment	0.45	1	0.45	0.45

Step 10: The "Perspective Index" (PI) is a product of PIN and FacI (Table 6). The PI value denotes the relative weight of each perspective. For this company, a collaboration viewpoint is deemed to be most crucial.

Table 6: Collaboration Index Calculation

BSC Perspective	FcI	Perspective weight (PIN)	Perspective Index (PI)
Customer perspective	0.275	0.06875	0,004726563
Finance perspective	0.5375	0.134375	0,018056641
Internal business process	0.275	0.06875	0,004726563
Learning and growth	0.358974	0.0897435	0,008053896
Partnership perspective	0.45	0.1125	0,01265625
Collaboration Index (CI)			0,048219911

4.2 Interface constraints (φ) calculations

As indicated in Figure 2, the system (product) must first be broken down into its "components, sub-system, and modules" to analyse the ICs. The number of interfaces and the number of constituents considered are the two key factors that influence the. At each system level, the mean of all values is used to get the IC value.

The chest of drawers (SS1), storage unit (SS2), and desk (SS3) are the three subsystems that make up the office desk system. The office desk is made up of six modules, which are M1 (drawers), M2 (pedestal), M3 (cabinet), M4 (foldable door), M5 (planar top), and M6 (dictation slides) when the system is further broken down. Similar to this, breaking down modules will result in the following parts: (module M1 will yield the following components D1, D2, D3, D4, D5, D6, D7, D8, and D9, module M2 will yield P1, P2, P3, P4, PH5, P6, P7, P8, P9, P10, P11, P12, P13, P14, P15, and P16, module M3 will yield C1, C2, C3, C4, C5 and C6, module M4 will yield F1, F2, F3, and F4, module M5 will yield PT1 AND PT2, and module M6 will yield CS1, CS2, and CS3), as depicted in Figure 3. Figure 3 represents the office desk system in the block diagram.

The number of components ($n_{co} = 9$) in module M3 and the sum of interfaces for component C1 is $\vartheta_{C1} = 4$, the total number of interfaces in M3 is ($\sum \vartheta_{Co} = 22$) from Figure 3. The interface weight (relative criticality) of component C1 (Equation 6) is:

$$w_{C3} = \left[\frac{\vartheta_{Co}}{\sum \vartheta_{Co}}\right]_{M3} = \frac{4}{22} = 0.182 \quad (6)$$

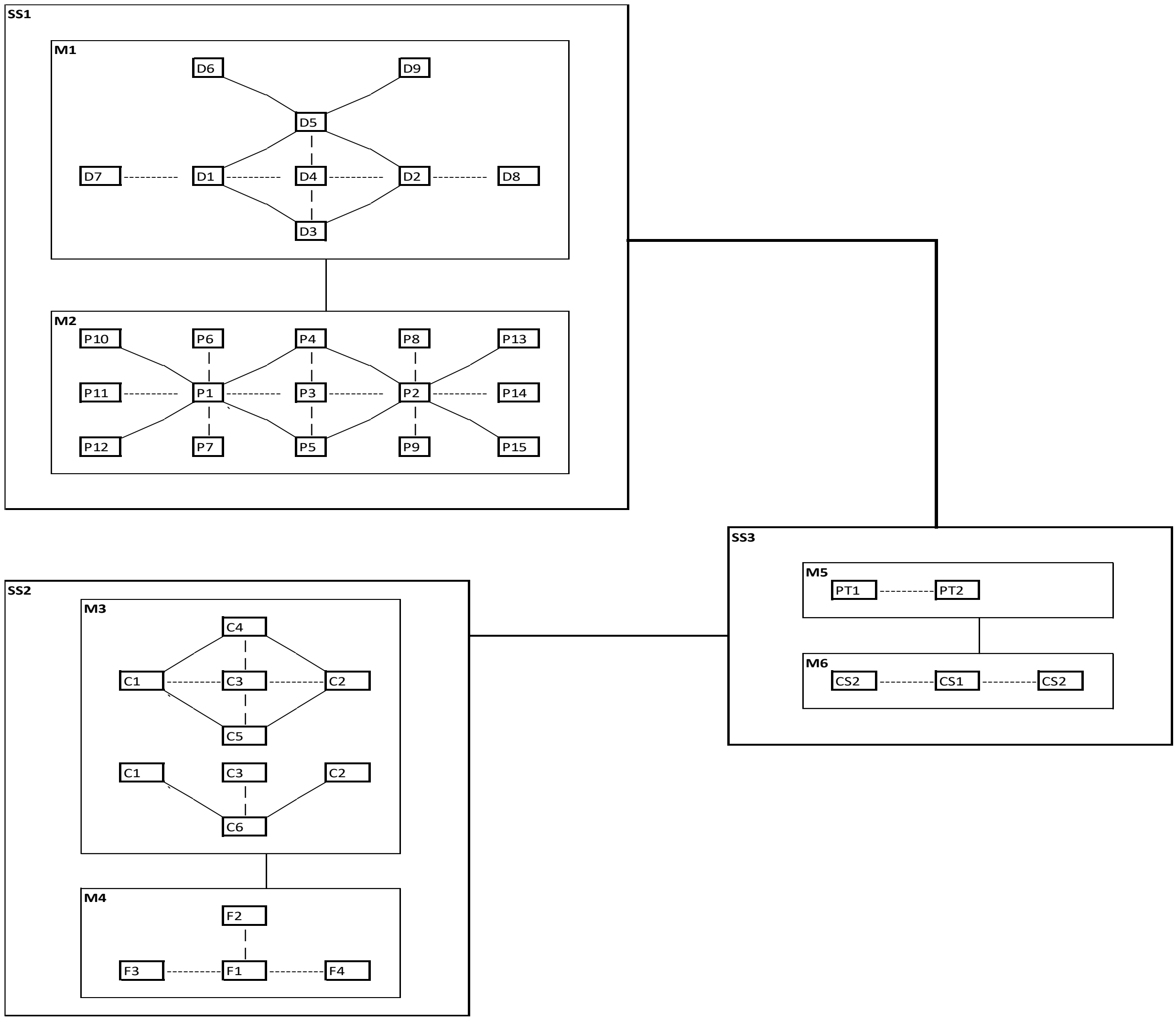

Figure 2: Decomposition of the office desk system

System	Office Desk											
Subsystem	Chest of Drawers SS1				Storage unit SS2				Desk top SS3			
Modules	Drawers	M1	Pedestal	M2	Cabinet	M3	Foldable door	M4	Plannar top	M5	Dictation slides	M6
Components	Side wall left	D1	Side wall left	P1	Side wall left	C1	Door	F1	Top (leather)	PT1	Surface	CS1
	Side wall right	D2	Side wall Right	P2	Side wall Right	C2	Lock	F2	Wooden top	PT2	Slide left	CS2
	Back wall	D3	Back wall	P3	Back wall	C3	Top rail	F3			Slide right	CS3
	Bottom	D4	Top	P4	Top	C4	Bottom rail	F4				
	Front	D5	Bottom	P5	Bottom	C5						
	Handle	D6	Leg 1	P6	Divider	C6						
	Slide left	D7	Leg 2	P7								
	Slide right	D8	Leg 3	P8								
	Lock	D9	Leg 4	P9								
			Slide left 1	P10								
			Slide left 2	P11								
			Slide left 3	P12								
			Slide right 1	P13								
			Slide right 2	P14								
			Slide right 3	P15								
			Lock	P16								

Figure 3: Product Structure and respective product levels.

Tables 7 up to Table 12 shows the number of modules and their respective components. The number of interfaces per component is shown in the interface column.

Table 7

Drawers	M1	Interfaces
Side wall left	D1	4
Side wall right	D2	4
Back wall	D3	3
Bottom	D4	4
Front	D5	5
Handle	D6	1
Slide left	D7	1
Slide right	D8	1
Lock	D9	1

Table 8

Pedestal	M2	Interfaces
Side wall left	P1	8
Side wall right	P2	8
Back wall	P3	4
Top	P4	3
Bottom	P5	3
Leg 1	P6	1
Leg 2	P7	1
Leg 3	P8	1
Leg 4	P9	1
Slide left 1	P10	1
Slide left 2	P11	1
Slide left 3	P12	1
Slide right 1	P13	1
Slide right 2	P14	1
Slide right 3	P15	1

Table 9

Cabinet	M3	Interfaces
Slide wall left	C1	4
Slide wall right	C2	4
Back wall	C3	5
Top	C4	3
Bottom	C5	3
Divider	C6	3

Table 10

Fordable door	M4	Interfaces
Door	F1	3
Lock	F2	1
Top rail	F3	1
Bottom rail	F4	1

Table 11

Planner top	M5	Interface
Top leather	PT1	1
Wooden top	PT2	1

Table 12

Computer station	M6	Interfaces
Surface	CS1	2
Slide left	CS2	1
Slide right	CS3	1

Similarly, in "subsystem" SS2, there are ($\_\sum \vartheta_{\text{mo}} = 2$) modules, and Equation 7 specifies their relative criticality Modules M4 and M3 make up "Sub-system" SS2's two modules. Both modules in Figure 3 have w_{mo}=0.5 and share($\_\vartheta_{\text{mo}} = 1$) with one another.

$$w_{mo} = \left[\frac{\vartheta_{mo}}{\sum \vartheta_{mo}}\right]_{sub} = \frac{1}{2} \tag{7}$$

The SS2 IC factor φ_{sub} is given by Equation 8.

$$\varphi_{sub} = \varphi_{mo}{}' + n_{mo}.[\prod w_{mo}]_{sub} \quad (8)$$

Where $\varphi_{mo}{}'$ is given by Equation 9.

$$\varphi'_{mo} = \sum[\varphi_{mo}]_{sub} = 0{,}000114306 + 0{,}009259259 = 0{,}009373565, \quad (9)$$

Therefore

$$\varphi_{sub} = 0{,}009373565 + 2 \times (0.5 \times 0.50) = 0{,}509373565$$

At the systems level, complex ICs are produced by the permutation of modules and components at the sub-system level. At the systems level, the ICs are reliant on the quantity of sub-systems, and the sub-system ICs determine how well a product works.

S comprises of sub-system SS3, SS1 and SS2, therefore($\vartheta_{sub} = 3$), SS2 and SS1 have a single interface with subsystem SS3, therefore subsystem SS3 has double interfaces (Figure 2). The “relative criticality” of each sub-system in a system is given by Equation 13, where is ($\sum \vartheta_{sub} = 4$), for sub-system SS2 w_{sub} is:

$$w_{sub(SS2)} = \left[\frac{\vartheta_{sub}}{\sum \vartheta_{sub}}\right]_{syst} = \frac{1}{4} = 0.25 \quad (10)$$

For SS1 = $w_{sub(SS1)} = \left[\frac{\vartheta_{sub}}{\sum \vartheta_{sub}}\right]_{syst} = \frac{1}{4} = 0.25$ (11)

For SS3 = $w_{sub(SS3)} = \left[\frac{\vartheta_{sub}}{\sum \vartheta_{sub}}\right]_{syst} = \frac{2}{4} = 0.5$ (12)

The IC for the whole system is given by Equation 3.2.8

$$\varphi_{syst} = \varphi_{sub}{}' + n_{sub}.[\prod w_{sub}]_{syst} \quad (13)$$

$\varphi_{sub}{}'$ is the sum of all the φ_{sub} (IC) that makes up a sub-system.

$\varphi'_{sub} = \sum[\varphi_{sub}]_{syst} = 0{,}009259269 + 0{,}509373565 + 1{,}09375 = 1{,}612382834$ Therefore $\varphi_{syst} = \varphi'_{sub} + n_{sub}.[\prod w_{sub}]_{syst} = 1{,}612382834 + 3 \times (0.25 \times 0.25 \times 0.5) = 1{,}706132834$

The average IC ($\varphi_{mo}(Aver)$) at different levels of the product structure is shown in Table 5.13:

Average “interface constraints” at the module level $\varphi_{mo}(Aver)$

$$\frac{(\varphi_{M1}+\varphi_{M2}+\varphi_{M3}+\varphi_{M4}+\varphi_{M5}+\varphi_{M6}+\varphi_{M7}+\varphi_{M8})}{8} = 0{,}075390447$$

Average IC at the sub-system level $\varphi_{sub}(Aver)$

$$\frac{(\varphi_{syst1}+\varphi_{syst2}+\varphi_{syst3})}{3} = 0{,}5375$$

Average IC at the system level $\varphi_{syst}(Aver)$ =1,706

Level of modularisation (LM)

Equation 14 was used to find the “level of modularisation” .

$$f(\varphi) = e^{-\lambda\varphi^2} \quad (14)$$

Where λ is “collaboration index” and it was computed in Section 5.3 and the “interface constraints” φ was computed in Section 5.4. These results are used by the model to determine the “level of modularisation” and to determine the dynamics of the “supply chain”. The the “interface constraints” used in the experiments was taken from Table 13; the average the "interface constraints" (φ) at the module level is 0.0754, at the sub-system level the the "interface constraints" (φ) is 0.5375 and at the system level, the average the "interface constraints" (φ) is 1.706. The "level of modularisation" is constant throughout the run until there is a change of the the "interface constraints". The results are displayed in Table 13. (Please note that the "interface constraints" (φ=1) is an arbitrary value and was placed for discussion purpose)

Table 13: Level of modularisation

	Interface constraint	collaboration	Level of modularity
Component	0.0754	0,048219911	0,996371
Module	0.5375	0,048219911	0,974415
Subsystem	1.706	0,048219911	0,92103

5 DISCUSSIONS

The results show an increase in IC from the component up to the system level (from 0.0754 to 1.706) which indicates that "modularisation becomes more restricted at system level", similarly this agrees with the work that was done by Hsuan [9], who stated that an increase in interface constraints results in a reduced level of modularisation value.

Low interface constraints, at the component level, led to more number of elements available to customise. Low "interface constraints" led to high "level of modularisation" and this can lead to customer confusion and dissatisfaction [35],[36]. The interface constraint at sub-system levels is relatively higher than the component level and can result in lower level of modularity. Modularisation for the wooden office desk can be effectively performed at the sub-system level, instead of the component level, which means customers can choose modules such as drawers, foldable doors and pedestals to customise their product.

The collaboration index of 0,048219 between the boards supplier and the firm shows a high level of loyalty. Liu & Yang [38] argue that loyalty programmes can help a company to gain competitive advantage over its competitors and that several loyalty programmes can exist even in a saturated marketCooperation be enhanced through internet; a lower CI results in a higher "strategic partnership", characterised with SME businesses [37]

6 CONCLUSIONS

When we examine the smaller businesses within the furniture sector, the value of customer loyalty becomes clear. The company's size can be difficult because it could not have the necessary resources, expertise, or market share. The problem is to identify a worthwhile partner with whom to work in collaboration, to grow market share to reach customers, and to increase resources like time, money, and networks while maintaining your company's distinctiveness to draw in customers.

The method that was created is a useful tool that practitioners in the manufacturing sector can use. The method provides a measure or indicator to the level of customisation, allowing the ideal level of customisation at which the company should operate.

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APPLICATION OF MBSE TO MINIMISE LOSS OF INFRASTRUCTURE VALUE AT SOUTH AFRICAN WATER UTILITIES

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ABSTRACT

A typical bulk water utility comprises an engineered system that includes water treatment works, booster pumping stations, bulk distribution pipeline networks and storage reservoirs. The entity supplies potable water to water authorities to be supplied to households. The utility consistently and continually creates infrastructure asset projects to improve and maintain existing or implement new systems. This paper investigates if the systems engineering (SE) practice is applied during the design phase of the infrastructure asset development lifecycle in South Africa. The study results found that SE practice is not formally adopted in the bulk water utility but applied as and when required. The reason cited for the lack of formal adoption is the lack of skilled workforce. Therefore, the study recommends that utilities invest in training their employees on SE practices to gain maximum benefit from its application. The study proposes a hybrid model-based system engineering (MBSE) method suitable for bulk water utilities. The hybrid MBSE model requires a software tool compatible with a document-centric approach.

Keywords: systems engineering, model-based systems engineering, water utility, infrastructure

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1 INTRODUCTION

The South African Government mandates public utilities through various legislations to plan, design, construct, operate, maintain and eventually replace infrastructure assets to supply reliable, safe, and sustainable services to the public continuously and consistently in a cost-effective manner. A public utility is a state-owned enterprise performing public services, including water supply services, sanitation services, road services, storm-water drainage, energy supply, solid waste removal, communication and postal collection and delivery [1]. Public utility enterprises operate and maintain systems forming interconnected and interrelated networks of infrastructure assets working together for a common purpose. Rapid population growth, urbanisation, and industrialisation place more demands on managing these infrastructure assets' lifecycles. To this event, the utility environment is getting overly complex. According to Rebovich [2], enterprises show attributes of a complex system driven by information and communication technology (ICT) advances. The ICT revolution's propagation reduces barriers to interactions among people, businesses, organisations, nations, and processes previously isolated in space or time. Events are harder to control, and engineering systems become increasingly complex.

A typical bulk water utility system includes treatment works, booster pumping stations, a bulk distribution pipeline network and a storage reservoir. The enterprise supplies potable water to the municipality through the distribution pipeline network, which supplies to households through the connector pipeline network to the internal reticulation pipe network. However, the boundaries between these networks are not apparent to the public eye and create a complex environment.

Literature has documented several modern large-scale infrastructure asset projects that failed and subsequently lost value due to a misfit between the designed system's operational capability and stakeholder requirements. These projects tend to be abandoned, or newly designed infrastructure assets are used with limited operational capability despite the tremendous amount of time and capital invested. Many water utilities in South Africa (SA) are experiencing an unprecedented increase in delays, cost overruns, and failure of modern-day large-scale construction projects. Studies on the cause of delays, cost overruns, and failure of these mega infrastructure assets construction projects highlighted delays in approving design drawings, design changes, and continuous design errors [3].

According to Bar-Yam [4], modern-day large-scale infrastructure asset projects generally involve integrating multiple impossible functions with traditional methods. They are expected to satisfy additional reliability, safety, and security constraints. Design-related issues are essentially the reasons for mega infrastructure assets construction project failures. Designs constitute a significant part of the initial phase of the infrastructure asset development cycle. Therefore, an erroneous design will result in an incorrect final product.

The study aims to find the currently adopted infrastructure asset engineering practices by water utility industries in SA and investigate the application of the MBSE method to address the loss of value of newly constructed infrastructure due to a misfit between infrastructure asset operational capability and stakeholder requirements. This will help highlight best practices suited for the bulk water utility environment and develop a framework for adopting these practices. Furthermore, the study will also propose a commercially available MBSE method suitable for bulk water utilities in SA. Adopting system engineering (SE) discipline and applying model-based system engineering (MBSE) methods by utilities, particularly in South Africa, may reduce the risk of wasteful expenditure and reputational damage posed by the loss of asset value due to a misfit between infrastructure asset operational capability and stakeholder requirements.

2 LITERATURE REVIEW

2.1 Infrastructure Asset Lifecycle

Utility infrastructure assets include all core assets integral to delivering services, including water supply, electricity supply, transport, and community facilities. According to the International Accounting Standard (IAS), the infrastructure includes all immovable assets such as Property, Plant and Equipment (PPE). The conception (initiation), defining (planning and design), execution, operation and maintenance of any infrastructure asset follow a logical sequence of phases called the system development lifecycle [5]. The first three phases form the project lifecycle. Lifecycle refers to the interconnected and interrelated cycle of stages the asset goes through during its life span [6].

The concept/planning/design stage is the foundation of the project lifecycle; it determines the needs, mission statement, requirements, constraints, and communication upon which the remaining phases are built [5]. According to Nicholas & Steyn [5], it is a crucial phase where the seeds of the project's success or failure are planted. Therefore, specific, unambiguous, and explicit requirements must be captured within the concept stage for successful system execution and utilisation. A requirement is a statement about an intended product that specifies what it should do or how to do it [8]. Business requirements inform the user requirements, outline the system requirements, and ultimately, the system requirements must satisfy the business requirements. Requirements gathering is, therefore, an iterative process whereby each step within the hierarchy influences the other.

2.2 Historical and Current State in the Utility Environment

As the engineering environment evolves and technology advances, seemingly some large-scale projects are arguably still developed following the traditional processes such as the engineering design process. Literature has documented several large-scale projects that failed and subsequently lost value, seemingly due to a misfit between the designed system's operational capability and stakeholder requirements [4].

These projects are either abandoned, or newly designed infrastructure assets are utilised with limited operational capability despite the tremendous amount of time and capital invested. Modern-day large-scale infrastructure asset projects generally involve integrating multiple functions that are impossible with traditional processes. They are expected to satisfy additional constraints of reliability, safety, and security [4].

Bar-Yam [4] states that a study performed in 1995 by Standish Group International found that under 20% of the projects were on time, on budget, and function. Over 50% of the projects were over budget and scheduled while not meeting original functional specifications. The remaining 30% of the projects were called impaired, meaning "abandoned" [4]. According to Tshidavhu and Khatleli [3], only as little as approximately 20% of complex projects in Africa are completed and used beneficially as intended by owners. Most of the failed complex projects have recently been in the utility space.

2.3 Engineering Design Process

The utility consistently and continually creates infrastructure asset projects to design and implement new systems or improve existing ones to solve engineering problems. As such, the classic engineering design process is adopted by utilities to aid in solving engineering problems. The classic engineering design process is primarily a five-step process, as shown in Figure 1 [7].

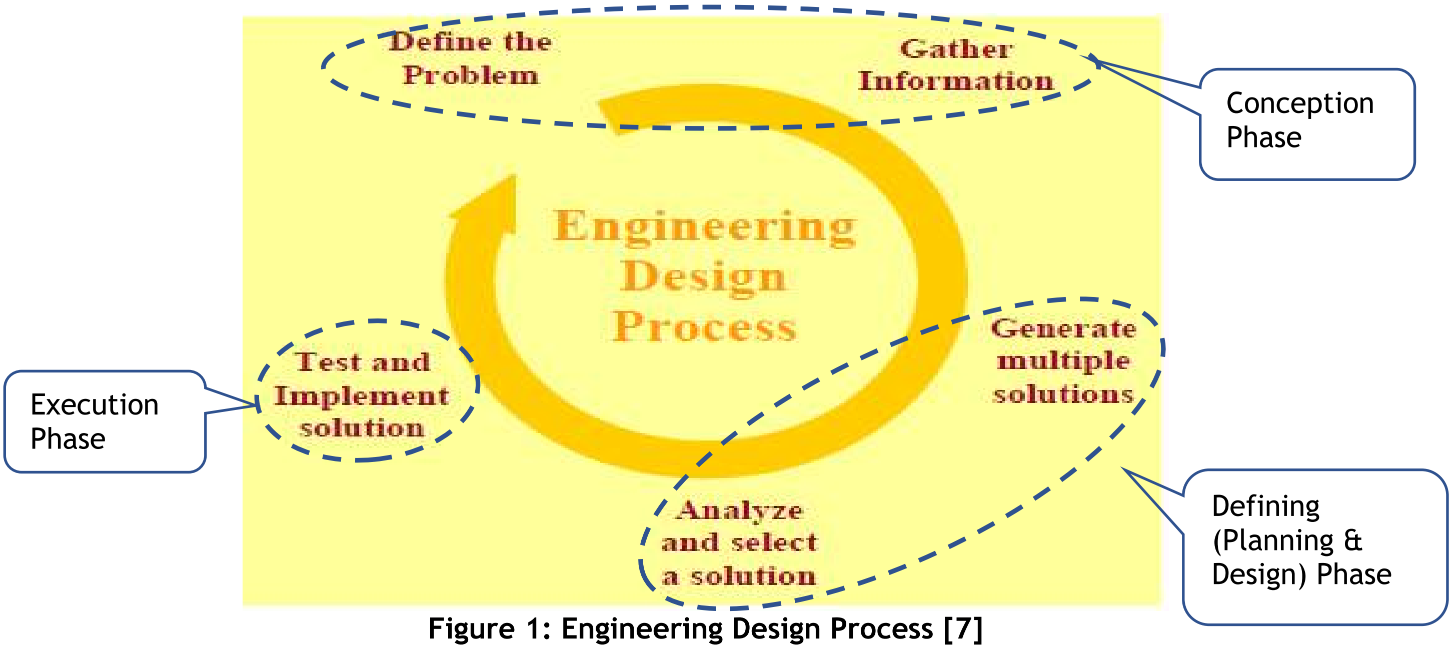

Figure 1: Engineering Design Process [7]

According to Khandani [7], engineering problems are open-ended, suggesting that they have more than one correct solution. The ultimate solution is a system with specific properties based on stakeholder needs and requirements. However, stakeholder needs and requirements are usually vaguely specified on their own. To this end, the engineering design process requires continually refining the design. Khandini [7] argues that refining the design is expensive or unproductive, resulting in cost overruns, project delays and a lack of technical performance.

The refining and developing of the best solution only occur during the later stages of the design process. At this stage, to evaluate each solution objectively against the requirements, the design engineer uses a quantitative basis to evaluate each design alternative. According to Khandini [7], the decision matrix is a widely used method to formalise decision-making. The first step in creating a decision matrix is for the design team to rank the desirable attributes or criteria for the design solution in order of importance. These attributes include safety, manufacturing considerations, ease of fabrication and assembly, cost, portability, compliance with government regulations, etc. A value factor related to that attribute's relative importance is assigned to each attribute. The design engineer needs as much information as possible to evaluate accurately. Unfortunately, engineers seldom have enough information to make a perfect evaluation. In most cases, they must use engineering judgment, and the decision is subjective [7].

The engineering design process considers only the project management aspect and not the system management aspects during the infrastructure asset development cycle. The development cycle refers to manufactured systems that follow a deliberate and logical sequence of prescribed activities. It forms the basis for system and project management, and both aspects occur within this cycle [5]. According to Nicholas & Steyn [5], system management aims to understand what the end item must do to satisfy stakeholder requirements. Project management aims to specify what the project team must do to produce the end item.

2.4 System Engineering Process

The SE process combines several techniques to ensure that all requirements are satisfied by the designed solution. The four main techniques are requirements analysis, functional behaviour analysis, architectural synthesis, and validation and verification, as shown in Figure 2 [9]. Often, these domains are treated as individual SE efforts.

- Requirements analysis: This high-level inquiry begins with exploring the stakeholder's needs and results in a general statement of the system's functionality.
- Functional behaviour analysis concerns "what" the system must do to answer the customer's need and "how" well the system must perform these functions. Describing behaviour to meet requirements is, in essence, constructing the logical system model.
- Architectural synthesis: This is concerned with physical structures in answering the customer's needs for the system. Architectural synthesis (physical structures) tends to follow functional behaviour (what and how) in the development phase rather than vice versa. This is synonymous with a form that follows function.
- Validation & Verification (V&V): At the end of the development phase of the system life cycle, the objective is to ensure that the design process has converged on a complete and workable solution to the entire problem posed to the design team. This process is known as V&V.

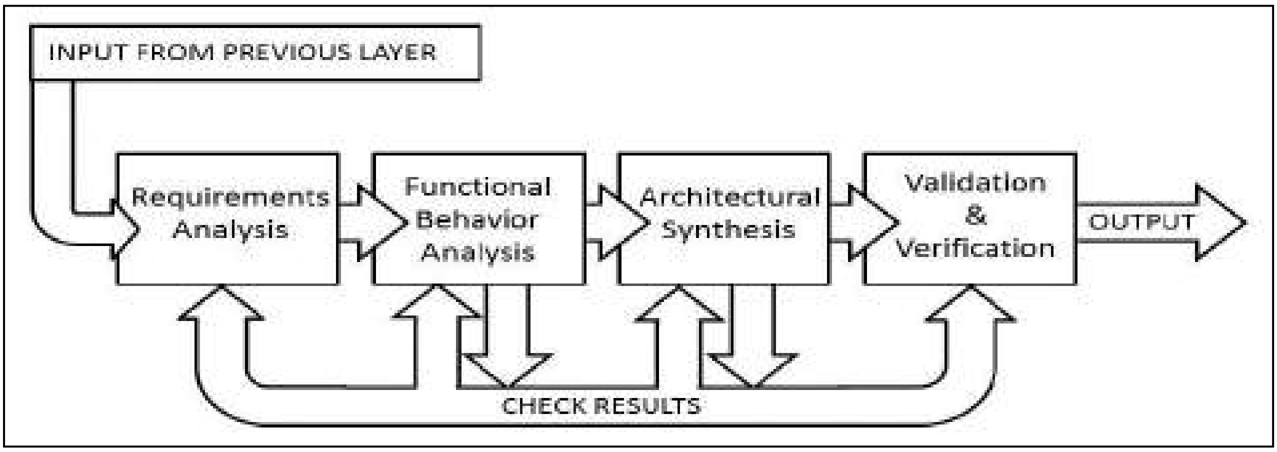

Figure 2: An Illustration of the typical System Engineering Process [9]

SE methods are suited to manage uncertainties through iterative development processes during the project lifecycle phases [10]. Long and Scott [9] state that the technological MBSE approach is based on a layered process of analysing and solving system design problems. A layered structure takes shape as the system is designed in increasing detail. The engineering process follows these layers, drilling deeper and deeper into the system design. As seen in Figure 3, every iteration of the system engineering process increases specificity, removes ambiguity, and resolves the unknown [9].

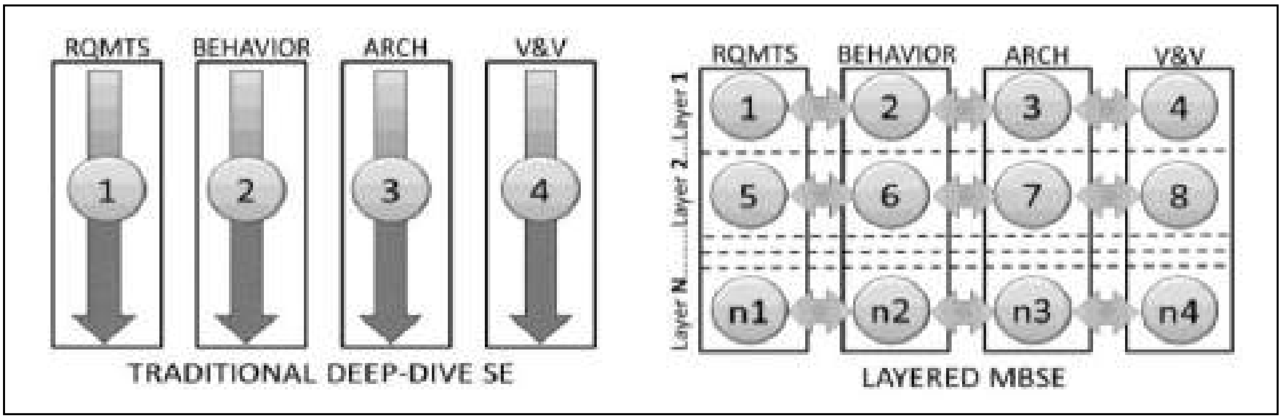

Figure 3: Illustration of the difference between the traditional DBSE and technological MBSE Approaches [9]

The domains (requirements, functional behaviour, architecture, and validation and verification) are addressed in context at the level of increasing detail as each successive layer is peeled back [9]. The layered technological model-based approach works through each domain in each layer. In contrast, the traditional document-based approach does not offer any iteration between domains, nor does it show the iteration between layers [9].

2.5 Model-Based System Engineering Practice

An MBSE methodology is a set of related methods and tools used to support the discipline of SE in a model-based context [11]. Estefan [11], defines a methodology as a collection of related processes, methods, and tools:

- Process: Logical sequence of tasks performed to achieve a particular objective. A process defines what is to be done without specifying how it is to be done.
- Method: Technique for performing a task. The method defines how it should be done.
- Tool: Enhances what and how. Most tools used to support SE are computer or software-based, known as Computer-Aided Engineering (CAE).

INCOSE defines MBSE as "a formalised application of modelling to support system requirements, design, analysis, verification and validation activities beginning in the conceptual design phase and continuing throughout development and later lifecycle stages" [14]. A modelling practice forms the basis for MBSE. It considers the entire engineering problem, uses consistent language to describe it and produces coherent, designed and verifiable solutions to all the system requirements posed by the problem [9].

MBSE elevates modelling in the SE process to a central and governing role between and within lifecycle stages [11]. In an engineering system, most of the data is captured in a model and is kept throughout the system's lifecycle [12]. This event creates an enabling environment resulting in the following benefits:

- Enhancing linkages improves communication, exchange of information, and traceability within phases and between stages during the asset lifecycle, which assists in circumventing higher project costs and schedule overruns during project construction, installation, and system operation.
- Creating a physical or virtual reality early in the project mitigates the possibility of stages behaving as self-sufficient entities but acting as part of a more extensive system [1].
- Improve the enabling environment by supplying an accurate system model to evaluate consistency, correctness, and completeness.

Several MBSE methodologies are commercially available and published in the open literature: IBM Telelogic Harmony-SE, INCOSE Object-Oriented System Engineering Method (OOSEM), IBM Rational Unified Process for System Engineering for Model-Driven System development (MDSD), Vitech Model-Based System Engineering Methodology, JPL State Analysis (SA), Dori Object-Process methodology (OPM).

An MBSE methodology for water utility was provided by [13], as shown in Figure 5. However, this case study illustrates the practicality of applying MBSE methodologies to increase the resilience of systems that supply water to consumers and demand points within a supply network. The study was informed by natural disasters, such as flooding, the chance to increase the probability of water infrastructure being damaged, jeopardising water supply to customers. According to [13], the MBSE methodology was found to allow decision-makers and engineers to:

- Evaluate the resilience of systems through static and dynamic methods
- Discover future system states and resilience strategies through architecture exploration.

- Furthermore, the model integration architecture provided a holistic view. It provides details at both high and low levels of granularity and puts stakeholder requirements in context with the rest of the portfolio models.

The literature review has shown that it is possible to benefit from MBSE and that MBSE processes can add value to a water utility environment. A water distribution system is multifaceted, with diverse stakeholder requirements. Therefore, the MBSE process's capability to manage many-to-many relationships between requirements and system elements without losing tractability and accuracy will prove advantageous for system design, development, and overall asset lifecycle management. Furthermore, it is possible to couple MBSE methodologies with 4IR technologies, such as digital twins coupled with IoT.

2.6 Gap Analysis

In the classic engineering design process, considerable information about the system contained in specifications, interface control documents, system description documents, analysis reports, verification plans, procedures, and reports are often generated. The information in these documents is often difficult to support and synchronise and challenging to assess regarding its quality (correctness, completeness, and consistency). Decision-making is based on a subjective method that depends on the amount of available information. This subjectivity leads to a flawed decision-making process.

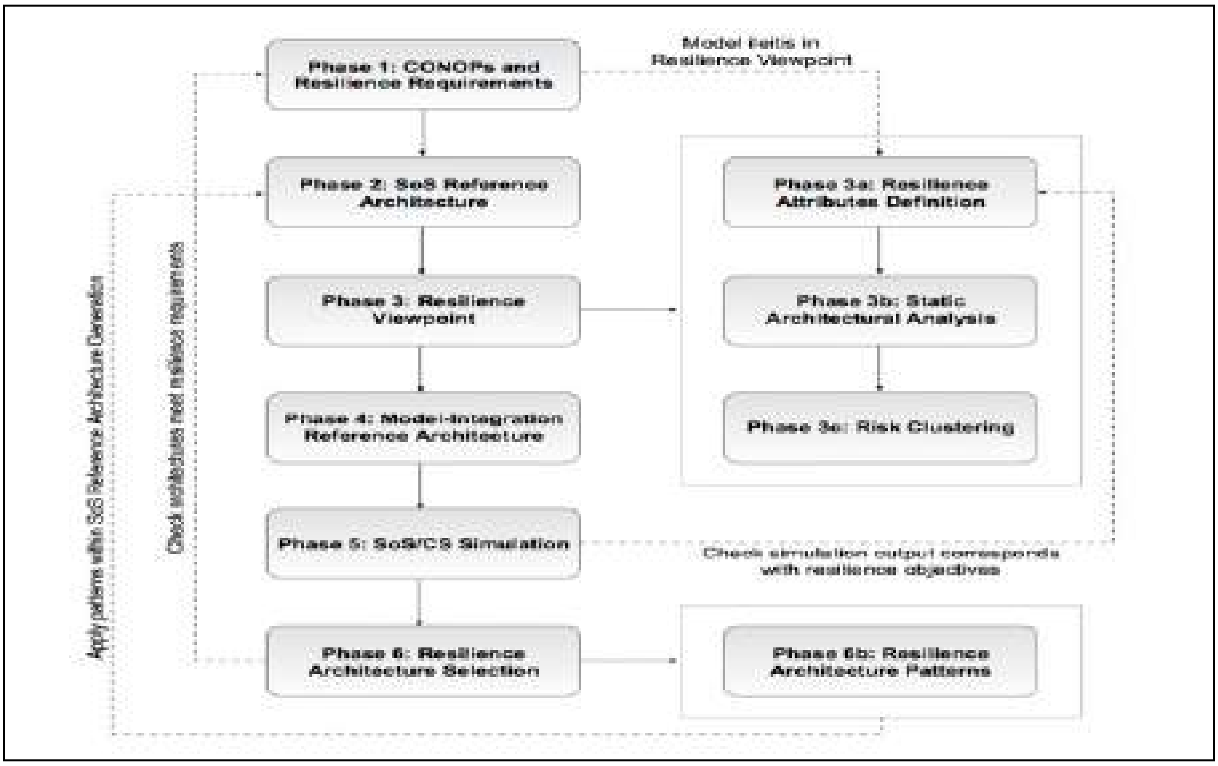

Figure 4: MBSE Methodology for Water Flooding Resilience [13]

In an MBSE approach, most of the information is captured in a system model or set of models. A system model is a primary tool of the SE process. MBSE formalises the application of SE using models. The International Council on Systems Engineering (INCOSE) describes the benefits of an MBSE approach as follows:

- Improved communications.
- Increased ability to manage system complexity.

- Improved product quality.
- Enhanced knowledge capture.
- Improved ability to teach and learn SE fundamentals.

However, constraints and difficulties in implementing an MBSE approach must be overcome. The MBSE approach significantly differs from an engineering design process approach, forcing changes to engineering processes, tools, and communication methods to succeed and requiring a substantial financial investment for training and tooling. Changing how information is communicated (using models instead of simple text and matrix) is a difficult process involving all stakeholders, which could be thousands of people on a large complex system project. Technical issues around the application, models, data standards, security, and information configuration management must be resolved at any program's start. In addition, an MBSE approach can change the labour distribution curve. Instead of a flat-line deployment of SE resources across the system development life cycle, an MBSE approach can emphasise more effective use of SE resources early in the life cycle, forcing cost expenditures earlier than an engineering design process approach. This is because MBSE tools typically include functionality that focuses more effort on completing requirements and interfaces throughout the early phases [15].

3 CONCEPTUAL MODEL

The literature review presented in the preceding chapter of this study provided essential background on the SE practice and the tools and methods available for practical function. It has shown that the MBSE method is vital in supporting the development lifecycle of an infrastructure asset. This chapter developed and discussed a conceptual model to prove its effectiveness.

Construction projects within the infrastructure environment are fast becoming overly complex. On the other hand, MBSE is steadily becoming more important for project lifecycle phases, particularly conceptualisation and development stages. It is a foregone conclusion that asset-centric organisations must adopt a technology-driven SE approach to be successful. A hybrid model is found to be suitable for bulk water utility organisations. The hybrid model integrates the traditional document-centric approach with a technological model-centric approach or fully embraces the latter approach to minimise the loss of value of newly constructed complex projects. However, applying MBSE in the construction project's infrastructure project lifecycle seems unknown or unfamiliar. Therefore, it must be investigated to find the applicability of MBSE and the influencing factors. In this chapter, a conceptual model is proposed for the utility environment. A hybrid conceptual model is derived to solve the research problem, as shown in Figure 5.

Projects have been planned, designed, and constructed in the utility environment using a document-centric classic engineering design process approach for many years. Therefore, a gradual phase-out strategy should be adopted instead of a complete overhaul. This hybrid method incorporates aspects of the traditional document-based system, which is closely related to the classic engineering design process approach, with a technological MBSE approach.

The hybrid method shall be applied iteratively and recursively to solve engineering problems. These activities will be consistent with the Objective-Oriented System Engineering method (OOSEM). It shall transform business needs and objectives into business requirements, which informs user requirements and ultimately outlines system requirements during the DBSE process. The method is intended to ease integration between DBSE and MBSE processes, as shown in Figure 8. The model employs a top-down system engineering approach to support analysis requirements, functional analysis design synthesis and verification of the system. This process captures the systems as-is and potential improvement areas.

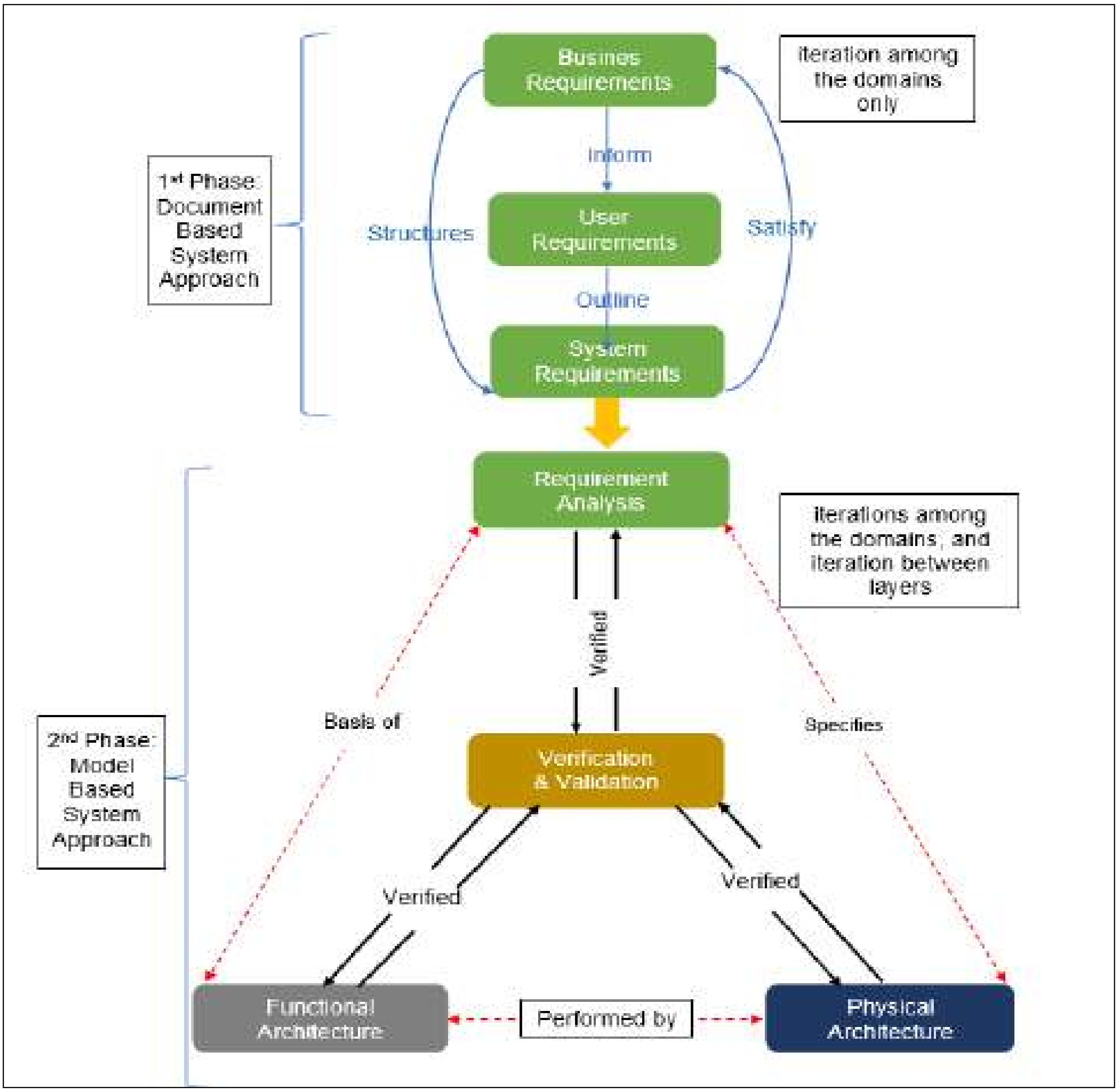

Figure 5: Proposed Hybrid Conceptual Model

Requirements are related directly to the performance characteristic of the system being designed. They are the primary focus of the DBSE process. The primary purpose of the hybrid model is to transform the requirements into design synthesis.

- Requirement Analysis. The first step in the MBSE process is requirement analysis. In this analysis, customer requirements are translated into a set of requirements that define what the system must do and how well it performs. To avoid rework, the systems engineer must ensure the requirements are understandable, unambiguous, comprehensive, complete, and concise.
- Functional Analysis. The functional analysis allows for a better understanding of what the system must do, how it must do it, and to what extent the constraints and conflicts associated with lower-level functions. It provides information necessary for optimising physical solutions. The functional analysis process's outcome is the product's functional architecture.

- Design Synthesis. Design synthesis defines the product in terms of the physical and software elements that make up and define the product. The result is often referred to as physical architecture. The physical architecture is the basic structure for generating the specifications and build-to-baselines.
- Verification. For each application of the system engineering process, the solution must be compared to the requirements. Each requirement at each level of development must be verifiable. Baseline documentation developed during the DBSE process must establish the verification method for each requirement.
- Available Tools. The INCOSE object-oriented system engineering method (OOSEM) is the best technological model suited for the water utility environment. This technology can be tailored accordingly to yield the expected results. OOSEM leverages object-oriented concepts with traditional top-down systems engineering methods and other modelling techniques [11]. It is, therefore, a hybrid methodology and supports the system development process.

Deployment of this contextual model requires preparing the utility to predict future difficulties inherent to it. Deploying SE principles and processes in an organisation remains a non-trivial activity requiring a precise deployment method [16]. According to Cornu et al. [16], an appraisal tool is needed by management to:

- An overview of the readiness of organisational units under their responsibilities to face a deployment of SE processes.
- Identify synthetically what and where their organisations' weaknesses endanger future deployment.

Cornu et al. [16] argue that a maturity model can be used. In a deployment context, the maturity model appears relevant since it is easy to use, open-ended and enables an initial assessment to track progress achieved while making managers and design stakeholders aware of their organisation's maturity [16]. The maturity model is a matrix with one dimension describing the assessment criteria and the other the maturity levels. It detects which criteria improvements must be made to move from a given level to a better one. Table 1 provides five maturity levels proposed and a catchphrase illustrating the typical mindset of people in the organisation assessed at a specific level. The table includes a reference to the CMMI® level. CMMI® level aims to help companies assess their processes' performances and provide guidelines to improve them. In contrast, the proposed maturity model aims to assess the readiness of companies and entities within companies to deploy SE. Therefore, the two models are complementary.

Table 1: Maturity Levels

#	MATURITY LEVEL	DESCRIPTION	MAX CMMI® LEVEL
1	Initial	SE is Non-existent	1
2	Low	SE is not adopted, but its principles are applied	
3	Neutral	SE is known but not in use due to a lack of skills in the Company	2
4	Good	SE is applied as and when required	
5	Excellent	Fully adopted and applied	3

4 RESEARCH METHODOLOGY

This study gravitates more toward a position of objectivism and positivism. Therefore, the quantitative method approach is adopted for this research. This research concerns what and how or why something has happened. Therefore, a survey method is being utilised to collect information from respondents.

Survey research allows various methods to recruit participants, collect data, and utilise various instrumentation methods [17]. Data can be collected through face-to-face, telephonic, or written questionnaires.

In this research, a written questionnaire consisting of close-ended questions is an instrument that is being used to conduct a survey. It is formulated in such a way as to gather information from respondents used for statistical analysis. The research questions are related to the research problem and structured to gather the relevant information required to solve the problem.

Data analysis and discussion are carried out using descriptive and inferential statistics. The descriptive analysis provides a helpful initial examination of the data even when the ultimate investigation concern is inferential. Inferential statistics focus on hypothesis testing. It allows the researcher to infer large populations from relatively small samples. Data is analysed using a statistical package for the social sciences (SPSS) computer program.

5 RESULTS: DATA ANALYSIS AND DISCUSSION

5.1 Response Rate

An online questionnaire was sent to 60 engineers and technologists in the operations, design, asset management and asset planning departments within the utility in SA, and Thirty-five responses were returned.

5.2 Data Analysis

The data collected shows that 36% of the respondents are involved with asset management and planning, 30% in project execution, 21% in design and 13% in operation and maintenance. The response seems to be reasonably balanced across the infrastructure asset project lifecycle. In conclusion, the responses will probably better reflect the organisation's currently adopted infrastructure asset engineering practices.

It is clear from the data collected that the water utility mainly employs project management and asset management standards. These standards do not aid with the infrastructure asset lifecycle management but specify what the project team must do to effectively produce the end product and manage the asset management document hierarchy. This observation is in agreement with Nicholas & Steyn [5], statement that “system management aims to understand what the end item must do to satisfy stakeholder requirements. Project management aims to specify what the project team must do to produce the end item”.

The responses show that the organisation uses a general engineering design process instead of system engineering practices for the infrastructure asset lifecycle approach. This observation is expected since the organisation focuses more on project management than system thinking principles.

Data collected shows a high probability that most respondents have extensive and practical experience in SE principles even though the organisation does not seem to apply the SE approach during the infrastructure asset lifecycle. It is also clear from the responses that there is a high probability that the enterprise is mature enough to consider SE and to use SE as and when needed. Given employees' competency level in SE principles, the enterprise should be able to deploy it quickly, considering the cost factor.

Contrary to the observation above, the results show that the lack of skilled employees is one reason system engineering practices are not used but are generally known. This sign could mean the respondents misunderstood DBSE for the general engineering design process.

Although the results show a high probability that the entity applies document based system engineering (DBSE) approaches to the infrastructure asset development lifecycle, it might not be accurate. This observation can be explained by the fact that DBSE processes are linked to general engineering design processes. In DBSE, similarly to the general engineering design process, considerable information about the system is contained in specifications, interface control documents, system description documents, analysis reports, verification plans, procedures, and reports. Therefore, decision-making is based on a subjective method that depends on the amount of available information. This subjectivity leads to a flawed decision-making process.

According to Khandani [7], in the engineering design process, stakeholder needs and requirements are usually vaguely specified. Therefore, the engineering design process requires continually refining the design. Khandini [7] argues that refining the design is expensive or unproductive, resulting in cost overruns, project delays and a lack of technical performance.

Finally, as expected, the results show that, amongst others, cost, schedule, and performance improvements will be realised with the application of the MBSE.

System Engineering practice and commercially available MBSE tools were found using the Chi-Square Tests at a 95% confidence level to be statistically significant in predicting the effectiveness of the end product. Furthermore, commercially available MBSE tools were found using the Chi-Square Tests at a 95% confidence level to be statistically significant in helping the effort of an infrastructure asset project lifecycle. To this end, utility management should investigate integrating the most suitable commercially available MBSE tool in the infrastructure project lifecycle in South Africa.

6 CONCLUSION

Firstly, the focus of this study is to find the currently adopted system engineering practice by water utility industries in SA.

The study found that the water utility in SA has employed the classic engineering design process approach to managing a complex infrastructure assets development effort. According to Khandani [7], decision-making in this process requires refining and developing the best solution subjectively during the later stages of the process. As such, large-scale projects arguably fail due to this process. Therefore, the classic engineering design process is no longer relevant and effective for large-scale engineering infrastructure asset project development in South Africa. The study further suggests that the traditional document-based approach is applied to the classic engineering design process. This combination should be expected since the two methods are primarily document-centric processes.

Secondly, the study aims to investigate the application of MBSE to address the loss of value of newly constructed infrastructure due to a misfit between infrastructure asset operational capability and stakeholder requirements.

Given that the utility applies a document-centric approach, a hybrid model suits the asset-centric bulk water utility organisations in SA. The hybrid model comprises a model-based system engineering tool compatible with and incorporates a document-centric approach. The study found the INCOSE object-oriented system engineering method (OOSEM) to be the most suitable commercially available MBSE tool for utility infrastructure project lifecycle in South Africa. According to Estefan [11], OOSEM leverages object-oriented concepts with traditional top-down systems engineering methods and other modelling techniques). It is, therefore, a hybrid methodology and supports the system development process.

It is recommended that future studies be extended to other utilities in South Africa, particularly electrical energy and transport. Future studies are further recommended to pilot SE practices within the utility with a dedicated team of engineers focusing on a specific infrastructure asset development effort. It is also recommended that future studies investigate the integration of digital twins and SE applications in detail within the utility environment. It is recommended that utilities focus their attention and invest in training their employees on SE practices and their applications. This training will assist in dispelling the misunderstanding between system engineering practices and the general engineering design process.

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THE PROMISE OF SIMULATION TO SOLVE PRODUCTION PLANNING PUZZLES AT A SOUTH AFRICAN ELECTRONICS MANUFACTURING FACILITY

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ABSTRACT

With increases in product demand and changing landscape globally of the electronics industry, South African companies are at a critical point where puzzling out the correct scheduling material, equipment and resources is key. This paper explores how simulation technology can potentially transform traditional work scheduling practices in planning departments currently using Excel spreadsheets. We present potential benefits of integrating simulation to model operations for scheduling purposes by testing different scenarios, testing feasibility, reducing throughput time, reducing bottlenecks, and improving decision-making processes overall. Our research method involved a case study of a SA electronics manufacturing company to simulate an assigned production line using SIMUL8. We discuss current practices, the challenges, and barriers to implementation. Thematic analysis was conducted on the data to identify emerging and recurring themes. We found that SIMUL8 technology has enabled us to spot Kaizen points, effectively reducing throughput times and eliminating waste.

Keywords: Simulation, Production Planning, Lean Manufacturing, Simul8

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1 INTRODUCTION

This study takes place in a South African based, Electronics manufacturing and subassembly plant. The Western Cape branch of this manufacturing firm is at a critical point where puzzling out the correct scheduling material, equipment and resources is key for their process optimization. Generally, there has been a large increase in the products requested from both local and international markets, increasing the forecasted job orders significantly as presented in Figure 1 below.

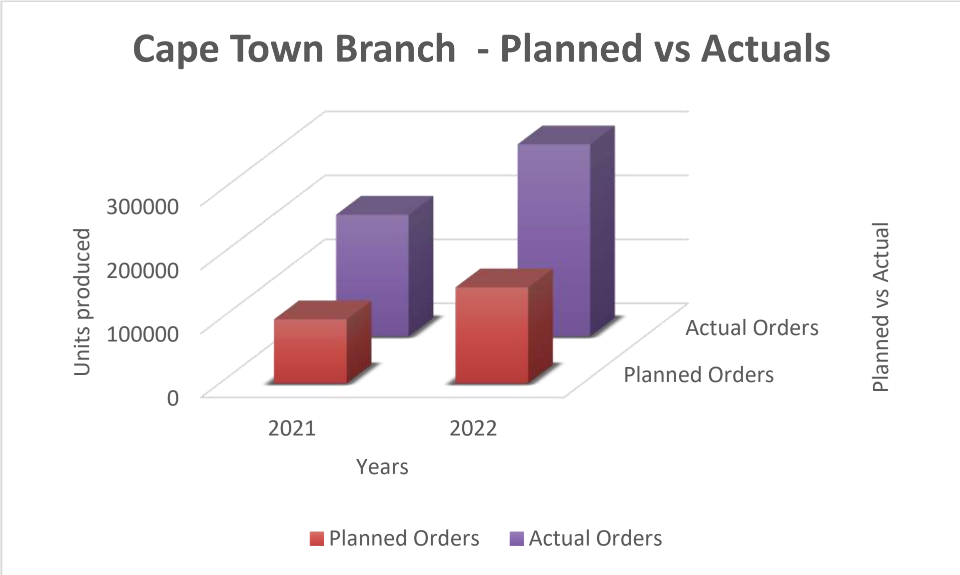

Figure 1:The company's Planned vs Actual orders

As seen in the figure above there has been an increase in the number of new products and an increase in the actual jobs orders requested. This significant increase, almost 55% from year 2021 to 2022, has forced management to generate new production management solutions to this expanding product mix. Current practices at the facility include the production manager and planner making use of an advanced excel programme with which to schedule and plan jobs according to Production allocations and worker availability. This system has worked successfully in the past, prior to these staggering increases to order numbers, however the challenge now becomes when the orders have increased to such an exponential rate. There are just too many variables to consider and with planning showing another increase of about 50% on the 2022 figures for 2023, something urgently needs to be done.

There are various tools amongst the Total Quality Management and operations research methodologies from which to choose in the alleviation of this increasing production demand. [1]–[3] . One such study done by [4] investigating the overall utilization level of the Metro rail line in the UK. Simulation modelling is a tool that enables us to model a process, giving us a visual representation that facilitates the decision-making process. Creating continuous flow in processes is the ultimate objective of lean production as it establishes systems that effectively meet expectations while adhering to quality standards [5].

Process observations in one of the production lines, Hereafter coded as "Line C" for anonymity purposes, at the company has led to the realization that there is a high level of discontinuity in operations. Simulation modelling has been used to model this manufacturing process to compare the effects of continuity vs discontinuity in the production line.

2 PROBLEM STATEMENT

The identified problems faced on the production line are as follows:

- an application of batch layouts over continuous flow layouts on certain designated activities
- a stoppage in production operations during the lunch time shift change
- Low Utilization of critical machine resources

Simulation modelling will be applied to these three major scenarios to display the effects of designated changes to the production line's outputs.

2.1 Project objectives

The project objectives are as follows:

- simulating the "LINE C" production processes using SIMUL8
- performing a bottleneck analysis of the simulation results and investigating the reason behind the long throughput times.
- creating alternative shift scenarios within the Simulation to reduce the discontinuity in production during teatime & lunchtime.
- testing different "What If" scenarios and assess their results.
- increasing Machine utilization.

3 LITERATURE REVIEW

3.1 Simulation Modelling

SIMUL8 is a computer simulation modelling package that can be used to build a simulation model that virtually represents a mechanism or a system. The aim is to imitate a real system, which helps with exploring it, experimenting with it, and understanding it without altering the real system. SIMUL8 helps to compare different sets of scenarios and allows to formulate judgments after considering all angles as seen in these examples here[6]–[8]. SIMUL8 demonstrates the workflow through a system, one incident at a time, with all the key interactions on the computer screen graphically displayed. SIMUL8 is a software package designed for discrete event simulation or process simulation. It has been developed by the American firm SIMUL8 Corporation. It has been used successfully in many specific case studies, namely in a composite manufacturer, used to answer the complex scheduling and sequencing part requirements through the production line. SIMUL8 may seem to be a simple probabilistic tool, however in this flexible production environment, it was able to plan the production across the entire plant in a synchronized and balanced workflow manner. [9]

3.2 Discrete Simulation

Discrete simulation is based on the mathematical branch of discrete mathematics [10]. These discrete probabilistic numbers found within the computations of computer simulations are a branch of discrete mathematics. Discrete mathematics is the branch of mathematics dealing with objects that can assume only distinct, separated values. The term "discrete mathematics" is therefore used in contrast with "continuous mathematics", which is the branch of mathematics dealing with objects that can vary smoothly (and which includes, for example, calculus); whereas discrete objects can often be characterised by integers, continuous objects which require real numbers. The study of how discrete objects combine with one another and the probabilities of various outcomes is known as combinatorics. Other fields of mathematics that are considered part of discrete mathematics include graph theory and the theory of computation. Topics in number theory such as congruencies and recurrence relations are also considered part of discrete mathematics The study of topics in discrete mathematics usually includes the study of algorithms and their implementations and efficiencies. Discrete mathematics is the mathematical language of computer science, and as such, its importance has increased dramatically in recent decades. The response of the simulation is made subject to discrete simulation parameters embedded into the design of the simulation, the precedent of which has been set by Pegden and Sturrock [11], Zaayman and Innamorato [12] and Constante [13], who advocate the use of discrete simulation in their future predictive studies.

In this study the contribution being to identify bottlenecks and provide management with the appropriate tools to identify potential problems and suggest solutions. This study takes place in a production line at a facility producing fans. [14] but it is similar to our case study here.

4 METHODOLOGY

4.1 Research Methods

Following a literature survey of methodologies, a step by step approach and sequence that the researcher has taken in order to answer the research questions and ultimately gather data in order to understand and solve the research problem at hand. Aims, perspectives Objectives and overarching research questions guided the choice of research methods.

Qualitative research is typically ethnographic inductive knowledge: Meaning you Read something – Gain an experience – Describe the implications and then explain further. However Quantitative research is Deductive. Making use of hypothetical deductive logic. Typically, you would Read – develop an idea – gather evidence – test the findings – and finally discuss. [15]. The selection of the research method is now discussed. [16] argues that the key questions to be answered by the methodology are to be done using his five-question approach, which holds the research objectives, and research questions at the forefront of the researchers mind at all times when making the decision. As is usually the case with a component of a design, the strategy to be followed was shaped on the basis of the project framework, the research objective and the set of research questions. Our research method involved a case study of a SA electronics manufacturing company to simulate an assigned production line using SIMUL8.

4.2 Selection Criteria for the Simulation Software

Choosing an appropriate simulation program is an important stage in the process of reaching a sound simulation project or study. Our choice might have a crucial importance for the success of our analysis. Generally, this decision depends on the nature of the specific simulation project. [17]

Domonkos [17] goes on to mention the most popular and generally known software and a overall breakdown. Application orientation means that they are intended to solve certain specific types of tasks. Universal simulation programs have general application. At present, the best-known specialized simulation software tools are:

ARENA (www.arenasimulation.com), AUTOMOD (www.automod.com), EXTEND (www.imaginethatinc.com), FLEXSIM (www.flexsim.com), MICROSAINT(www.maad.com/index.pl/micro_saint), PROMODEL (www.promodel.com), SIMUL8 (www.simul8.com), SIMPROCESS (www.simprocess.com),WITNESS www.lanner.com),GPSS/H www.wolverinesoftware.com), SIMSCRIPT II.5 www.simprocess.com),etc. Other Programs – these are suitable for modelling simpler processes, such as those that do not capture the dynamics of the system, i.e. static models with a less complicated structure. Examples for these programs are MS Excel and other programs for optimization, such as MATLAB, which are not specialized simulation software, but allow the user to create essential simulation models with certain limitations.

Derived from a number of researchers who made use of this approach including [18], as well as more recently [19], and [20] each present a decision analysis spreadsheet using criteria-based matrix assessment of different variables. A similar tool was the developed for the process of selecting which software to utilise. This decision analysis is a side-by-side comparison of potential software to be chosen for use of the design. This method allowed the researcher to define critical functionality, giving each feature a weighting to assist in selecting objectively. Each of the listed criteria had a level of importance/weighting placed on it [21]. The numbering scheme of 1 to 5 was utilised for simplicity, with “5” being most important and “1” being least important. Five design software programs were chosen to be used for the decision analysis matrix

Table 1: Software Selection Criteria & Evaluation

Software Evaluation Matrix			Dassault	Siemens	ARENA	SIMIO	SIMUL8
	Criteria	**Weight**	**Catia/Delmia**	**NX/Techno-matics**	**Arena Simulation**	**SIMIO**	**SIMUL8**
Software Features	**Critical functionality**		**46**	**66**	**53**	**96**	**100**
	Production plant simulation capabilities	**5**	2	3	3	5	5
	3D modelling and factory integration	**5**	3	4	3	4	5
	Important functionality						
	Ease of use and design	**5**	1	3	2	5	5
	Factory design function	**5**	2	2	2	4	4
	Nice-to-have functionality						
	Productivity features	**1**	1	1	1	5	4
	Industrial and mechanical design focus	**1**	5	5	2	1	1
			45	**36**	**36**	**42**	**51**
Vendor	Stability	**3**	3	2	3	4	5

	Size – Support staff	**3**	5	4	4	3	5
	Years in business	**3**	5	3	3	3	3
	Investment in R&D	**3**	2	3	2	4	4
Costs			**20**	**32**	**20**	**44**	**32**
	Software implementation	**4**	2	3	2	3	3
	TCO (Total Cost of Ownership, i.e. copyright, licensing, maintainability)	**4**	1	2	1	4	3
	Time to implement	**4**	2	3	2	4	2
Client Service and Support			**8**	**16**	**8**	**16**	**18**
	Experience and skill level	**2**	3	5	2	3	4
	Responsiveness	**2**	1	3	2	5	5
Technical			**48**	**68**	**40**	**72**	**80**
	Ability to customise functionality	**4**	1	3	2	4	4
	Data migration	**4**	1	2	2	2	3
	Ease of use	**4**	2	3	1	5	5
	Productivity features	**4**	3	4	2	4	3
	Security	**4**	5	5	3	3	5
Product Stability			**39**	**45**	**39**	**45**	**48**
	Uptime percentage	**3**	4	3	3	4	5
	Scalability	**3**	1	4	3	5	5
	Testability	**3**	4	4	3	3	3
	Documentation	**3**	4	4	4	3	3
Other			**4**	**4**	**2**	**4**	**3**
	User interfaces look and feel	**1**	4	4	2	4	3
Total Score			210	267	198	319	332
	Overall Ranking of software		4th	3rd	5th	2nd	**1st**

From Table 1 above, there are six main headings: Software features; Vendor costs; Client services and support; Technical; Product stability; and Other. Each of these has more detailed descriptive criteria which have been broken down into further detail and allocated a weighting of importance. For each software program a rating score was given based on an evaluation of the software's capability to perform the named criteria. The total score was calculated by multiplying the software's score against the weighting and adding up the score of each of the criteria individually to arrive at the grand total seen at the bottom.

4.3 Construction of the Simulation Model

The simulation process in simul8 was started by defining the simulated workday. The clock properties as set in SIMUL8 are displayed in Figure 2 below. A workday in this simulated production environment starts at 07:30 AM and stops at16:00 PM, with no overtime is considered in this model.

Figure 2: Clock Properties

The basic building blocks of a simulation model in Simul8 are displayed in Figure 3 below. These items are used in the development of simple and comprehensive simulation models. The start points control incoming work items, the queue acts as a buffer zone, processing of work items occurs at all activities and all completed work items are directed to the end point [23].

Figure 3: SIMUL8's Building Blocks

The simulated process consists of 30 activities, each having an individual processing time and required human resources, as displayed in Figure 4 below. The detailed processes in Figure 4 are those of processes that will be referred to in upcoming sections of this report. All activities requiring a set up and tear down time are split up in the simulation model. As an example, process 5 below will be split up as follows: 5.1. set up time, 5.2. Activity time and 5.3. Tear down time.

Steps	Processes	Time (Min)			Used Means		
		Set-up Time	Activity Time	Tear-down Time	Human Resources Required	Machine Resources	Batch Quantity
1	Process 1		5		Aero Technician		
2	Functional Test	2	10		Aero Technician		
3	Process 3		2		Aero Operator		
4	Process 4		2		Aero Operator		
5	Washing of PCBs	1,5	120	1	Aero Operator	Washing Machine	Min 1, Max 12, Multiples of 1
6	Process 6		2		Aero Operator		
7	Masking Curing		60		Aero Operator		
8	Certonal Coating		1		Aero Operator		
9	Masking Removal	2	2		Aero Technician		
10	Inspection		1		Aero Operator		
11	Process 11		3		Aero Operator		
12	Process 12		10		Aero Technician		
13	Process 13		1		Aero Technician		
14	Process 14	2,5	15,5		Aero Technician		
15	HASS test	24	120	6	Aero Technician	HASS Chamber 4 Part Jig	Min 1, Max 4, Multiples of 1
16	Vibration Test	18	10	4	Aero Technician	Vibration Chamber, 2 Part Mounting Plate	Min 1 Max 2, Multiples of 1
17	Process 17	2,5	15		Aero Technician		
18	Process 18		2		Aero Operator		
19	Process 19		1		Aero Technician		
20	Process 20		1,5		Aero Operator		
21	Process 21		1		Aero Operator		
22	Process 22		1		Aero Technician		
23	Process 23		2,5		Aero Technician		
24	Process 24		3,5		Aero Operator		
25	Process 25		1		Aero Technician		
26	Process 26		3		Aero Operator		
27	Process 27	2,5	18		Aero Technician		
28	Process 28	3	13,2		Aero Technician		
29	Process 29		10		Aero Operator		
30	Packing Documentation		2		Aero Technician		

Figure 4: Processing Information

The process consists of specific activities that are to be performed as a batch quantity. As per Figure 4 above, these batch quantities exist at activities 5, 15 and 16. In the model, these are set up using simu8's routing in option, which tells SIMUL8 how work items should be brought into each of the activities [23].

In Figure 5 below, the batching operation is applied to activity 5.2 which requires a batch of 12 units for processing. All work items will accumulate in the queue for 5.2 until all 12 have been collected for processing.

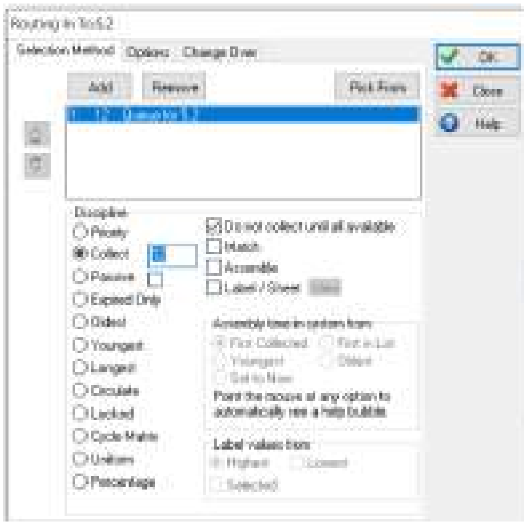

Figure 5: Routing in settings

5 FINDINGS AND DISCUSSIONS

The findings of the study are as follows:

5.1 Scenario 1: A traditional vs continuous batch layout

In a batch layout process, the raw materials are charged into the system at the beginning of the process, and the product is discharged all at once at the end. In contrast, products in a continuous flow layout are charged into and discharged from the system throughout the duration of the process, as displayed in Figure 6 below. [22]

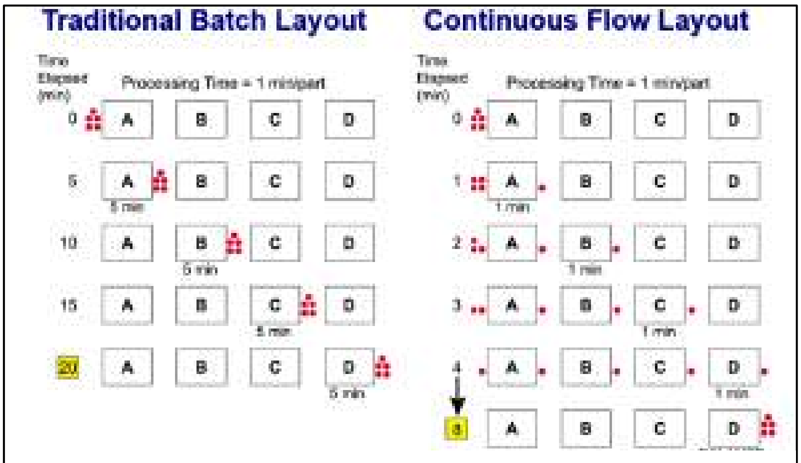

Figure 6: Traditional Batch vs Continuous Flow Layouts

Due to shared business resources, processes 5, 15, and 16 as shown in Figure 4, are intended to be completed in batches. Observations made on LINE C, however, indicated the existence of additional process steps that operators and technicians are carrying out as batching operations because they feel it will save them more time. These steps, which are shown in Table 2 below, do not have any unique resource needs that force them to be carried out as batching activities.

Table 2: Additional Batching Processes

Process	Process Description	Batch Size
2.1	Functional Test set up	12
7	Masking curing	12
8	Certonal coating	12
9	Masking removal	12
10	Inspection	12
30	Packaging documentation	12

Using Simul8, LINE C was modelled to view the impact these additional batching operations on the process. The first observation is that there is a build-up of work in progress in queues before the occurrence of each of these processes. Such WIP build ups are displayed in Figure 7and Figure 8 as snapshots of material flow before processes 2.1 and 7 respectively.

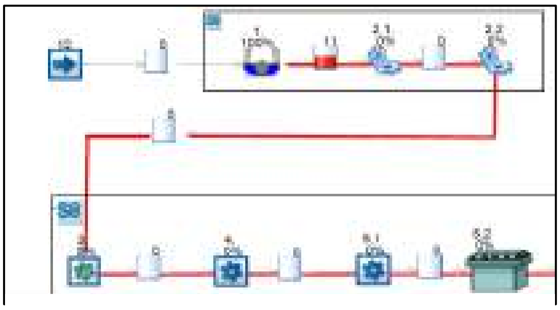

Figure 8: Snapshot of flow of materials at process 2.1

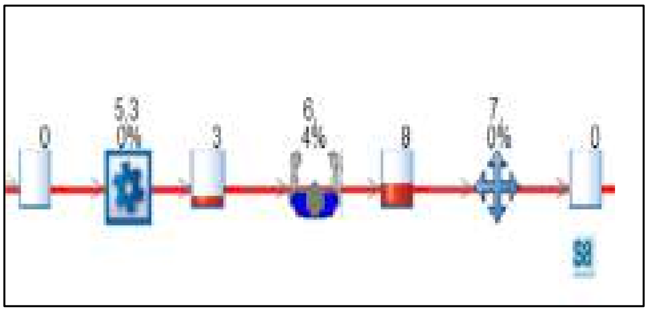

Figure 7: Snapshot of process leading to operation 7

Using a continuous flow layout, a different simulation model was created, eliminating the acquired batching processes described in Table 2 altogether. To ascertain the effects of batching the process time in the system, the results from the two simulation models are compared and displayed in Table 3 below:

Table 3: Effects of batching on process timing

	Batching applied	Continuous Flow	Time saved
Time In system	2003.337 Minutes	1440.16 Minutes	563.117 Minutes 9.39 hours
Process Completion Time	Thursday, 15:24PM	Wednesday, 14:31 PM	

5.2 Scenario 2: Change in shifts

Production in LINE C, operations are carried out by 2 technicians and 1 operator, each having a set of designated tasks. These human resources currently work under the same shift schedule, which is displayed in Table 4 below. Figure 9 is a simul8 generated Gannt chart displaying the different shifts in play, with machines having a full day shift from 07:30 am-16:00 pm.

Table 4: Current Working Shifts

CURRENT SHIFT SETTINGS				
Start	**End**	**Shift Names**	**Working**	**Total Time for A, B, C**
07:30 AM	10:00 AM	Morning Shift	A, B, C	02hrs: 30Min
10:00 AM	10:15 AM	Teatime	None	0
10:15 AM	12:30 PM	Post Tea Shift	A, B, C	02hrs: 15 Min

Key

A	Technician 1
B	Technician 2
C	Operator

12:30 AM	13:30 PM	Lunch Time	None	0
13:30 AM	16:00 PM	Post Lunch shift	A, B, C	02hrs:30 Min
				07hrs: 15 Min

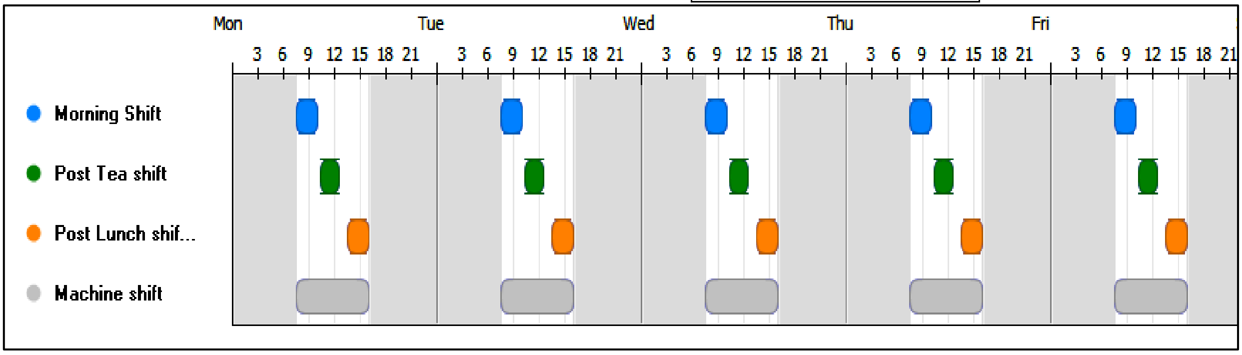

Figure 9:Working shifts Gannt Chart

From Table 4 above, we denote that there are no human resources available to carry out production operations for 75 minutes in a workday, where tasks are suspended until the next shift change.

In Figure 10 below, we find the process at 09:59am, before teatime. Process 5.1 which is to be completed with a batch of 12 parts using a washing machine resource, currently has a WIP of 11 parts with the 12th part still in processing at activity 2.2.

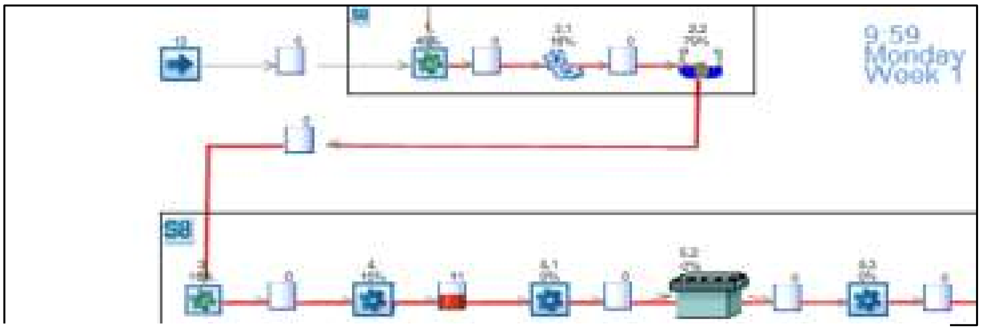

Figure 10: Effects of shifts on continuous flow

By 10:00 AM however, the process will stop due to human resource unavailability at teatime and production will resume at 10:15 AM. This production flow discontinuity leads to a longer throughput time and the underutilization of available machine resources, given that the 2 hour long washing operation at 5.2 could have started earlier if there was continuity.

LINE C was simulated with a proposed alternating shift pattern which allows production to continue during the previously idle 75 minutes. Table 5 below displays the proposed alternating shift schedule and required resources. In this scenario, there are 2 proposed alternating groups. Group 1 and 2, each containing 1 operator and technician respectively. This scenario proposes the addition of 1 operator to the current set of human resources being utilised.

Table 5: Proposed Shift Change

Start	End	Shift Names	Working	Group 1 Total Time	Group 2 Total Time
07:30	10:00	Morning A	Group 1 &2	02hrs:30 Min	02hrs:45 Min
10:00	10:15	Morning B	Group 2	Teatime	
10:15	10:30	Morning C	Group 1	01hrs: 45Min	Teatime
10:30	12:00	After Tea	Group 1&2		02hrs:30 Min
12:00	13:00	Lunch A	Group 2	Lunchtime	
13:00	14:00	Lunch B	Group 1	03hrs	Lunch Time
14:00	16:00	Last Shift	Group 1&2		02hrs
Total Production Time				07hrs:15Min	07hrs:15Min

Group 1	1 Technician
	1 Operator
Group 2	1 Technician
	1 Operator

Results for the process duration under the utilization of both shifts were collected and compared as presented in Table 6 below:

Table 6: Current Vs Proposed Schedule results

	Current Schedule	**Proposed Schedule**	Time saved
Minimum Time in system for 1 week	939.43 Minutes	792,992 Minutes	159.016 Minutes
Maximum Time in system 1 week	1440.16 Minutes	1281,144 Minutes	2.65 Hours
Process completion Time	Wednesday, 14:31 PM	Wednesday, 11:52 AM	
Technician Utilization	75,40%	66,61%	
Operator Utilization	61,46%	35,90%	

5.3 Scenario 3: Increased Capacities

LINE C utilises three main shared machine resources, namely the washing machine, HASS chamber, and the Vibration Chamber. These are resources additionally utilized for various products within the company. Simulation models are developed to analyse different ways in which the utilizations of these resources can be maximized. This is accomplished by simulating forecasted job orders over 1 week, 6 months and 12 months.

5.3.1 HASS Chamber

The jig design currently used for the HASS test is a 4-part jig, accommodating a batch of 4 to be processed at once. The process is simulated using a 6-part jig design and the critical results compared as per Table 7 below:

Table 7: HASS Testing Improvement Scenario Results

Simulated period	1 week		6 Months		12 Months	
Units simulated	12		288		576	
Jig design used	4-part Jig	6-part Jig	4-part Jig	6-part Jig	4-part Jig	6-part Jig
HASS Chamber utilization	34%	24%	22%	17%	21%	16%
Process completion Time	Wednesday 14:31Pm Week 1	Wednesday 14:59 Pm Week 1	Friday 11:10 am Week 22	Friday 11:20 am Week 22	Friday 11:58 am Week 46	Friday 11:28 am Week 46

With this suggested jig, the procedure may have a longer completion time, but the chamber's utilization is lower in all scenarios. Given that this chamber is shared resource between several manufacturing lines, this modification would be seen favourably as frees up the resource for usage on other items.

5.3.2 Vibration Chamber

The vibration chamber currently utilizes a 2-part mounting plate. The usage of a 4-part jig is simulated and results from both cases are compared as presented in Table 8 below:

Table 8: Vibration Testing Improvement Scenario Results

Simulated period	1 week		6 Months		12 Months	
Units simulated	12		288		576	
Jig design used	2- part jig	4-part jig	2- part jig	4-part jig	2- part jig	4-part jig
Vibration Chamber Utilization	14%	12%	10%	9%	9%	8%
Process completion Time	Wednesday 14:31Pm Week 1	Wednesday 14:38 pm Week 1	Friday 11:10 am Week 22	Friday 09:39 am Week 22	Friday 11:58 am Week 46	Friday 10:19 am Week 46

Simulated period	1 week		6 Months		12 Months	
Units simulated	12		288		576	
Jig design used	2- part jig	4-part jig	2- part jig	4-part jig	2- part jig	4-part jig
HASS Chamber utilization	14%	12%	10%	9%	9%	8%
Completion Time	Wednesday 14:28Pm Week 1	Wednesday 14:13pm Week 1	Friday 11:10 am Week 22	Friday 09:39 am Week 22	Friday 11:58 am Week 46	Friday 10:19 am Week 46

Simulated period	1 week		6 Months		12 Months	
Units simulated	12		288		576	
Jig design used	2- part jig	4-part jig	2- part jig	4-part jig	2- part jig	4-part jig
HASS Chamber utilization	14%	12%	10%	9%	9%	8%
Completion Time	Wednesday 14:28Pm Week 1	Wednesday 14:13pm Week 1	Friday 11:10 am Week 22	Friday 09:39 am Week 22	Friday 11:58 am Week 46	Friday 10:19 am Week 46

Simulated period	1 week		6 Months		12 Months	
Units simulated	12		288		576	
Jig design used	2- part jig	4-part jig	2- part jig	4-part jig	2- part jig	4-part jig
HASS Chamber utilization	14%	12%	10%	9%	9%	8%
Completion Time	Wednesday 14:28Pm Week 1	Wednesday 14:13pm Week 1	Friday 11:10 am Week 22	Friday 09:39 am Week 22	Friday 11:58 am Week 46	Friday 10:19 am Week 46

Simulated period	1 week		6 Months		12 Months	
Units simulated	12		288		576	
Jig design used	2- part jig	4-part jig	2- part jig	4-part jig	2- part jig	4-part jig
HASS Chamber utilization	14%	12%	10%	9%	9%	8%
Completion Time	Wednesday 14:28Pm Week 1	Wednesday 14:13pm Week 1	Friday 11:10 am Week 22	Friday 09:39 am Week 22	Friday 11:58 am Week 46	Friday 10:19 am Week 46

Testing this "What if" scenario reveals that the equipment's utilization is lower, and the process completion time is significantly lower on the longer simulations. This proposal's viability would need to be evaluated by looking at the costs involved and how they would affect the organisation.

5.3.3 PCB Washing Machine.

This washing machine is a single means equipment, with a 120-minute processing time. Having a single means equipment with a long processing time causes system backlogs. This proposed scenario is set to help the organisation determine the expected time save, should they venture in purchasing an additional washing machine with a shorter processing time. The process was simulated with a 60-minute processing time washing machine and the results are displayed in Table 9 below.

Table 9: Washing Machine Improvement Scenario Results

Simulated period	1 week		6 Months		12 Months	
Units simulated	12		288		576	
Process Duration	120 Min	60 Min	120 Min	60 Min	120 Min	60 Min
Washing Machine Utilization	10%	6%	7%	5%	7%	5%
Process Completion Time	Wednesday 14:31Pm Week 1	Wednesday 14:02 pm Week 1	Friday 11:10 am Week 22	Friday 10:29am Week 22	Friday 11:58 am Week 46	Friday 10:45 am Week 46

6 CONCLUSION & RECOMMENDATIONS

6.1 Conclusions

The scenarios tested above have presented Simul8's capabilities as a process optimization tool, enabling us to test the effects of continuity in production processes. Virtualisation and simulation's true power has been demonstrated in this research. It sets itself up to be utilised as a major driver for the change and integration of technology into the traditional systems in which manufacturers find themselves operating. This tool is a wonderful enabler to facilitate future design that suits managers, operators, workers and clients.

The accuracy of the SIMUL8 generated information was tested by comparing the current state process completion times for the above scenarios against real time durations from LINE C. These times which were generated by the simulation are in proximity and within tolerance.

The main findings can be summarised as follows: scenario 1 displays the benefits of continuity in production operations, with a 9.39 hour save in processing time, scenario 2 leveraged the change in shifts and yielded a saving of 2.65 hours per shift, which currently outperforms the current system, and lastly, a decrease in machine utilization and an overall decrease in processing time were experienced in scenario 3. Other major benefits included service orientation towards the clients, marketing flexibility increased as the product mixes could be varied.

Some barriers to implementation were the human factor of taking the worker lunch breaks together and building a comradery of a team good environment. The intangible impact of going on break with your work colleagues and having down time with them does have a positive impact on the teamwork.

Despite these negatives, this concept has the potential to reduce waste in human and machine environments. Implementing SIMUL8 as a tool into the planning approach has the ability to improve productivity if incorporated into the business processes of the managing of a factory. It has increased the connection between man, machine and information in the company. SIMUL8 potential can be harnessed by the increased communication between the shop-floor level and top management level, bringing an increased ability to integrate and synchronise the factory.

6.2 Recommendations

It is recommended that the proposed scenarios be tested for feasibility before their potential implementation into the organisation's operations. Other than the specific case, further research might explore real-time monitoring. For example, investigations could be made into sending prompts to the manager of the central business hub when an adjustment has been made, integrating the work traffic situation on the roads for travel time and route calculations.

- More information on scheduling adjustments would help establish a greater degree of accuracy with regard to production output and holding time calculations.
- More broadly, the real-time monitoring and status of all production lines would be invaluable: production outputs, expected targets, number of staff, productivity metric currently operating at, costs, among others, all in real time.

The area of security and privacy is another topic in need of further study. With the rise of the age of the Internet, there is bound to be cybercrime and theft of company information as that would be the future currency of the world. Ethical codes of conduct considerations and how this affects the people working in these facilities are needed. Considerably more work will need to be done to determine how the knowledge of workers can be upgraded alongside the machinery, with regard, for example, to skills level upgrades, rates of learning and development scores.

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SCOPING REVIEW – A ROADMAP TO THE SUCCESSFUL IMPLEMENTATION OF OUTSOURCING MAINTENANCE ACTIVITIES WITHIN THE SOUTH AFRICAN PULP AND PAPER INDUSTRY

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ABSTRACT

Outsourcing is a tool to realise the strategic intent of an organisation. Before outsourcing, the maintenance manager must know the factors, opportunities, and threats. The study aimed to perform a scoping review of these factors, opportunities and threats within the Pulp and Paper Industry. The review also aimed to understand maintenance outsourcing trends in South Africa. Scopus and Web of Science were used as databases to collect twenty-one articles. Using ATLAS.ti, eleven categories were coded in these articles, and Sankey diagrams were used to visualise the data. The results found strategy, supplier performance and employee impact to be critical factors. Cost reduction and access to vendor expertise were key opportunities, while poor supplier performance and loss of organisational know-how were key threats. Outsourcing was found to be common in Europe, Asia, and North America. An opportunity exists to explore the local context.

Keywords: Outsourcing, Maintenance, Pulp and Paper Industry

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1 INTRODUCTION

1.1 Background

South Africa is rich in mineral and natural resources. It is a developing country with several industries that contribute to the Gross Domestic Product (GDP). One of these industries is the Process and Manufacturing Industry. This industry is responsible for converting the country's resources into valuable end products. These end-products can be used to grow the country's economy or exported for income. Figure 1 below shows the relative contribution of the various industries to South Africa's GDP [1]. As can be seen from the diagram, the Process and Manufacturing Industry accounts for 14% of the South African GDP. As such, it is the fourth largest industry in the country. Shown in Figure 2 is the percentage contribution of each category within the Process and Manufacturing Industry. The Pulp and Paper industry (indicated as the wood products, paper, and printing category) accounts for 11% of the Process and Manufacturing Industry – a significant portion, fourth behind food and beverage, petrochemical and steel. The Pulp and Paper Industry is thus a key element of and contributor to South Africa's GDP.

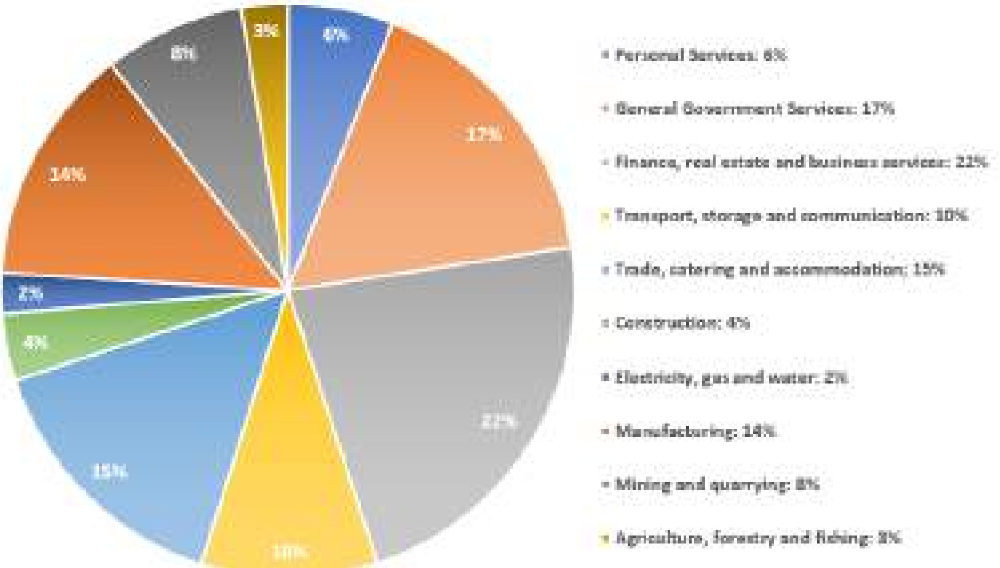


Figure 1: Relative contribution of the various industries to South Africa's GDP

Source: Statistics South Africa [1]

The Pulp and Paper industry contributes R18.2 billion to South Africa's economy. It employs over 750 000 people and exports over R9.35 billion worth of products [2], [3] and [4]. The industry faces several challenges, such as environmental legislation, restrictions on water use, labour, and transport costs [3]. Another challenge is the declining consumption of paper and paper-based products. With digitalisation, the demand for newspapers, magazines and other print media has declined by more than 1.57% year-on-year since 2014 [3]. According to Liu, et al. [5],the Covid-19 outbreak in 2019 momentarily increased the demand for personal hygiene paper products, food packaging products, corrugated packaging products and paper-based medicinal materials. This level of growth cannot be sustainable as the world returns to normality. The industry requires strategic interventions to ensure its sustainability and profitability.

Maintenance is a key lever in delivering the strategic business objectives of an organisation. It can lead to cost-effectiveness, profitability and overall asset reliability [6]. Several tools are available to deliver these strategic business objectives. One such tool is the outsourcing of maintenance activities within the business. Before the decision to outsource is made, careful consideration must be given to benefits, risks, and decision factors [7]. In addition, determining the type of maintenance activities to be outsourced must be considered to gain the most benefit from the decision to outsource.

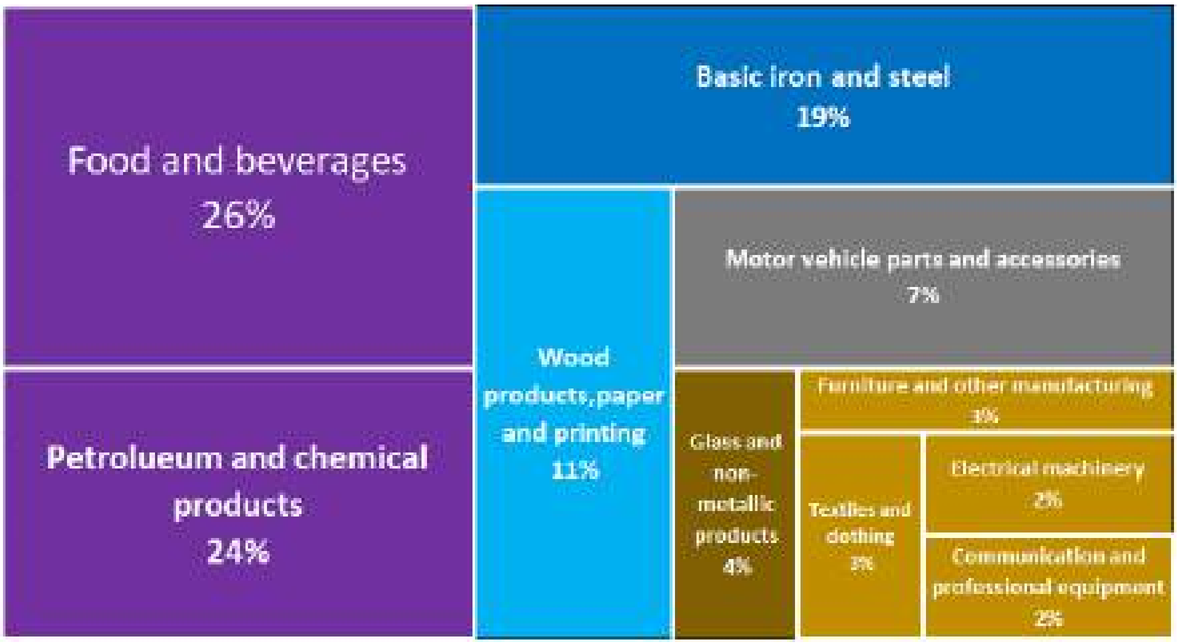


Figure 2: Contribution of categories in the Process and Manufacturing Industry

Source: Statistics South Africa [1]

Due to the large contribution of the pulp and paper industry to the South African economy, there is an opportunity to examine the present status of outsourcing within this industry. Preliminary findings indicate an increasing trend to outsource maintenance activities within the South African pulp and paper industry [8]. A scoping review of the existing literature was performed to determine and identify gaps for future research in this space. A scoping protocol as developed by Arksey [9] and Peters [10] was used for the scoping review. The protocol summarised consists of the following steps:

- Identify the research question
- Identify the relevant studies
- Study selection
- Charting the data
- Collating, summarising, and reporting the results

1.2 Objective

The objective of this scoping review was to review the published research, analyse the existing work and identify gaps in the literature. This will be used to determine the opportunities and threats that influence the maintenance outsourcing decision. The data can further be used to determine trends, differences and similarities between the pulp and paper industry and other processing industries.

1.3 Review Questions

The Joanna Briggs Institute [10] suggests that the review question(s) assist in developing the scoping review protocol, facilitate effective literature search, and provide structure for the review report. In addition, the review question(s) must include elements of PCC (Population, Concept, Context) to provide the reader with important information about the scope and focus of the review. To this end, the following review questions were formulated:

- What are the factors to consider when making the decision to outsource maintenance activities?
- What are the opportunities and threats to outsourcing maintenance activities?
- What maintenance activities have been outsourced in the Pulp and Paper industry?

2 REVIEW METHODOLOGY

2.1 Search Strategy

The literature on outsourcing maintenance activities in various industries is well-developed. A preliminary search in the Scopus database for "Maintenance Outsource" revealed 7270 documents. Research output has increased from 1 document in the year 1991 to 672 in the year 2020. A refined search to include "Pulp and Paper Industry" returned only 91 documents. Many of the papers were maintenance outsourcing research based in the Swedish and Finnish Pulp and Paper Industry. Therefore, an opportunity exists to explore the outsourcing of maintenance within the context of the South African Pulp and Paper Industry.

An initial search was done using keywords and key phrases relevant to the research topic. The keywords and phrases were *"outsourcing," "maintenance outsourcing,"* and *"pulp and paper industry."* The two databases utilised for the search were Scopus and Web of Science. These two databases contain high-quality peer-reviewed journal articles for the purposes of academic research [11]. After the initial selection, the Boolean operators AND, OR were used to refine the search results to a manageable level for further screening and selection. Specific syntax must be used to obtain the correct results, as shown in Table 1 below. The results of the initial search, with the refined search using Boolean operators, are shown in Table 2.

Table 1: Search strategy syntax in Web of Science and Scopus

Database	Syntax
Web of Science	TS= (*maintenance outsource* AND *pulp and paper industry*)
Scopus*	TITLE-ABS-KEY ("*maintenance outsourcing*" OR "*pulp paper industry*")

*Note: In Scopus, if you are searching for a phrase which contains the word "*and*," omit the word "*and*" from your search string. For example, "*pulp paper industry*" will find the phrase "*pulp and paper industry.*"

Table 2: Search strategy results from selected databases

Key phrase	Web of Science	Scopus
Outsourcing	30 824	29 456
Maintenance outsourcing	1 227	1 299
Pulp and paper industry	30 177	36 628
Maintenance outsourcing AND *pulp and paper industry* *Maintenance outsourcing* OR *pulp paper industry*	2	453

2.2 Inclusion and Exclusion Criteria

The following criteria were used to reduce the number of documents to a manageable level for further screening and selection:

Inclusions

- Previous masters and doctoral theses
- Studies that describe the benefits and risks of maintenance outsourcing
- Studies that describe outsourcing in the pulp and paper industry
- Studies that describe outsourcing in a processing industry and/or environment
- Previous scoping reviews

Exclusions

- Articles not relevant to the research questions
- Research not published in English
- Duplicates from the two databases
- Research published before the year 2002 (i.e., research older than 20 years)
- Studies on outsourcing in activities other than maintenance (i.e., IT, software, HR, mining, automotive).
- Documents that could not be downloaded as PDF

2.3 Screening and Selection

The raw data from Scopus and Web of Science was exported to Microsoft Excel® for screening and selection. The screening and selection processes are based on the inclusion and exclusion criteria described in Section 2.2 above. Table 3 and Table 4 as shown in Appendix A shows the results of the screening and selection. The process from initial search to final selection is charted in the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) chart shown in Figure 3 below [12], [13].

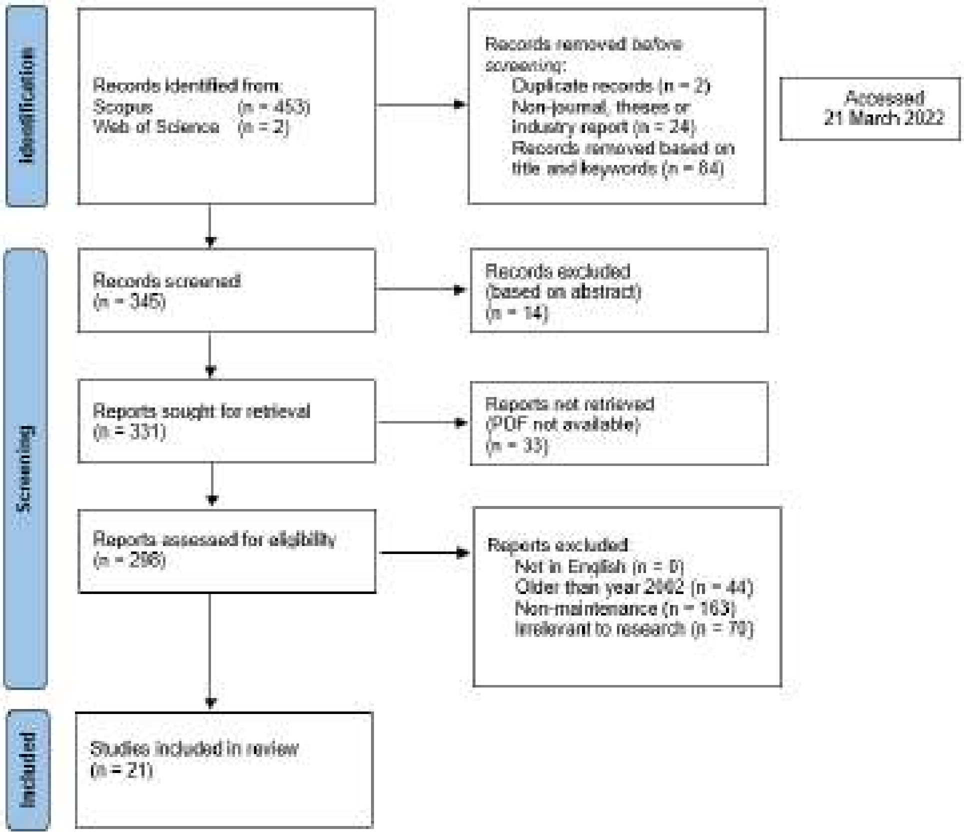


Figure 3: PRISMA flow diagram for search strategy

2.4 Year of Publication

A review of the 21 articles reveals that the output of outsourcing literature has been steady over the years. Certain years have seen an increased output, particularly in 2018, 2014 and 2009. This confirms that outsourcing is a mature subject in several fields.

2.5 Country of origin

Based on the reviewed documents, the United States of America (USA) is the highest research contributor. This is expected, as the USA is the world's largest pulp and paper producer [14]. Finland produced several research papers. This is due to the large forest footprint in the Scandinavian area. Finland has a highly developed pulp and paper industry, with several original equipment manufacturers (OEM's) in the area. South Africa is the largest pulp and paper producer in Africa and rated 11th in the world. There is still, however, the opportunity to build on the body of knowledge on outsourcing in the South African context.

2.6 Document sources and document types

18 of the 21 documents obtained were journal articles. These documents were from high-quality journals such as the *Supply Chain Management* and the *International Journal of Quality Management*. Four documents were obtained from industry reports and masters/doctoral theses. These offer a more practical perspective as compared to journal articles. Three documents were obtained as book sections. This provided a more theoretical framework for outsourcing and was useful in the research.

2.7 Key concept and relevant research identification

Qualitative research methods involve non-numerical data collection followed by an explanation based on the attributes of the data. Qualitative research helps build an understanding of how and why certain outcomes were achieved. Content analysis is a research method used to identify patterns and themes within qualitative data. This approach involves systematically coding and categorising specific aspects of content in textual data. The intent is to uncover trends and patterns. This is done by quantifying the frequencies and patterns of words present in the textual data [15].

The software program ATLAS.ti was used for the content analysis of the textual data. The 21 research articles were imported into ATLAS.ti. Important information from each article was highlighted as a "quotation", and these quotations were then categorised into eleven codes. These codes were further analysed to draw conclusions. Sankey diagrams were used to visualise the information. A Sankey diagram is a visualisation tool used to depict flow from one set of information to another. The items being connected are called nodes and the connections are called links. The thicker the width of the link, the stronger the relationship between the nodes. In this context, the Sankey diagrams were used to determine the importance of a maintenance outsourcing factor, threat or opportunity [16].

3 RESULTS

3.1 Factors in making the decision to outsource

The literature identified seven (7) key factors when deciding to outsource. Documents that discussed factors, motivations or selection criteria were coded in ATLAS.ti. These were then placed in the code groups "factors" and "selection criteria." ATLAS.ti then determines the number of times the specific code group appears in all 21 documents. The frequency of the code group was then calculated as a percentage for each factor. This is shown in Figure 4(a). The Sankey diagram, as shown in Figure 4(b), represents the information in Figure 4(a). The thickness of the line between the code group on the left and individual factors on the right indicates the strength of the factor. A thicker line indicates that the literature deems that factor to be more important.

Based on the results, strategy, supplier performance, and employee impact are the most important factors when making the decision to outsource. According to Quinn [17], managers can leverage their company's skills and resources for increased competitiveness by concentrating the firm's resources on a set of core competencies and strategically outsourcing those activities for which the firm has neither critical need nor special capability. Quinn [17] argues that strategic outsourcing has four benefits:

- Maximise the efforts of internal resources by focusing on what the firm does best. This is the firm's core competence.
- A well-developed core competence is a barrier to competitors seeking entry into the same market.
- Leverage the expertise of external suppliers. Expertise that would otherwise not be available internally in the firm.
- Improved response to changes in markets, technological developments, and customer needs.

Quinn [17] gives an example of strategic outsourcing which allowed the American company Nike to achieve a compounded growth rate of 30%, and an increase in return on equity to shareholders by 20%. Using examples from the manufacture of highly engineered products in the Cummins engine, Venkatesan [18] describes three principles consistent with making strategic outsourcing decisions:

- Focus on critical components that the company is good at making.
- Outsource components that other companies can manufacture well, cost-effectively and in large quantities.
- Use outsourcing to encourage employee commitment to improve the quality of manufactured products.

Because maintenance is a key and critical lever to delivering business outcomes [6], it forms part of the firm's core competence and should not be completely outsourced. Certain elements of maintenance, such as corrective maintenance, as described by Gómez [19] can be outsourced to service providers that have developed capability for specific equipment. Not all activities can and should be outsourced. Those activities that are inextricably linked to the organisation's business processes should not be outsourced. This can cause serious organisational disruptions, as explained by Shaomin [20] and Fernandez, et al. [21].

In terms of supplier performance Singgih, et al. [22] developed a model to assess the performance of a maintenance outsourcing provider in the private healthcare industry. This model is based on the fact that the service provider needs to satisfy certain criteria in order to be deemed well-performing. Criteria include dependability, flexibility, service quality, cost, turn-around time, contractual relationship, flexibility in billing, knowledge sharing, equipment types, firm capacity, technician skill, administration, diagnostic accuracy, part availability, routine reporting, clarity, and attitude.

While Singgih, et al. [22] apply these criteria specifically to the private healthcare industry, these can be generalised and useful in other industries, including the pulp and paper industry.

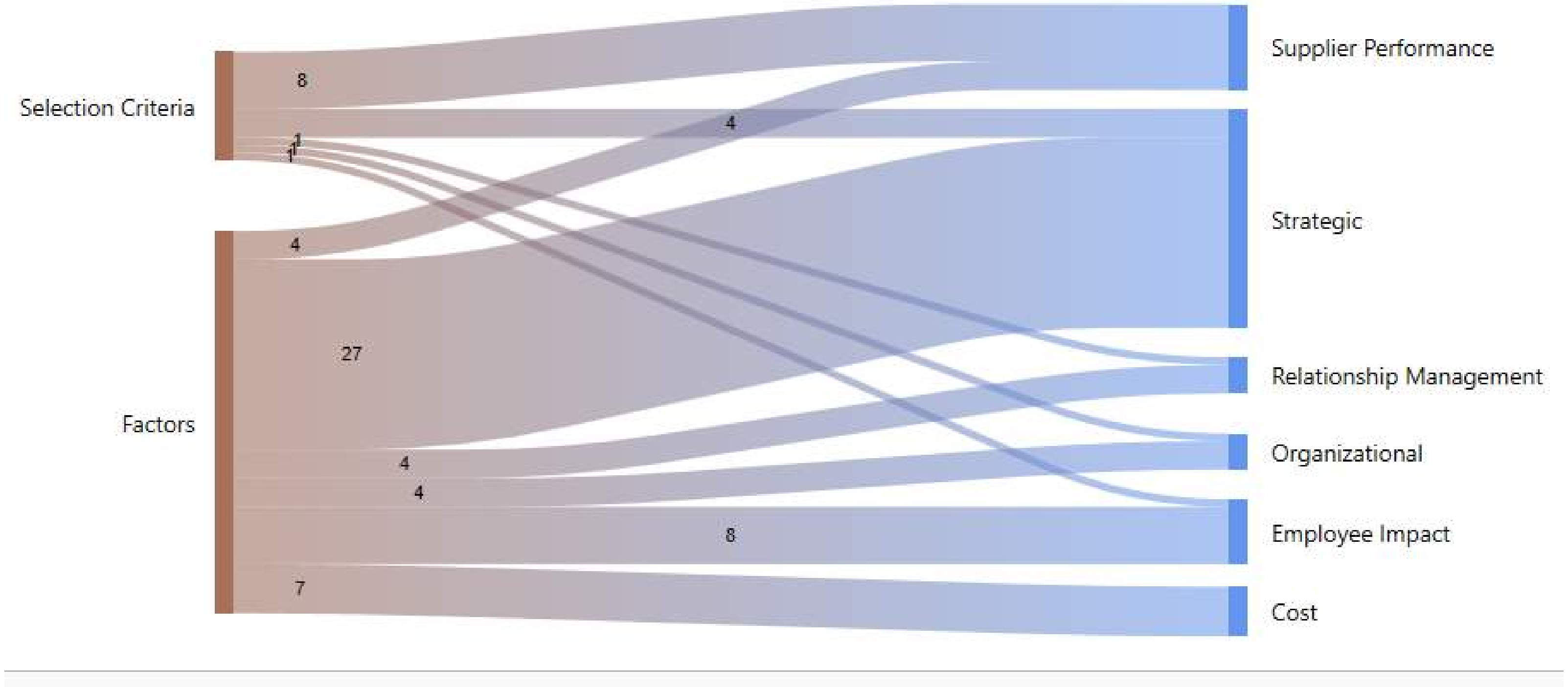
It is critical that a significant change, such as outsourcing a maintenance activity, is well communicated to existing staff. According to Bertolini, et al. [23], a company must evaluate if it is ready to outsource by reviewing its employee structure, personnel capabilities, and how they might respond to this change. While the authors of this study are based in Italy, the principle is universally applicable and is especially important in the South African context, which has a highly unionised employee workforce. Kessler, et al. [24] explored employee responses to outsourcing along three dimensions:

- Treatment by the existing employer during the outsourcing process.
- Are there attractive employment prospects with the new employer.
- Treatment once the outsourcing process has been finalised.

Thus, managers must be sensitive to the impact that the decision to outsource may have on employees, and this impact is treated with sensitivity.

	Cost		Employee Impact		Maintenance Activity Type		Organizational		Relationship Management		Strategic		Supplier Performance		Totals	
Factors	7	13%	8	15%	0	0%	4	7%	4	7%	27	50%	4	7%	54	100%
Selection Criteria	0	0%	1	7%	0	0%	1	7%	1	7%	4	27%	8	53%	15	100%
Totals	7	10%	9	13%	0	0%	5	7%	5	7%	31	45%	12	17%	69	100%

(a)



(b)

Figure 4: Normalized results(a) and Sankey diagram(b) of outsourcing factors

3.2 Opportunities and threats to outsourcing

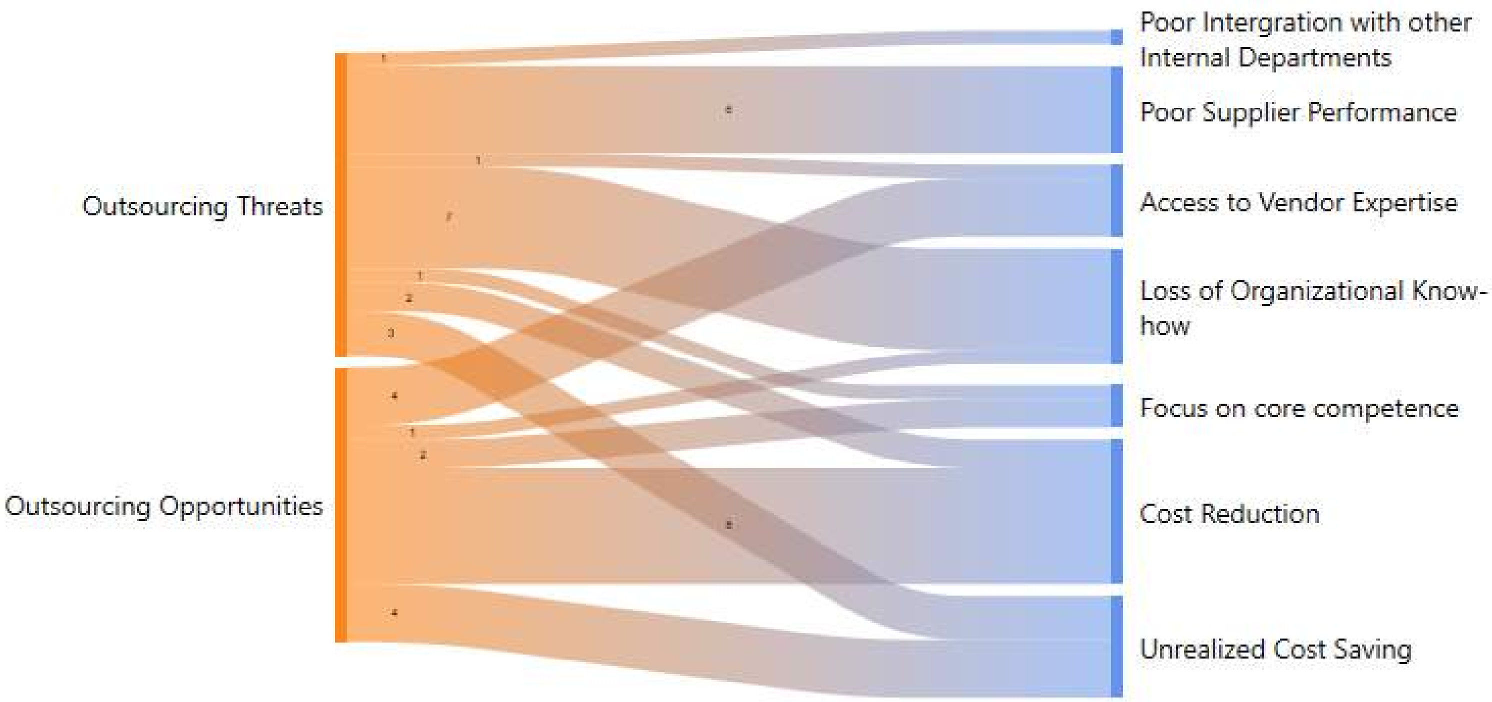
The literature identified four (4) main opportunities and four (4) main threats to outsourcing. Figure 5 (a) and (b) show the analysis using ATLAS.ti found “access to vendor expertise” and “cost reduction” to be key opportunities to outsourcing. “Poor supplier performance,” “loss of organisational know-how “and “unrealised cost savings” were the key threats when outsourcing. Kremic [7] provides a detailed account from various literature sources on the opportunities and threats to outsourcing. From a cost point of view, the first reason often cited for the outsourcing decision is to save money [25]. Economies of scale and access to specialised services are used to achieve this cost saving. In addition, fewer employees mean less infrastructure and support systems. There is also an opportunity to transfer fixed costs into variable costs, thus enabling a company to achieve better cost control. Now, while firms may save costs by outsourcing, there is a threat of unrealised cost reduction. Indirect costs may include monitoring the outsourced activity, drawing up contracts, and onboarding the service provider.

Significant time and capital may be spent in developing the relationship with the service provider. In addition, the social costs such as low morale, absenteeism and lower productivity are often intangible and difficult to quantity [7]. As such, firms risk not realising the benefit of outsourcing as intended.

Another reason often cited for outsourcing is access to vendor expertise. Maintenance is a complex field. As such, outsourcing to firms with the required specific knowledge is logical. According to Belcourt [25], one must “outsource when somebody else can do it better than you.” The use of expert knowledge reduces risks and liabilities to the firm. Experts have detailed knowledge of the equipment and systems and can assure the firm that any maintenance work done will be executed to high standards and comply with legislation. In addition, well-developed experts have access to the latest technology, innovation and best practices which can be applied to the firm. While access to vendor expertise is a great benefit, the opposite applies. Employees that move to the outsourced company take the tacit knowledge gained over many years of experience. This is particularly applicable where the activity that will be outsourced is highly integrated with other functions within the firm. Pulp and paper mills are vertically integrated, and maintenance is inextricably linked with operations. Outsourcing the incorrect maintenance activity will lead to a loss of company-specific knowledge of critical assets and equipment for which the mill has a competitive advantage. As such, the mill may lose its core competence. Managers should be wary of this threat when outsourcing certain maintenance activities.

	Access to Vendor Expertise		Cost Reduction		Focus on core competence		Improved Flexibility		Loss of Organizational Know-how		Poor Intergration with other Internal Departments		Poor Supplier Performance		Unrealized Cost Saving		Totals	
Outsourcing Opportunities	4	21%	8	42%	2	11%	0	0%	1	5%	0	0%	0	0%	4	21%	19	100%
Outsourcing Threats	1	5%	2	10%	1	5%	0	0%	7	33%	1	5%	6	29%	3	14%	21	100%
Totals	5	13%	10	25%	3	8%	0	0%	8	20%	1	3%	6	15%	7	17%	40	100%

(a)



(b)

Figure 5: Normalized results(a) and Sankey diagram(b) of opportunities and threats

[194]-11

3.3 Maintenance outsourcing in the Pulp and Paper Industry

The literature on maintenance outsourcing in several industries is well-developed. This ranges from the mining industry, facilities management, petrochemical industry, aviation industry and various public sectors [26], [27], [28], [29], [30] and [31].

This section will detail maintenance outsourcing trends in both the global and local context.

Considering international trends [32], Pulli [33] describes how Finnish pulp and paper industry maintenance activities could be outsourced to Vietnamese firms. Vietnam has a large pool of highly skilled young professionals at a discounted rate when compared to Finland. Pulli [33] argues that outsourcing certain activities could be mutually beneficial to both countries – Finland would have access to skilled labour at a discounted price, and Vietnam would benefit from the economic injection of foreign currency into the local economy. Argul [34] presents the factors that have led to the decline of the pulp and paper industry in the state of Maine in the United States of America and the steps required to restore the industry to its former glory. While the thesis does not cover outsourcing directly, it does give an account of how significant a pulp and paper mill can be to its surrounding community and how important it is to ensure mills are sustainable for future generations. Outsourcing is one such strategic lever that can be used to restore struggling organisations. Henderson [35] covers the five levels of outsourced maintenance, performance requirements, and the changes to be made by the supplier with reference to the Australian pulp and paper industry. The paper covers what type of maintenance activities should be outsourced and the level of competence required by the supplier to effectively execute the outsourced maintenance activity. To produce results, suppliers must invest in maintenance management as their core competence, while the firm must be willing to develop a partnership with the service provider.

Considering the local context, Pogue [3] covers the economic and socio-political trends in the South African pulp and paper industry. He focuses primarily on the need for skills development to propel the industry into the future. Summers and Visser [36] investigated the factors influencing the decision to outsource maintenance activities in the process industry and shed light on the perceptions around maintenance outsourcing in the South African context. The processing industry includes mining, petrochemical, pulp and paper, manufacturing, textiles and food and beverage.

The Broad-Based Black Economic Empowerment (BBBEE) Act was enacted in 2003. It aimed to address the participation of previously disadvantaged individuals in the South African economy. All organisations – including those in the pulp and paper industry - must comply with this Act. Mncube [37] describes how outsourcing maintenance activities could assist the Forestry division of SAPPI [38] to comply with the Codes of Good Practice of the BBBEE Act. Ngcobo [39] studied the socio-economic impact of outsourcing – amongst other activities – mechanical services within the Forestry division of Mondi. Ngcobo [39] found that outsourcing had negative impacts on the community. It resulted in increased unemployment, lower morale, and higher rates of insecurity amongst the community and employees. The community perceived outsourcing as the root cause of the poor relationship between rural communities, Mondi [40] and contractors. This is in line with van Niekerk and Visser [41], who advocate the importance of relationship management to ensure the successful outsourcing of maintenance activities.

3.4 Summary

The literature results provided factors, opportunities, threats, and examples of maintenance outsourcing in the pulp and paper industry. A careful analysis of what it would cost, the impact on employees, the structure and maturity level of the organisation, and strategic intent were key factors to consider that were found in the literature. A cost reduction should not be seen as the only benefit, and the literature identified several opportunities for outsourcing maintenance. These included access to vendor expertise, increased focus on core competence and improved flexibility. The literature found that there may be unrealised cost reduction if the decision to outsource is not carried out well. In addition, loss of company know-how, poor integration and poor performance were significant threats. The maintenance manager must be aware of these threats and opportunities before deciding to outsource.

The results illustrated how outsourcing to Vietnamese companies in the Finnish pulp and paper industry could benefit both countries. It discussed the levels of maintenance that could be outsourced in the Australian pulp and paper industry and revealed the impact of a paper mill on the surrounding economy as seen in the state of Maine in the USA. Outsourcing in various industries in South Africa is well-developed. However, the literature found the maintenance outsourcing body of knowledge in the pulp and paper industry to be limited. There is an opportunity to add to this body of knowledge.

The result answered all three review questions and revealed gaps that may be industry specific for further research.

4 CONCLUSION

The scoping review provided factors, opportunities, threats, and examples of maintenance outsourcing in the pulp and paper industry. The literature identified seven (7) key factors when deciding to outsource. Strategy, supplier performance and employee impact were the most critical of these deciding factors. In addition, there are four (4) main threats and four (4) main opportunities to the outsourcing decision. Cost reduction was seen to be the most important opportunity, while loss of organisational knowledge was seen to be the greatest threat. The results answered all three review questions. In addition, it revealed a gap in literature in terms of outsourcing maintenance activities in the pulp and paper industry within the South African context.

It is recommended to solicit the views of maintenance managers in the processing and pulp and paper industry using the Delphi technique. This process could be used to identify the potential threats, opportunities and factors considering the local context. Once this has been identified, actions can be identified to implement the outsourcing decision. A roadmap could be developed to determine the enablers for successfully implementing the outsourcing decision.

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APPENDIX A – RESULTS FOR SCREENING AND SELECTION

Table 3: Screening and selection results in Scopus and Web of Science

				Exclusion Criteria							
Title	Year	Cited by	Document Type	Duplicate	Jounal/Report/Theses	English	Older than 2002	Relevant keyword	Relevant abstract	Relevant research	PDF available
The role of outsourcing in the innovative activity development of food manufacturing plants	2021		Conference Paper	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Critical factors in selection of offshore software maintenance outsourcing vendor: A systematic literature review	2020		Article	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Managing safety risks in airline maintenance outsourcing	2020	4	Article	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Outsourcing selective maintenance problem in failure prone multi-component systems	2018	2	Conference Paper	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Performance modelling for maintenance outsourcing providers based on the Kano model	2018	1	Article	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Maintenance outsourcing as joint venture: Partnership between building and industrial service provider Caverion and the pulp company Metsä Fibre [Maintenance outsourcing als joint venture: Partnerschaft zwischen dem Gebäude- und industriedienstleister caverion und dem zellstoffunternehmen metsä fibre]	2017		Short Survey	No	No	Yes	No	Yes	Yes	Yes	Yes
A model for outsourcing and governing of maintenance within the process industry	2017	5	Article	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Maintenance outsourcing contracts based on bargaining theory	2017	3	Book Chapter	No	No	Yes	No	Yes	Yes	Yes	Yes
The state of Maine's pulp & paper industry	2016		Article	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Research on power system communication operation and maintenance outsourcing model	2014	1	Conference Paper	No	Yes	Yes	No	Yes	Yes	Yes	Yes
A decision-making framework to integrate maintenance contract conditions with critical spares management	2014	25	Article	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Outsourcing versus in-house maintenance of medical devices: A longitudinal, empirical study	2014	4	Article	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Slow to learn: Regulatory oversight of the safety of outsourced aircraft maintenance in the USA	2014	7	Article	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Assessing maintenance contracts when preventive maintenance is outsourced	2012	21	Article	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Understanding the use value dimensions of outsourced maintenance services	2010		Conference Paper	No	Yes	Yes	No	Yes	Yes	Yes	Yes
The role of relationship management in the successful outsourcing of maintenance	2010	4	Article	No	Yes	Yes	No	Yes	Yes	Yes	Yes
Outsourcing maintenance in services providers	2009	21	Conference Paper	No	Yes	Yes	No	Yes	Yes	Yes	Yes
The performance and trend for Russian and world markets of wood and pulp & paper industries	2007		Review	No	Yes	Yes	No	Yes	Yes	Yes	Yes
The challenges facing the Australasian pulp & paper industry	2005		Review	No	Yes	Yes	No	Yes	Yes	Yes	Yes
An analytical method for maintenance outsourcing service selection	2004	56	Article	No	Yes	Yes	No	Yes	Yes	Yes	Yes
A decision-making tool for optimizing pulp and paper mill operations	2003		Conference Paper	No	Yes	Yes	No	Yes	Yes	Yes	Yes

Table 4: Summary of documents for further analysis

Document	Year	Country	Source	Source Description
The role of outsourcing in the innovative activity development of food manufacturing plants	*2020*	*Russia*	Journal	Earth and Environmental Science
Managing Safety Risks in Airline Maintenance Outsourcing	*2020*	*USA*	Journal	International Journal of Aviation, Aeronautics, and Aerospace
Outsourcing selective maintenance problem in failure prone multi-component systems	*2018*	*France*	Journal	International Federation of Automatic Control)
Performance modelling for maintenance outsourcing providers based on the Kano model	*2018*	*Indonesia*	Journal	International Journal of Technology
Maintenance outsourcing as joint venture - Partnership between Caverion and Metsä Fibre	*2016*	*Finland*	Thesis	Lappeenranta University of Technology
A model for outsourcing and governing of maintenance within the process industry	*2017*	*Sweden*	Journal	Operations Management Research
Past Present and Future of Maines Pulp and Paper Industry	*2018*	*USA*	Thesis	University of Maine
A decision-making framework to integrate maintenance contracts with critical spares management	*2014*	*Australia*	Journal	Reliability Engineering and System Safety
Outsourcing versus in-house maintenance of medical devices - A longitudinal, empirical study	*2014*	*Columbia*	Journal	Pan American Journal of Public Health
Slow to learn - Regulatory oversight of the safety of outsourced aircraft maintenance in the USA	*2014*	*Australia*	Journal	Policy and Practice in Health and Safety
Assessing maintenance contracts when preventive maintenance is outsourced	*2012*	*UK*	Journal	Reliability Engineering and System Safety,
Understanding the use value dimensions of outsourced maintenance services	*2010*	*Italy*	Conference	International Conference on Advances in Production Management Systems
Factors that influence the decision to outsource maintenance in the process industry	*2021*	*South Africa*	Journal	South African Journal of Industrial Engineering
Outsourcing maintenance in services providers	*2009*	*Spain*	Book	Safety, Reliability and Risk Analysis: Theory, Methods and
Markets and Market Forces for Pulp and Paper Products	*2013*	*Finland*	Book	The Global Forest Sector
Maintenance outsourcing contracts based on bargaining theory	*2017*	*USA*	Journal	Optimisation and Dynamics with Their Applications
An analytical method for maintenance outsourcing service selection	*2004*	*Italy*	Journal	International Journal of Quality & Reliability Management
Outsourcing to Vietnameses market in paper industry	*2018*	*Finland*	Thesis	Hame University of Applied Sciences
Five levels of outsourcing operations and maintenance in the pulp and paper industry	*2000*	*USA*	Conference	2000 Annual Pulp and Paper Industry Technical Conference
Advantages and Disadvantages of Maintenance Outsourcing in manufacturing -special reference to Jubail	*2015*	*Saudia Arabia*	Journal	European Journal of Business and Management
Success Factors for Software Development Outsourcing Vendors - A Systematic Literature Review	*2009*	*Pakistan*	Conference	2009 Fourth IEEE International Conference on Global Software Engineering
Outsourcing decision support - a survey of benefits, risks and decision factors	*2006*	*USA*	Journal	Supply Chain Management
A Profile of the Paper and Pulp Sub-Sector	*2014*	*South Africa*	Report	Fibre Processing and Manufacturing Sector Education and Training Authority

LOW-COST ACCURACY ENHANCEMENT OF MACHINE TOOLS USING ARTIFICIAL INTELLIGENCE AND THEORETICAL-BASED ERROR MODELS

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ABSTRACT

The production of high-precision components is a critical requirement for stakeholders in the automotive, automation, aeronautical, and manufacturing industries. Consequently, improving the accuracy of machine tools is fundamental to enhancing the quality of these components. This study analyses the effectiveness of reducing machine errors, at a low cost, to enhance the accuracy of machine tools, which plays a role in increasing production output, reducing post-processing of workpieces, and lowering material wastage. To reduce these errors, compensation values generated by a neural network and geometric error model are used to adjust the servo-controlled positions in the numerical control program. More specifically, an Ant Colony Optimisation and Backpropagation hybrid neural network and product of exponential theory geometric error model are used as compensation strategies. The geometric and planar positioning errors are identified using machining tests and laser interferometry techniques. Lastly, a quantitative, comparative analysis is performed to validate the efficacy of both error models.

Keywords: machine tools, neural network, geometric errors, ant colony optimisation

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1 INTRODUCTION

The performance of machine tools is incontrovertibly linked to their precision, which serves as a quantitative measure of their overall aptness for a given application. Ergo, the enhancement of machine tool accuracy diversifies the scope of manufacturing applications [1], curtails material wastage, improves productivity [1], [2], reduces production costs [3], and minimises environmental impact [3], [4]. This offers machine tool stakeholders an incentive to pursue the development and implementation of precision-enhancing techniques. Moreover, In the year 2021, following the global pandemic, there was a notable increase of approximately 20% in the acquisition of machine tools [5]. This widespread escalation in machine tool utilisation underscores the imperative for producing increasingly dependable machinery to meet the heightened demand.

A facet of that dependability resides in the machine's capacity to yield precise three-dimensional workpieces, which is a significant performance criterion in modern manufacturing [6]. Conventionally, the capacity of a CNC machine to yield accurate parts has been impeded by a spectrum of inherent and external effects, comprising four broad constituents: thermal error (40%), geometric error (25%), control system error (15%), and cutting force-induced error (20%) [7]. A significant majority, exceeding 50%, of modern CNC machines incorporate compensation models that address a subgroup or even the entirety of the aforementioned errors [6]. Therefore, the pertinence of error mitigation is concomitant with the progression of the technology. Particularly in the case of software-based error compensation which can be performed at a lower cost than mechanical improvements [8].

Accordingly, this paper provides an overview of methodologies for mitigating machine tool errors as a mechanism to enhance accuracy. This is accomplished through two distinct approaches that leverage the potential of artificial intelligence and mathematical error modelling techniques. Firstly, a brief outline of a theoretical geometric error modelling framework is presented. This framework combines a well-established kinematic model, specifically the product of exponential theory, with a Fourier series approach to effectively model individual geometric errors in three-axis machines. Secondly, an artificial intelligence error modelling framework, combining Ant Colony Optimisation (ACO) with Gradient Descent Optimisation (GDO) in a feedforward neural network, is summarised. Finally, the efficacy of the accuracy enhancement models is evaluated through a practical case study utilising a three-axis machine tool specifically designed for engraving operations within an educational setting.

2 BACKGROUND

Ultimately, the objective of an error model is to generate accurate predictions of a machine tool's error, encompassing either a distinct subgroup like geometric errors or a synthesis of errors manifested from the interplay of multiple error sources. It does this by formulating the nonideal behaviour of the machine through mathematical or computational modelling. Each approach maintains its distinctiveness: one engages in the iterative refinement of its observed understanding of the machine's behaviour to make predictions, while the other leverages constraining assumptions to encapsulate the machine's behaviour.

Thus, the purview of machine tool error research, particularly quasi-static geometric errors, has focused on analytical modelling techniques that relate the inherent nonconformities in the machine structure to the tool position. This has been done using rigid-body kinematics and homogeneous transformation matrices [9]–[15]. While most kinematic modelling techniques share a common application of homogeneous transformation matrices, the distinction lies in their respective definitions of how the nonideal behaviour exhibited by the machine components is propagated to the tool, and in the statistical representation of the measured individual geometric errors. Moreover, the modelling of the individual errors has been achieved through statistical regression and fitting techniques that assume a linear [15], polynomial [16], B-spline [17], or Fourier series [18] nature for these errors. Figure 1 provides a visual representation of the various facets integral to the process of geometric error modelling.

This research utilises the product of exponential theory kinematic model. It has been stated that product of exponential theory is more geometrically intuitive and there are fewer coordinate frame assignments, compared to the Denavit-Hartenberg approach [12]. Also, the model of product of exponential theory, proposed by Fu et al. [12], was an expansion of screw theory, thus it can be viewed as an updated approach. Furthermore, this study employs a Fourier series-based approach to characterise geometric errors for a three-axis machine. Distinct from previous studies, the assumption that all geometric errors exhibit quasi-periodic behaviour was utilised. Finally, the geometric errors were measured with a laser interferometer (direct measurement) over the entire working length of the x- and y-axis. Note, the z-axis geometric errors were not observable due to the size of the laser optics and the limited vertical stroke between the z-axis and the machine bed, hence they were neglected.

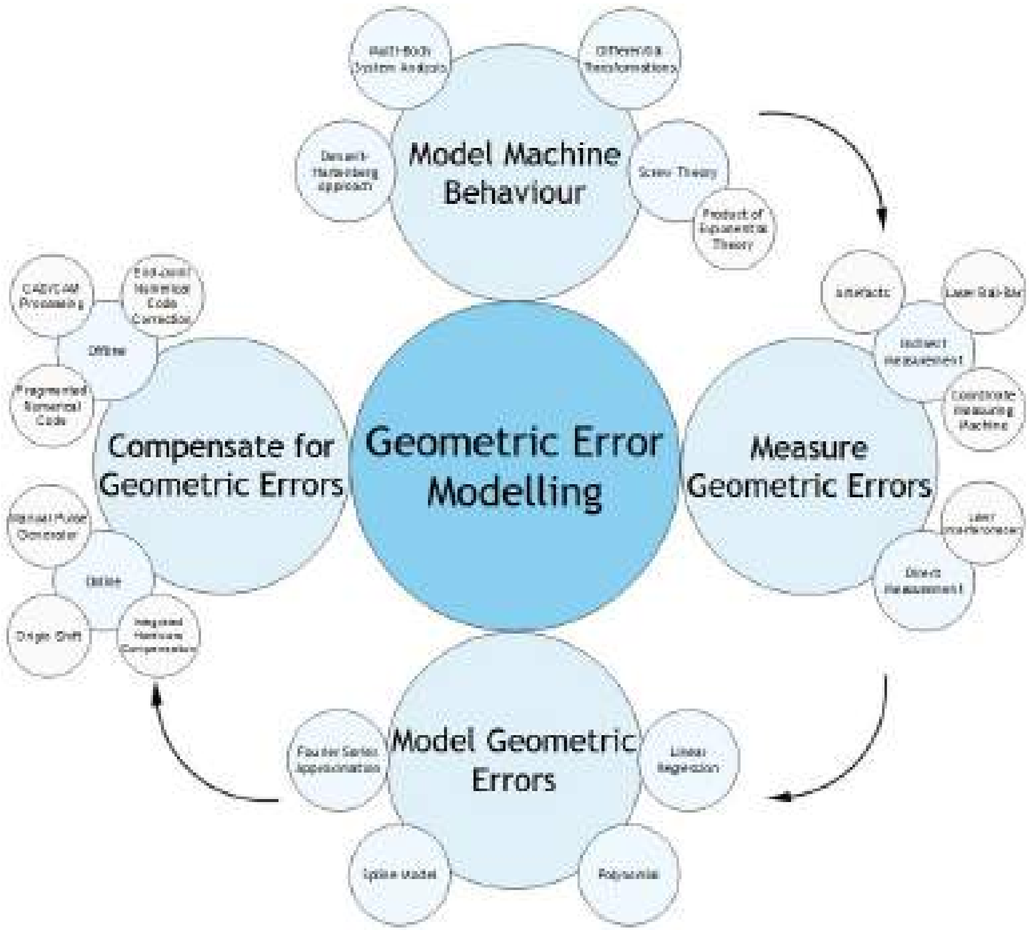

Figure 1:Geometric Error Modelling Process

In contrast to an analytical modelling approach, a subset of connectionist artificial intelligence known as a neural network has been used as a machine tool error function approximator. A neural network is a computational model that consists of an input, hidden, and output layer of interconnected artificial neurons (see Figure 2) [19], [20]. Unlike an analytical model, a neural network model uses training patterns to learn the underlying error function of the machine. The training data is a set of error-pertinent machine-related information e.g. tool position, feed rate, thermal conditions, spindle speed, etc. Classically, Gradient Descent

Optimisation (GDO) is used, in conjunction with supervised learning, to adjust the coefficients/weights of the neural network based on the back-propagation of an error signal [19]. The neural network's ability to nonlinearly map a machine tool error function hinges upon the iterative adjustment of these weights, driven by the evaluation of the neural network error signal, commonly referred to as the objective function. The error signal is the disparity between predicted and desired outputs, where the desired output represents the measured machine error. This iterative refinement process enables the network to progressively enhance its predictive capability by minimising discrepancies between predicted and actual outputs.

The application of neural network models to machine tool errors has ranged from traditional feedforward neural networks [21]–[23], to Cerebellar Model Articulation Controllers [24], Adaptive Resonance Theory neural networks [25], radial basis functions [26], and Bayesian neural networks [27]. Moreover, global optimisation algorithms such as Genetic algorithms [28] and improved Particle Swarm Optimisation [29] have been hybridised with neural networks to improve prediction accuracy and stability when modelling machine errors. Lastly, deep learning has been used to map machine errors [30], [31]. The utilisation of multiple hidden layers and historical data enabled the development of predictive models for forecasting future errors along the machine error continuum [30].

By employing global optimisation algorithms (Genetic algorithms and improved Particle Swarm Optimisation) alongside Gradient Descent Optimisation, researchers have demonstrated machine error reductions of 5-8%, compared to a non-globally optimised neural network, which is a nontrivial decrease [28], [29]. In general, the function of a global optimisation algorithm was to optimise the initial weights (neural network coefficients) or prune the architecture. Conversely, local optimisation algorithms, such as Gradient Descent Optimisation, minimise the objective function by adjusting the weights with computed solutions from the neighbourhood of their initial magnitudes. Therefore, working alone, Gradient Descent Optimisation can get trapped in local optima, due to poor initial weights, and converge on a solution prematurely [32]. This phenomenon can have a significant impact on the accuracy of error predictions, thereby influencing the model's capacity for enhancing overall accuracy. To address this issue, Max-Min Ant System, a global optimisation algorithm derived from the Ant Colony Optimisation meta-heuristic, was chosen. It has proven to be more effective in finding the global best weights compared to other globally optimised hybrid neural networks [32].

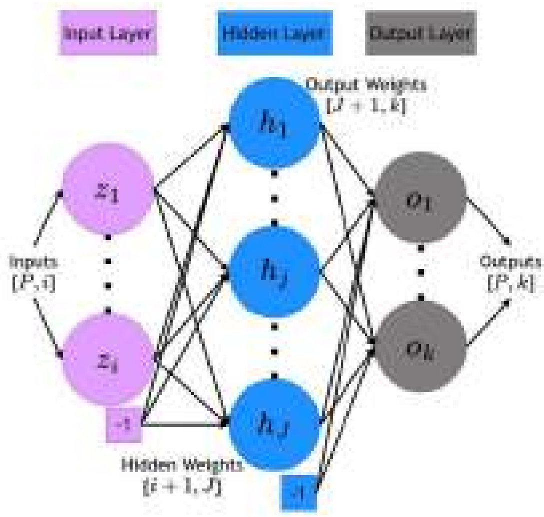

Figure 2: Neural Network

3 ANALYTICAL AND AI-BASED ERROR MODELING FOR THREE-AXIS MACHINE TOOLS

3.1 Geometric Error Model

The development of a geometric error model typically initiates with the derivation of a mathematical framework that establishes a relationship between the ideal and nonideal behaviours of machine components and the tool position. In the context of a three-axis machine and under the premise of a rigid body assumption, there are 21 quasi-static geometric errors [12]. Refer to Table 1 for an overview of the geometric errors, while Figure 3 provides a visual depiction illustrating the six constituent errors that impact a single axis. Fundamental to the product of exponential theory description of a three-axis machine is the twist, $\hat{\xi}$. A twist is an element of the special Euclidean group, $se(3)$, which represents the mathematical space of rigid body transformations [33]. More precisely, the exponential of a twist denoted as $e^{\hat{\xi}\theta}$, represents a homogeneous transformation matrix that facilitates the mapping of a rigid body from an initial configuration to a final configuration through a rigid motion relative to a fixed inertial frame. By multiplying a series of successive exponential twists, it is possible to compute the ideal and nonideal forward kinematics of a three-axis machine tool.

Table 1:Component Geometric Errors

Geometric Error	Symbol	Description
Roll Error	ε_{xx}, ε_{yy}, ε_{zz}	A rotational error about the axis of motion
Yaw Error	ε_{zx}, ε_{zy}, ε_{yz}	A rotational error about the vertical axis that is orthogonal to the plane in which the axis of motion is located.
Pitch Error	ε_{yx}, ε_{xy}, ε_{xz}	A rotational error about the horizontal axis that is orthogonal to the plane in which the axis of motion is located
Linear Positioning Error	δ_{xx}, δ_{yy}, δ_{zz}	A translational error in the direction of commanded motion
Straightness Error	δ_{yx}, δ_{zx}, δ_{xy}, δ_{zy}, δ_{xz}, δ_{yz}	A translational error in orthogonal directions to the axis of motion
Squareness Error	S_{xy}, S_{yz}, S_{xz}	A translational inaccuracy of the linear axis in motion due to the influence of a rigidly attached orthogonal axis. The axis in motion is rotated about the orthogonal axis.

This method propagates the component geometric errors of all three axes, modelling the individual impact of each error on the tool's position. It achieves this by modifying the ideal forward kinematics (inerrant machine motion) with axiomatic error twist representations - nonideal forward kinematics. An error twist is conveniently modelled as a translation and a rotation about a single coordinate axis. For example, the error twist coordinates (Equation 1) for the roll error and linear positioning error, on the y-axis (Figure 3), are defined as:

$$\xi_{YY} = [0 \quad \delta_{yy} \quad 0 \quad 0 \quad \varepsilon_{yy} \quad 0]^T \tag{1}$$

$$e^{\hat{\xi}_{yy}} = \begin{bmatrix} \cos\varepsilon_{yy} & 0 & \sin\varepsilon_{yy} & 0 \\ 0 & 1 & 0 & \delta_{yy} \\ -\sin\varepsilon_{yy} & 0 & \cos\varepsilon_{yy} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{2}$$

The error exponential twist (Equation 2) can be derived from the error twist coordinates. It allows the precise pose of an axis to be determined by considering the effects of the component geometric errors. Furthermore, this concept can be extrapolated to analyse the behaviour of other axes as well. By multiplying the nonideal error exponential twists for each axis, the machine component errors are propagated to the tool position. The order of multiplication is related to the configuration of the machine. In this case, the machine tool is organised in an FYXZ configuration, fixed reference frame (U) → y-axis → x-axis → z-axis → tool frame (T). Generally, the outcome of this process is an equation, for each axis, that describes the deviation of the tool position from the ideal position due to the influence of geometric errors ($[P_x \quad P_y \quad P_z]^T$). The vectors, $[P_x \quad P_y \quad P_z]^T$, represent the corrective components utilised within a software compensation scheme.

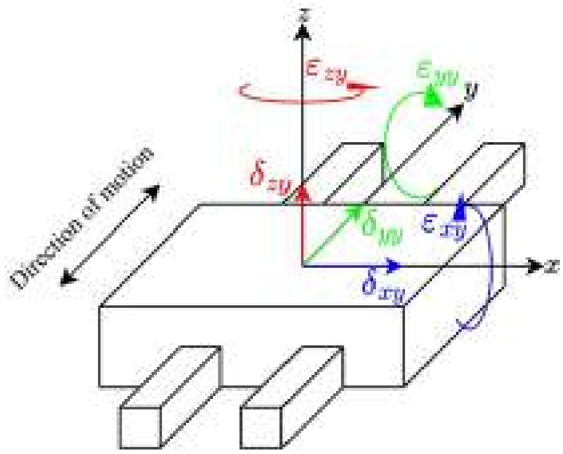

Figure 3: Y-Axis Geometric Error Components

Nevertheless, for the compensation scheme to be effective, it requires the ability to interpolate individual geometric errors at arbitrary locations within the operational range of the machine. This was accomplished through the modelling of the measured geometric errors, derived from laser interferometer tests. This non-contact measurement technique uses the interference patterns generated by splitting a laser beam into two paths: a reference path and a measurement path. The laser beam is directed towards a retroreflector mounted on the machine tool's spindle. As the machine tool moves, the retroreflector undergoes displacement (rotational or translational), resulting in a variation in the interference pattern. These variations were used by the laser systems software to quantify the geometric errors. In certain instances, such as linear positioning errors, the measurements obtained from the laser system and the corresponding displacement values attributed to the machine tool were compared.

The laser interferometer test was conducted at intervals of 10 mm, in the forward and reverse direction, over the x- and y-axis. The mean error data was subjected to a Fourier series approximation, which created a continuous curve that connected the measured points. This facilitated the estimation of values at unmeasured positions within the data set, see Figure 4. Thus, the Fourier series models provided predictions of the geometric errors at any position within the XY plane of the machine tool. Substituting these predictions into the kinematic model allows the determination of an error vector at any position within the machine's workspace. Ultimately, the magnitude and direction of the error vector were utilised to adjust the servomotor-controlled position of each axis, within the numerical code, this constitutes a software-based compensation approach.

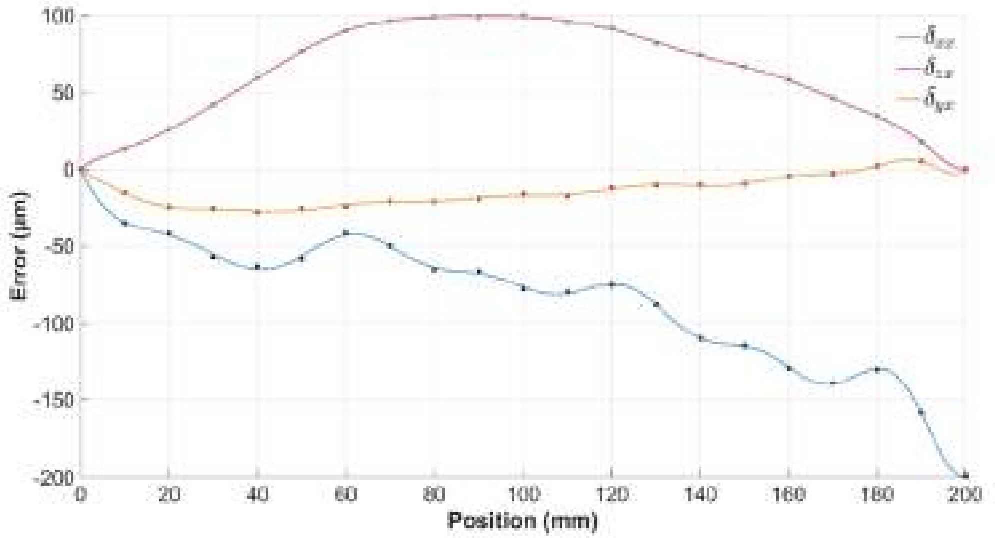

Figure 4: Fourier Series Approximation of X-Axis Translational Geometric Errors

3.2 Artificial Intelligence Model

The rationale behind incorporating the artificial intelligence model was to investigate the efficacy of a computational error modelling approach. The objective was to explore the potential benefits of reducing errors projected onto the workpiece, particularly planar positional deviations and radial deviations arising from circular interpolation, to enhance the overall machine accuracy. Instead of exclusively addressing a particular subgroup of errors, such as geometric errors, this approach analyses inaccuracies that are more intuitive to end-users familiar with the numerical code. The positional and radial deviations manifest due to the interplay among the four distinct error sources, which is effectively the cumulative influence of machine errors projected onto the workpiece. These errors are more comprehendible by end-users as they can be tested through machining experiments, thereby facilitating a clearer understanding. Moreover, by addressing these errors, under controlled conditions, the impact of all the fundamental errors on the workpiece accuracy is reduced.

Considering this, three computational neural network models were developed: labelled as A, B, and C in Figures 5-7. Firstly, model A attempts to correlate the machine error with the x- and y-position by matching its output with the positional deviation in the XY-plane. Secondly, Model C undertakes a comparable task but incorporates additional inputs of repeatability and squareness errors to offer a more comprehensive estimate of the machine's behaviour. Alternatively, model B attempts to characterise the circular interpolation error with the inputs shown in Figure 6. As detailed earlier, each model iteratively refines its output by adapting the network parameters (weights) in a magnitude corresponding to the value of the objective function. In this case, the objective function is the mean-squared error, ε_T, which is defined as the average of the sum of the squared differences between the desired machine error and the predicted machine error.

To improve the predictions of the models, the network parameters (weights) are computed by the Max-Min Ant System algorithm shown in Figure 8. In essence, the algorithm leverages the exploratory behaviour of multiple artificial ants to progressively establish and reinforce optimal paths to candidate weights that, when propagated through the network with the training patterns, provide the lowest mean-squared error. Artificial ants use pheromones to signify the best candidate weights which affect the choice of other ants through a probabilistic mechanism. The convergence of multiple ants along a particular path establishes a positive correlation with the deposition of pheromones, subsequently amplifying the probability of other ants selecting the same path.

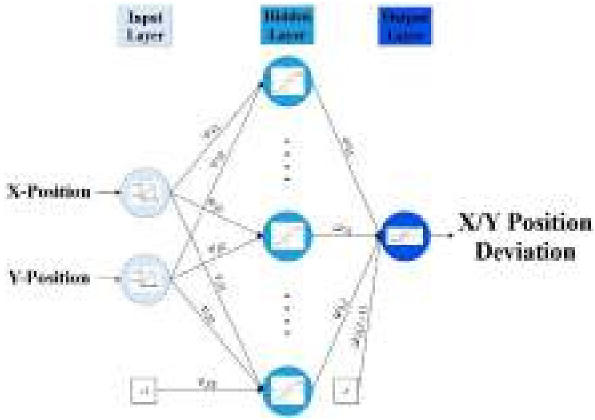

Figure 5: Neural Network A

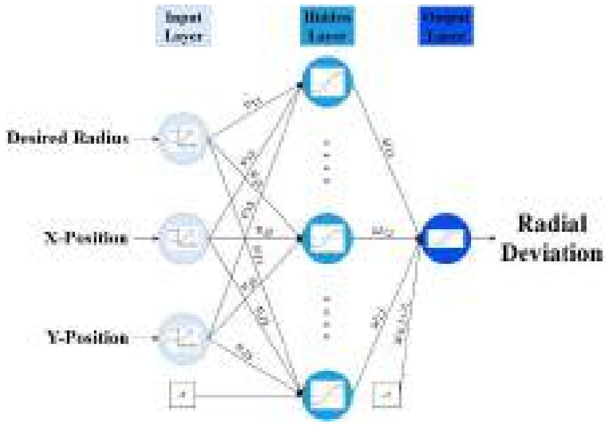

Figure 6: Neural Network B

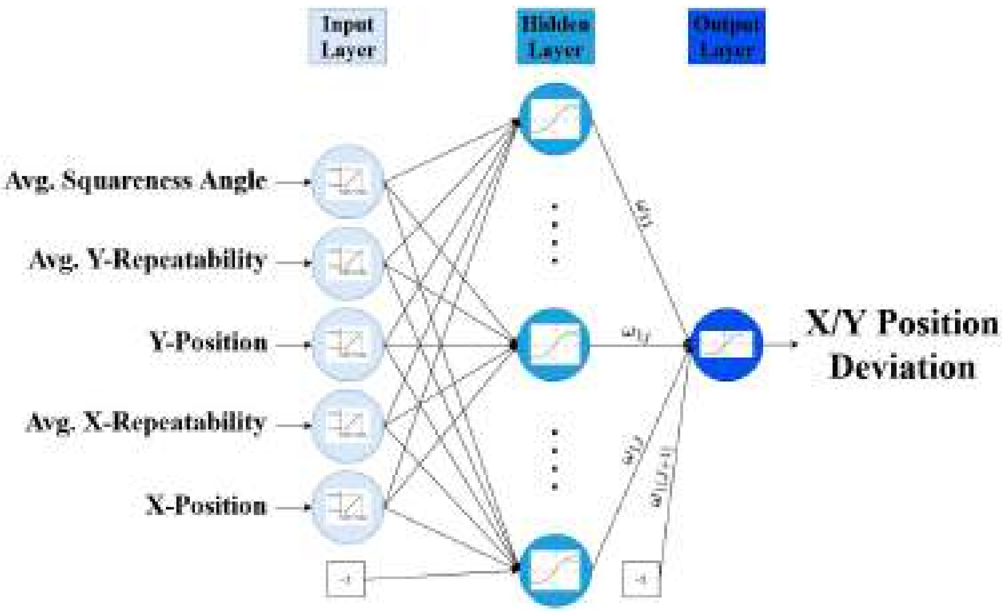

Figure 7: Neural Network C

In other words, as more ants gravitate towards a specific path, the intensified pheromone deposition augments the likelihood that other ants would choose that prevailing path. To foster a balance between exploitation and exploration, strategies such as pheromone smoothing, periodic updates ($f_\lambda = 20$) with the global best solution, and pheromone limits were implemented. This allowed the algorithm to navigate the optimisation landscape and maximise its potential to discover the global optimum weight combination. After the global optimum weights were identified, the neural network underwent further training using the Gradient Descent Optimisation method. Based on the predictions generated by the neural networks, the numerical code responsible for defining servo-controlled positions and subsequent machine movements was systematically adjusted, similar to the analytical model.

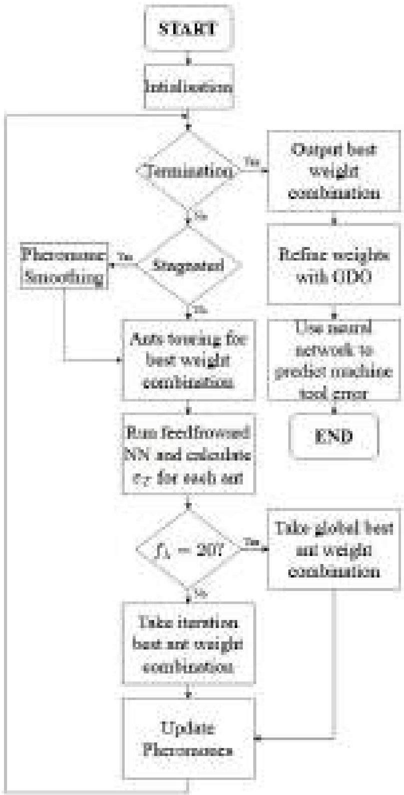

Figure 8: ACO-GDO Algorithm

The training data for each network was ascertained by three, low-cost, machining tests. Machining tests are quicker and cheaper to perform compared to a laser interferometer test, but the distinct errors are harder to discriminate [5]. In light of this, a random hole test (Figure 10) was performed where randomly positioned holes were drilled, relative to the machine's origin, into a flat plate. The hole positions were measured by a portable coordinate measuring machine (FaroArm Gage) and any deviation in the x- and y-direction was captured. Secondly, a circular test was performed (Figure 9), similar to ball bar tests, where circles were engraved at different positions in the workspace. The radial deviation at four orthogonal points on the circle's circumference was measured by a DSX510 optical microscope. Finally, the third test encompassed the engraving of squares positioned at various locations within the workspace (Figure 9). This evaluated the orthogonality between the x-axis and y-axis as a projection on the workpiece. The squareness was quantified by measuring the inside and outside corner angles with the microscope.

Lastly, to validate the performance of the software compensation achieved by modifying the numerical code with error model predictions, four independent tests were conducted. These included three more random hole tests and an additional circular test. A total of 287 holes were drilled across three plates, and their positions were measured, by a portable coordinate measuring machine, and compared to the computer-aided design (CAD) version of the plates to observe any deviations. In addition, to assess the predictive accuracy of network B, eight circles with different diameters were engraved using a G02 circular interpolation command. The radial deviations at four points along the circumference were then measured, with the DSX510 optical microscope, and compared to the pre-compensated values.

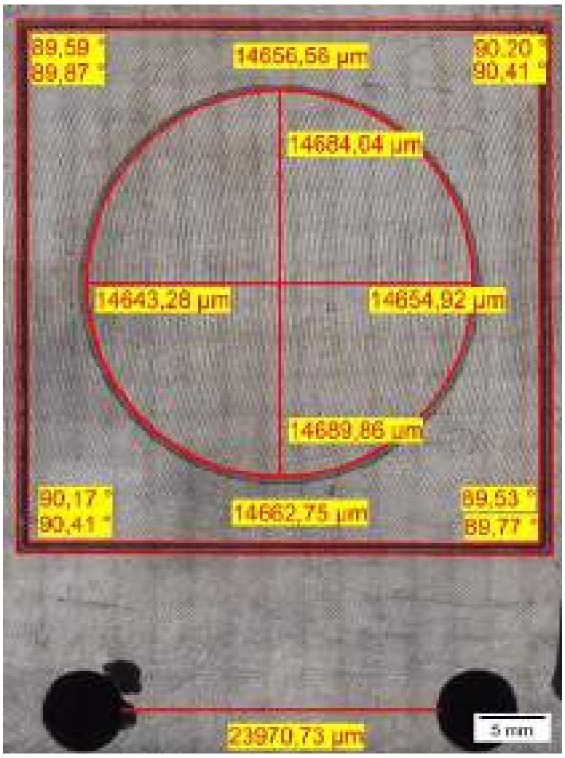

Figure 9: Circular and Squareness Test

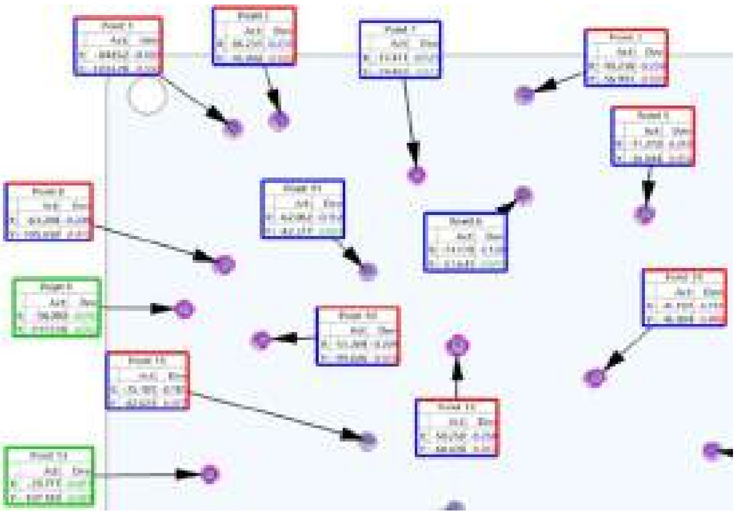

Figure 10: Random Hole Test

4 RESULTS

The effort to improve machine tool accuracy is accomplished through a four-step approach. Specifically, the requisite research has generalised the approach to the development of a formal mathematical or computational error model, an appropriate error measurement procedure, an implementation of error compensation, and an experimental investigation that verifies the quality of compensation [34]. Having covered steps 1 to 3, this section now presents the validation results obtained by testing the predictions provided by the analytical and artificial intelligence error models. These predictions were employed to rectify both the magnitude and direction of machine errors along the x and y axes. A comparison was made between the precompensation deviations and the post-compensation deviations to assess the quality of the model's predictions.

Table 2: Accuracy Validation

<table>
<tr><th></th><th colspan="4">Accuracy Improvement (%)</th></tr>
<tr><th></th><th>POE-Fourier</th><th>Network A</th><th>Network B</th><th>Network C</th></tr>
<tr><td>X-Axis</td><td>15</td><td>No Improvement</td><td rowspan="2">63</td><td>26</td></tr>
<tr><td>Y-Axis</td><td>44</td><td>43</td><td>61</td></tr>
</table>

Table 2 offers a summary of the average accuracy enhancement achieved on the three-axis machine tool. The results (POE-Fourier model, networks A and C) emerge from the mean deviation between actual and intended hole positions, following the adjustment of the initial x and y coordinates in the numerical code. For network B, the result is derived from the mean radial deviation across eight samples, where four points on the circumference are considered.

The percentage signifies the difference (improvement) between mean precompensation deviations and mean post-compensation deviations.

5 DISCUSSION

Given the results, Network A performed poorly concerning the x-axis deviation. In fact, there was an overcompensation resulting in a 28.5% decrease in accuracy. This may be attributed to overfitting, wherein the neural network learned both the underlying error function and the noise within the training set. Consequently, its capacity for generalisation was compromised resulting in poor performance. In contrast, such was not the scenario for the y-axis deviation. In this context, the generalisation ability was good, leading to accurate predictions and effective compensation.

Furthermore, the analytical model's focus solely on geometric errors, in contrast to the broader scope of the error spectrum captured by the training data of network C, contributed to the superior performance of the artificial intelligence model. An analytical model would always be more rigid in the aspect of adaptability and flexibility. In fact, the analytical model relied on particular assumptions such as quasi-static, quasi-periodic, geometric errors and rigid body motion, this was not the case with the artificial intelligence model.

On the other hand, the mapping between the input-output pairs, in the AI model, did not necessarily represent causality. The mapping was learned from the training data, and the model's primary objective was to make accurate predictions based on the observed patterns in the input-output pairs. The design of the experiments was such that the conditions were limited to a set of repeatable circumstances that the machine often encounters. This was to increase the confidence in the causal link between the inputs and outputs in the neural network model. However, without pre-existing knowledge about the overall positional deviation, the causality was confined to the specific training patterns captured under these conditions. Nevertheless, the predictions were successful in the endeavour of accuracy enhancement.

Lastly, network B effectively mapped the nonlinear correlation between the circumferential coordinates of four points situated on the circumference and the desired radius. The purpose of investigating the circular interpolation accuracy was to improve a fundamental machine motion. Commonly, complex machine motions contain an assortment of linear and circular movements. These movements are the substrate from which more complex movements are developed. Thus, an improvement in the circular interpolation movement can fundamentally improve the overall accuracy of the machine. A notable distinction between compensating for circular interpolation and positional deviation lies in the interaction between axes during machining operations. The errors on the x- and y-axes are not independent of one another during machining, thus network B was able to capture this interaction from the circular measurements. The predictions generated by model B inherently incorporated the combined influence of both axes, this distinguished it from the other networks. The analysis of the radial deviation indicated that the error resulting from interpolation could not be easily discerned from the positional deviation data. Lastly, in comparison to the pre-compensation deviations, network B exhibited overcompensation yet succeeded in diminishing the overall deviation (error).

6 CONCLUSION

Software solutions make adjustments to the numerical code employed by CNC machines for the manufacturing of parts. This is a low-cost solution since it requires no additional hardware, no access to the CNC programmable logic controllers (PLC), or expensive monitoring equipment [5]. To implement software-based compensation, it is imperative to possess error models that can effectively capture the machine's behaviour and make predictions about its error continuum. The implementation of compensation algorithms and numerical code corrections on a CNC machine is straightforward and does not demand substantial financial investment. Moreover, the cost associated with fine-tuning numerical code parameters and updating axis positions is orders of magnitude less than procuring and installing new mechanical components [8]. This paper employs this economically judicious methodology through the utilisation of both models.

This research has demonstrated the effective use of analytical and artificial intelligence error models for the compensation of machine tool errors. In general, the artificial intelligence model has superior performance compared to the theoretical model. However, this should not undermine the utility of geometric error models, as they continue to be effective in enhancing accuracy. Considering the performance exhibited by the artificial intelligence model, it becomes evident that the future of mitigating machine errors is firmly grounded in the domains of machine learning and artificial intelligence. It holds immense promise in the pursuit of developing a comprehensive universal model that can address all the systematic errors inherent to a machine. Over time, the adoption and continuous refinement of these models are anticipated to permeate and prove beneficial to researchers and stakeholders invested in machine tool performance. In conclusion, this research study holds potential in terms of augmenting machine tool accuracy, ultimately bolstering overall productivity and ensuring the long-term sustainability of end-users involved in CNC machine operations.

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THE INTERACTION OF DESIGN THINKING IN PROJECT MANAGEMENT: A REVIEW

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ABSTRACT

Design thinking (DT) is a problem-solving process that in addition to its utilities in project design, may empower project managers to access a wealth of innovative user-centric project management solutions. This paper presents the results of a structured review of the design thinking literature in the field of project management. The study reported on in this paper explores the various benefits and applications of design thinking in project management. A critical look at design thinking in project management emphasizes the challenge for project management to become much more user-centric to promote innovative outcomes be it products, services or strategies. It is evident that project management can benefit extensively by leveraging a DT mindset and process.

Keywords: Design thinking, Project management, User-centricity, Mindset, Structured review

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1 INTRODUCTION

The world is rapidly evolving because of the duel driving forces of globalization and digitization. Organizations need to be able to evolve and adapt so that they can remain relevant, innovative, and competitive. This rapid evolution and change has resulted in innovative but extremely complex projects. Organizations and their project management offices are expected to deliver on these explorative projects.

Organizations are increasingly faced with exploration projects which are ambiguous, there is little evidence of demand, no detailed requirements, few lessons learned or similar previous projects, and lastly, these projects may require easy scalability from short-term to long-term useability [1]. These diverging project needs requires the project team and organization at large to be able to adapt to change and pivot when necessary. This becomes an anti-pattern of the traditional project management framework that is aimed at optimizing and adhering to the triple constraints [2].

Project management has borrowed from multiple disciplines to create a holistic end-to-end framework that effectively solves and ensures the smooth delivery of a project. However, there seems to be a lack of involvement of the end-user/client during the initial stages, especially during requirements analysis. To encourage adaptability in organizations, there needs to be a shift from the view of project management success as it is traditionally described. The view that projects should stay within the prescribed and agreed-upon scope, time, quality, and cost parameters. Usually, these constraints are tightly monitored, allowing for little to no creativity and stifling innovation. In extreme cases, this rigidity results in a product or service that is not fit for purpose or not what the client envisioned. Design thinking focuses more on project success than project management. Therefore, organisations must shift their focus to Project Success, which focuses more on the output being fit for purpose, client-centred and delivered at the right time by allowing the plan to be iterative and flexible [3].

According to Liedkta [4] design thinking "is a hypothesis-driven process that is problem as well as solution-focused. It relies on abduction and experimentation involving multiple alternative solutions that actively mediate a variety of tensions between possibilities and constraints and is best suited to decision contexts in which uncertainty and ambiguity are high. Iteration, based on learning through experimentation is seen as a central task". Design thinking is aimed at understanding the challenges experienced by the user without organizations/businesses assuming that is what the end-user requires. The process entails a lot of refining and understanding of the problem from a user's point of view without worrying too much about the technical elements that are involved. Design thinking is more focused on the client experience rather than on how the product's functionality will be achieved.

Design thinking ultimately revolves around the people that you are designing for by critically considering their pain points and experiences to understand what is ultimately going to solve the problems that the end-user is facing. Design thinking is critical during requirements analysis as it is used to provide clarity on ill-defined or unknown questions, which may require extensive problem-solving to better understand the requirements. Design thinking is also crucial throughout the project process to foster innovation, creativity, and agility. Design thinking drives collaboration and a hands-on approach utilizing brainstorming, and end-user involvement by prototyping, sketching, etc. This ensures that the delivery team understands exactly what the end-user/client requires from them[5].

The field of project management is quite big with abundant literature, design thinking on the other hand is a relatively new concept. The literature regarding the junction between project management and design thinking is therefore limited. It is important to note that project management and the concept of design thinking are closely linked with agile, client centricity, and innovation concepts. The purpose of this study is to answer the following review questions:

RQ1: What are the benefits of design thinking (DT) in project management and

RQ2: How can design thinking be applied in project management?

2 RESEARCH METHOD

A systematic literature review method was used to retrieve, investigate and analyse the available data to answer the questions posed in this research with evidence-based literature. The underpinning guardrail for search parameters, inclusion, exclusion, and the general screening procedure was guided by the PRISMA model which was used to underpin the search parameters [6].

2.1 Search Strategy and Keywords

The search strategy was heavily impacted by the review questions. While exploring the design thinking concept multiple keywords were identified that assisted in zooming in on the "application" and "benefits" of design thinking. Design thinking is a relatively new concept that is not heavily researched, it is closely associated with various other concepts therefore the search strategy was iterative.

Inclusion criteria included Electronic bibliographic databases such as ScienceDirect and Web of Science, google scholar, ProQuest, and peer-reviewed scholarly journal papers and book chapters. A decision was also made to include grey data and literature. It is important to incorporate grey literature because design thinking is an emerging concept, however studies/sources that were incomplete or in progress were excluded. The review period of this study will be limited to the last 15 years.

The following keywords were used: "design think*" AND "project", "application" AND "design think*", "design think*" AND "approach", 3rd and 4th order of design, "design think*" AND "complex problem", "interconnected problems", "empathy mapping", "client centricity in projects", "design think*" AND "tool*" and "lean think*".

2.2 Screening and Selection

The screening and selection of information ensures that an efficient process is followed to select the most relevant information for the study. The study will consist of a structured approach to analysing the content of the most pertinent literature and secondary data that provides information on the review questions. The initial screening process yielded 103 literature sources that was ultimately reduced to 29 upon the conclusion of the PRISMA process. The final 29 references were analysed to conduct the review.

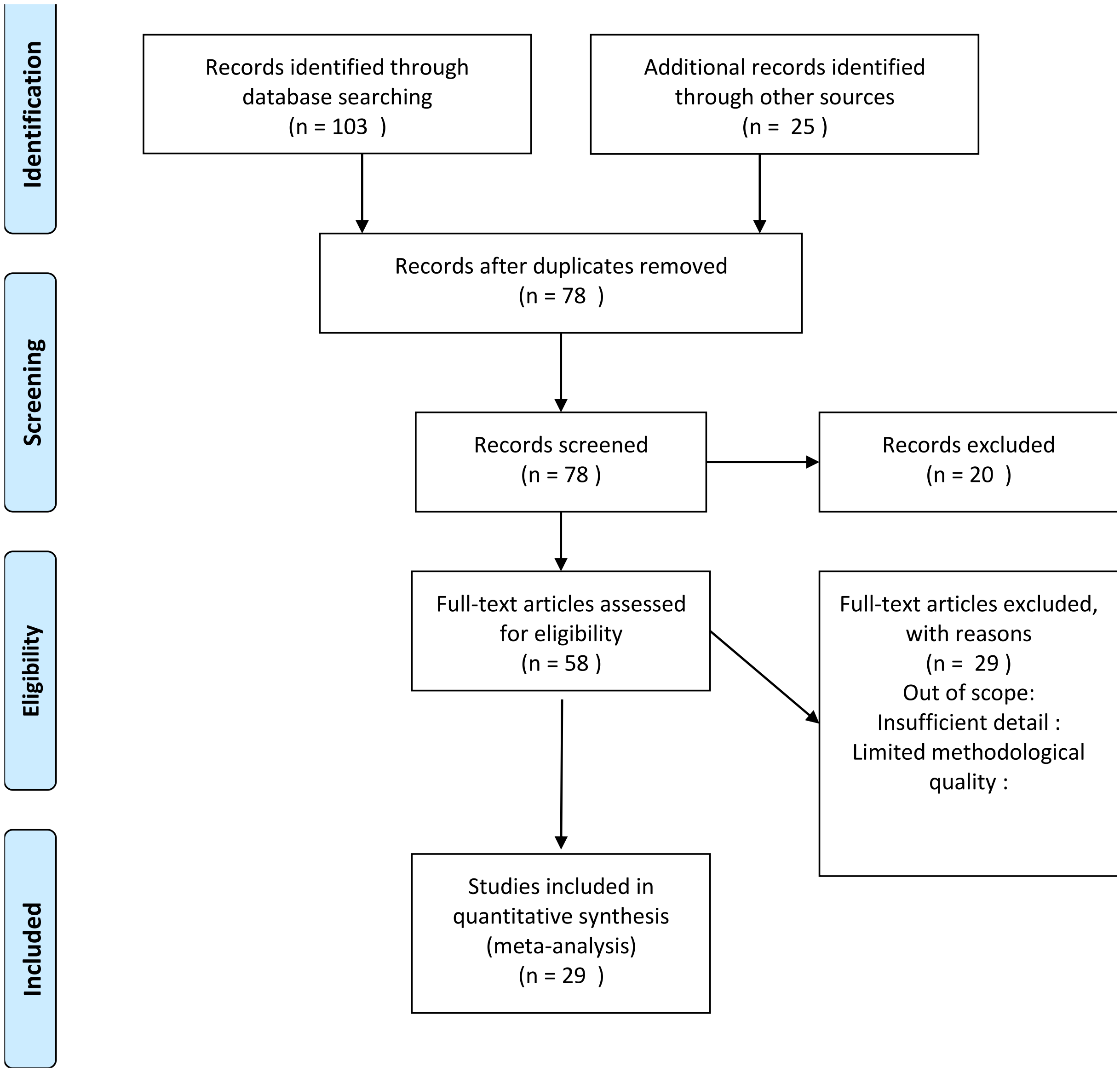


Figure 1: PRISMA literature selection and reduction process[6]

2.3 Data Extraction and Quality Assessment

The data was extracted and sorted as per the steps above and captured in an author matrix for further analysis of the data. The data was extracted by adhering to the following steps (1) Extract the data and populate into an author matrix as per the following characteristics author, year, purpose of the study, research design, key concepts, analysis of results and findings in relation to research questions.

(2) Filter the study characteristics: search dates, databases used, the field of study.

(3) Details of each filter developed and/or evaluated e.g., type of filter, terms used, and accuracy measures.

(4) The table below was be used to extract study information.

Table 1: Extract of the Author Matrix

Author Matrix					
Item	Author and Year	Purpose of design	Research design	Key words/Key concepts	Findings
1	What is Design Thinking and Why is it important? (Rim Razzouk, Valerie Shute)	Better understanding of its characteristics, processes, and differences between novice and expert design thinkers	qualitative research	design thinking, design process, expertise, expert and novice	Design thinking is key to solving complex projects Design is characterized as skills that drives synthesizing identifying problems and
2	The Use of Design Thinking for Requirements Engineering (Jennifer Hehn,Falk Uebernickel)	General design thinking background and problem solving using design thinking	Case study	Requirements engineering, design thinking	Benefits of design thinking structured process to determine requirements leverages and promotes team work and collaboration focus on usability instead of technicality
3	The Nature of Design Thinking: Design thinking research symposium (Kees Dorst 2010)				Fundamentals of design thinking and design thinking
4	The Design Thinking Mindset: An Assessment of What We Know and What We See in Practice (LARS GROEGER,JOCHEN SCHWEITZER and LEANNE SOBEL)	Understanding the key mindset attributes that contribute to design thinking	Literature Analysis	design thinking,leadership,mindset,innovation, human-centred design	Mindset is key instruments to driving design thinking and realising its full potential DT mindset in practice
5	Rethinking Project management Education: A humanistic approach based on Design thinking (Natalie Ewin, Jo Luck, Ratish Chung,Jacqueline Jarvis)	The importance of incorporating design thinking in project management		Design thinking, client centricity	Client centred approach to design thinking. The mindset and application of the mindset in design thinking process
6	Introduction to design thinking process (Stanford Institute of design 2016)	Design thinking process and application	Student Handbook ,Curriculum at Stanford University	Design thinking	Five process of design thinking and high level application thereof
7	Developing A design thinking Mindset: Encouraging Designerly ways in Postgraduate Business education -Design Thinking in Higher Education(Lars Groeger and Jochen Schweitzer 2020 41-720)	Design thinking mindset and application thereof in business education	exploratory study		summarized ,reclassified 11 Schweitzer mindsets to 7 well classified and better grouped mindsets
8	Design Thinking: A Fruitful Concept for IT Development? (Tilmann Lindberg, Christoph Meinel, and Ralf Wagner)	Understanding how design thinking can drive innovation in projects, particularly IT	qualitative guideline interviews		Problems experienced in the IT development failures of the IT Development

The quality assessment process consisted of rigorous screening and selection based on the above (screening and selection) parameters and criteria. The researcher was able to verify the credibility of the resources. The four quality criteria based on DARE (Database of Abstracts of Reviews of Effects) was applied and the following questions were answered below to improve the quality of the literature sources.

Table 2: Extract of the Quality Assessment Matrix

Item nu	Author and Year	Q1: Are the reviews inclusion and exclusion criteria described	Q2: Will this literature search cover the relevant studies in correlation to	Q3: is there proof that reviewrs have validated infromation	Were the studies adequately described	Total out of 12 (accapetable range
1	What is Design Thinking and Why is it important? (Rim Razzouk, Valerie Shute)	3	3	3	3	12
2	The Use of Design Thinking for Requirements Engineering (Jennifer Hehn,Falk Uebernickel)	3	2	3	3	11
3	The Nature of Design Thinking- Design thinking research symposium (Kees Dorst 2010)	2	3	2	2	9
4	The Design Thinking Mindset: An Assessment of What We Know and What We See in Practice (LARS GROEGER,JOCHEN SCHWEITZER and LEANNE SOBEL)	3	3	3	3	12
5	Rethinking Project management Eductaion: A humanistsic approach based on Design thinking (Natalie Ewin. Jo Luck, Ratish Chung,Jacqueline Jarvis)	3	3	3	3	12
6	Introduction to design thinking process (Stanford Instiute of design 2016)	1	3	2	3	9

2.4 Methods of Synthesis and Analysis

The data was analysed to answer the explicitly stated review questions. The process entailed:

(1) Cross referencing of the data extraction table (Table 1) and overlapping that information with the quality matrix (Table 2) to finalize the database of content to be analysed.

(2) The data was further broken down and categorized into a relevancy matrix by recording the key findings as per Table 3.
(3) The categorization lead to comparison of the respective contents by analysing the gaps, similarities, differences, and conclusions drawn from the data.
(4) Lastly the information was interpreted and analysed to answer the review questions.
(5) Analysis of the implications and conclusions of the study were further assessed for future research.

Table 3: Extract of Relevancy Matrix

Item number	Author and Year	Design thinking benefit to project Management	Design thinking applications	Supporting content
1	What is Design Thinking and Why is it important? Rim Razzouk, Valerie Shute 2012	Yes	no	Design thinking is key to solving complex projects . Design is characterized as skills that drive: synthesizing, identifying problems and
2	The Use of Design Thinking for Requirements Engineering Jennifer Hehn,Falk Uebernickel 2019	yes	yes	Benefits of design thinking: structured process to determine requirements Leverages and promotes team work and collaboration focus on usability instead of technicality
3	The Nature of Design Thinking- Design thinking research symposium Kees Dorst 2010)	yes	no	Fundamentals of design thinking and design thinking background
4	The Design Thinking Mindset: An Assessment of What We Know and What We See in Practice	yes	yes	Mindset is key instruments to driving design thinking and realizing its full potential
5	Rethinking Project management Education: A humanistic approach based on Design thinking	yes	yes	Client centred approach to design thinking. The mindset and application of the mindet in design thinking
[illegible]	[illegible]	[illegible]		[illegible]

The completion of the systematic literature review was guided by the methodology provided above. As noted, it was an iterative process that allowed to a certain degree of flexibility within the criteria and limitations explained above.

3 RESULTS

The design thinking (DT) process is structured in such a way that it is solution-oriented from a users perspective. DT defines a project in terms of its desirability, technicality feasibility, and its ability to provide value for the end-user and the overall marketability of the product or service [3]. The results are arranged in a similar fashion, defining the benefits of DT in project management followed by the application of design thinking in project management. The application of DT in project management explores the DT process, mindset and tools and techniques.

3.1 RQ1: Benefits of Design Thinking

Th project management discipline has evolved over time and will likely continue evolving. There are multiple frameworks and processes in the project space which aim to improve project delivery. To a certain extent the project management fraternity is already using some of the tools and processes of design thinking, however there isn't a lot of literature that outlines the benefits of DT in project management. In this section the emerging benefits of leveraging DT in project management will be addressed.

- ***Enables radical fearless innovation capability***

O'Connor [7] describes innovation capability as a complex interdependent system that needs to be addressed to reach a company's full innovation ability. He claims that there are three main enablers for innovation capability. They are described as nurturing and maximizing skills that have to do with problem solving; empowering the resources and market sensing of which all these aspects are driven by DT process, mindset and tools. These three prescribed characteristics [7] were summarised as [8] follows:

(I)Superior solutions can be achieved by leveraging the design thinking ideation phase which doesn't focus on just the obvious solution but rather guides the team into creative unorthodox solutions. Design thinking leverages diversity and a safe space which encourages the team to participate and own the innovation process.

(II)Lower risks and costs (better resource allocation) is driven by incremental iterative prototyping and a constant feedback loop. By prototyping in an iterative manner, the project team will be exposed to feedback which may often than not result in changes. These changes in a typical project environment can equate to a big loss however, DT mitigates the loss by phasing capital investment in an iterative manner. This ensures that the closer to the goal the more resources may be invested. DT gives project teams the autonomy to determine the feasibility of a project by experimenting in real-life at a lower cost.

- ***Understanding and unpacking ambiguity to manage complexity and the unknown.***

DT encourages a non-linear and non-sequential analytical approach to ambagious wicked problems. DT relies heavily on reflective conversation with the situation to gain better insights of the problem rather than jumping to solution mode [9]. Furthermore, design thinking from a mindset perspective encourages team members to be comfortable with the unknown. This is fostered by the overall design thinking process which focuses on empathy. Empathy in DT is the driving force to understanding the problem and being comfortable with being led by the end-user to illicit insights of the unknown [10].

- ***Enablement of a collaborative healthy team environment and team buy-in***

The Define and Ideate phase is the most collaborative phases in the DT process. It includes multiple disparate teams in a collaboration setting with the aim to reach one goal, to define and understand the problem with the end goal of solving it. This creates a sense of belonging, ownership and a common goal within the project space filtering into the overall organization space [7]. As teams get to work consistently, together in harmony, the team will get to realise the respective skills and knowledge they can leverage from each other, coherent patterns, teams cadence and team process. Ultimately the team will reach a level of predictability which the PMO can leverage off when assigning future projects[11].

- ***Promote project success instead of project management success (outputs vs inputs)***

Project management success is usually misplaced and misguided by focusing too much on delivering within the three constraints by any means necessary. Project management success focuses on the output (what is produced) which could be detrimental to the project especially if the output is not necessarily the desired outcome. DT emphasizes conceptualizing project success. Project success focuses on the intended outcome (what is required, wanted, or needed for achievement)[3].

- ***Delivery team alignment with business and organizational strategy***

Project management and DT are becoming less operational and more strategic. Using DT will assist the organization to determine their current identity, what they stand for, their target market and inform their business model. The insights can then be used to identify gaps, anti-patterns, and if restructuring is required. Due to the nature of collaboration which decomposes silos and hierarchy, DT gives a voice to employees who wouldn't necessarily sit in strategic spaces; therefore, the strategy will have a crucial input from the people who do the work [3]. DT can ensure the delivery teams are aligned with the business and organizational strategy as it evolves. This alignment will drive a shared vision from top-down and bottom-up. This will ensure that teams are on par with the organization's skills and knowledge requirements and strategic goals [9].

- ***Mitigate cognitive biases***

Human beings are naturally inclined to be biased which ultimately has an impact on the way we approach our work. This bias can hinder the team's ability to deliver at its full potential. Liedkta [4] states that a DT mindset and process is the key to minimizing cognitive bias which stifles creativity, defining the problem ,understanding the problem and solutioning the problem. These cognitive biases are categorised as follows [4], [9]:

(I)Decision making ability, teams tend to view problems from a personalized perspective which is driven by their ego, past experiences and their current state of mind (feelings and emotions). DT can mitigate this bias by encouraging the team to empathize which drives insights collection and ultimately the teams gets to "walk in the shoes of the end-user". (II)Ability to articulate and predict future needs of the end-user.

(III) Limit hypothesis thinking and focus on real life experiments.

- ***Knowledge sharing and continuous learning and improvement***

DT's iterative process focuses on collaboration, prototyping and testing. These activities are essential to ensuring there is knowledge sharing, continuous improvement and learning. The collaboration of disparate groups enables knowledge sharing between stakeholders that come from different backgrounds, perspectives, and disciplines. Knowledge is shared bottom-up and top-down through the hierarchy which is important in the effort of upskilling the organization [8].

- ***In depth understanding of the user to provide a fit for purpose solution*.**

DT is synonymous with user and client centricity. It is closely coupled with empathy, understanding the user, and the involvement of the user. DT focuses on designing and solutioning with the user in mind instead of having the technology dictate the solution. Project management can leverage off this benefit due to the extensive involvement of the user, the feedback they provide and the repetitive testing that occurs with the user [12]. The ripple effect of a user focus results in a thorough understanding of what the user needs and nudges the user as well as the delivery team to explore other needs which emerge from the insights gathered by means of workshops driven by DT tools[13].

- ***Soft skills improvement***

DT has been reported to be instrumental in mitigating the poor relational issues with the respective stakeholders and users being included in the delivery team. Often, this misalignment ultimately leads to project failure[14]. DT is embedded with soft skills in the end-to-end process to ensure that people management is managed effectively and efficient from an empathic perspective. DT fundamentals are leadership, collaboration, problem solving, integration and critical thinking. These fundamentals are visible in the respective DT phases. Project managers or senior leadership are not the only stakeholders expected to have and exercise soft skills. Instead, DT slowly integrates these skills by means of inclusion of the team and embracing the diversity of the team. Any team member at any given time is at liberty to lead, participate, provide solutions, make decisions and interact without roles and seniority being the determining factor.

- ***Ability to blend big and small projects and shorter release cycles***

According to Brown [15] the DT process enables the organization to manage and transition short term projects to long-term projects. The blend of these projects into one portfolio allows the organization to release iteratively from a smaller solution which will be transitioned to a bigger innovation driven solution. The team will utilise insights from the feedback of the short-term solution. The other benefit of this approach is that the PMO is flexible in its ability to pivot when the solution being desired is no longer required. Like the agile delivery framework, incremental value-adding solution releases with shorter cycles enable "quick to market" solutions. Long-term solutions are likely to be obsolete and no longer a requirement by the time it hits the market, this results in extreme financial and time losses [16]. Another factor to consider is that shorter release cycles ensure a cohesive stable team gets to deliver a solution. This is essential, especially in the technology-driven organizations where professionals move jobs every 12 to 18 months [15].

3.2 RQ2: The application of design thinking in project management

The design thinking process follows a process that is iterative and not particularly linear and one-directional. DT enables flexibility, agility and continuous improvement which is essential for complex project environments. The process is based on the work done by Standford University and Kernbach [17].

The Stanford model process called "model of d. school" compromises of 5 stages which are iterative and not necessarily sequential. The process starts with (1) Empathize (2) Define (3) Ideate (4) Prototype (5) Testing. The Double Diamond Model of the British Council [18] follows a flow that starts with (0) Triggered by problem (1) Discovery (2) Define (3) Develop and (4) Deliver. It is important to note that for the purpose of the research more emphasis will be put on "*the model of d.school*" as this process is the most holistic detailed end-to-end process. The double diamond will be used in the summary to provide a visual aid of the merging of this respective process.

- **Empathize**

Empathizing with your user is a heavily human-centred design phase. This part of the process entails heavily engaging and understanding the people in relation to the problem you are trying to solve as a project team. Empathizing deep dives into the user's physical and emotional needs, how they view and think of the world, understanding how and why they do the things they do and most importantly what is meaningful to them [19].The project team will get to capture the physical manifestations of their experiences which provides intangible insights. The insights create a driveway for innovative fit-for-purpose solutions. The project team will therefore be able to confidently execute with confidence and understanding [20].

It is however important to note that, translating insights may be harder than we think. The mind is trained to filter out information without even being aware of it happening. Therefore, it is always important to have team members who aren't necessarily emotional invested in the already assumed outcome, stakeholders such as business and technical teams may easily contaminate the process due to their natural impulse to solution mode[13]. Empathizing therefore provides the "fresh pair of eyes" that are integral in analysing insights for what they truly are rather than interpreting them to suit a particular pre-conceived narrative. Multiple papers focus on empathy for the end-user and not necessarily the delivery team. However, it is important to be empathetic to the delivery team as well [21]. In the project management space, empathy can allow the project manager or team lead to better understand the teams' abilities, strengths, and weaknesses, what the team members like working on, what they dislike etc. Effective empathy allows team members to feel what the other team member feels in real-time creating a safer conducive work environment for the team [22].

- ***Define***

The Define phase can be described as synthesizing of raw gathered data (in the empathize phase) and translating that information into useful meaningful data that can inform the problem of the user and setting the tone on how the team can proceed going forward [20]. The ultimate goal is to identify actionable items that will lead to solving the problems and issues experienced by the user. Typically, in a traditional project, this would be viewed from a technical perspective however the design thinking process moves away from technical and business requirements into a more human centred problem statement. The human centred problem statement including the tangible actionable items informs what we call “Point of View” (POV) [23]. By synthesizing, reconfiguring, and linking all the insights received from the user, as a design thinker you start making sense of the previously scattered and seemingly unrelated insights.

- ***Ideate***

The ideation phase is a solutions driven phase. This phase involves transitioning from identified problems to identify the solutions to address the user’s problems. Based on the POV that is synthesized in the define process, innovative ideas are deduced in this phase. Ideation phase is mainly focused on exploration and identification of solutions to the users’ problems which were identified in the define phase. The main objective of this phase to provide solutions that spark creativity and innovation in the team [13]. According to Razzouck [5] successful ideation phases leverage thinking out of the box and limiting the obvious solutions. Incorporate multiple perspectives which can provide a holistic approach from respective disparate groups. In a nutshell, fluency (multiple participants) flexibility (multiple perspectives) and innovation (creative unlimited though process) perfects the ideation phase.

- ***Prototype***

In basic terms, Prototyping can be described as the experimental modelling of a proposed solution to confirm its validity in relation the proposed solution ideas. It basically brings the proposed solution to life to determine the real-life impact it will have on the user. This process is also looked at from a human centred perspective [23].This process is iterative in nature, in the early stages the questions that inform the prototype maybe be broad, therefore the prototypes will likely be high level but at the same time not being cost and time intensive. Multiple iterations of this process ensure that the proposed solutions will be more refined and streamlined therefore the protypes will increase in accuracy and be more time and cost intensive [24].

Ideally a protype from the early stages and iterations should be of a state that a user can interact with it and therefore provide more insights and guide the process of elimination. Due to projects that span over multiple industries, the prototype can be anything from sketches and drawings, story boards, role playing, a gadget and image interphases. It is important to note the most effective way to implement prototyping is to have extreme bias towards the user experiencing the actual prototype. Being able to feel it, smell it, taste it, see it or even role play to evoke emotions that align with values and beliefs established during the empathy phase [14].

- ***Test***

The testing phase is geared at determining how accurate the team has framed the problem statement. The Testing phase is an opportunity to test the prototype in real life and real-time with the user. The project team will get to understand the user better by the feedback that will be provided in this phase. The team will also get to identify gaps and blind spots that might have been missed initially. The Prototype phases provides the team with a prototype that is a solution to the problem [23].

It is easy to deviate and go into solution mode by questioning whether the proposed solution is liked by the user. Rather focus on the users experience with regards to the framed problem, solution and prototype. Determine how you can improve and ultimately meet the desired solution [10].

By the end of this process, the feedback will inform further insights into understanding the user better. This will result in refinement of the proposed POV, solutions and prototypes that will go through the iterative process and ensuring the team is one step closer to the desired human centred solution for the user. It will also give an indication of what is working and what isn't working in the proposed solutions [25].

3.3 Design Thinking Mindset

In multiple publications the mindset is articulated as the starting point when it comes to the application of any methodology, framework, and process within the workplace. Project management is evolving to meet the demands of innovation and disruption in an effort to remain competitive. The key is to drive strategic projects which are aligned to the clients' needs rather than the traditional mindset of doing projects in order to meet the triple constraints [26]. With the correct mindset, synergies between the organization, the strategy, the business, and the client will be achieved. Project management doesn't exist in a vacuum, therefore, to have an impactful mindset change, the leadership of an organization is key in ensuring that a mindset change trickles down the hierarchy [27]. There is a close relationship between agile project delivery and design thinking particularly especially in terms of their similar mindset. According to Schweitzer [21], there are 11 mindset attributes, for the purpose of the review study these attributes have been grouped and synthesised into 5 attributes due to the duplication of concepts within the 11 attributes. Based on the literature, the emerging mindsets that drive a design thinking mindset are:

Empathy-empathize and focus on human needs and values

Empathy is described as "the ability to see and experience through another's eyes, to recognize why people do what they do" [20]. This is a valuable mindset to possess in project management due to the nature of cross functional teams consisting of multiple stakeholders, each with their own unique background, characteristics and personality traits. Empathy in context to the user will allow the project team to understand the needs of the user by observing the problem to be solved from a social perspective. The emphasis is on the impacted people as this drives the process in the direction of solving problems by personifying the problem. Thus, the team can connect with the client on a deeper level which results in extensive insights and user experience [21].

Foster radical collaboration and embrace diversity

Radical collaboration entails a mindset that is consciously willing to integrate and interact with the team. Empathy comes to play in this mindset by ensuring a safe space which is open and respects the different perspectives of team members. Creating a judgement free space, which simultaneously embraces teams' expertise, knowledge and specialization is key to this mindset in DT. DT enables team members to leverage and positively embrace the respective personalities, expertise, working preferences and leadership styles with the aim of reaching the common goal. This approach will yield a domino effect which allows the user to comfortably collaborate, voice their needs and allow them to be able to also seek guidance, and accept guidance from the team and SMEs [20].

Encourage experimentation, failure, and continuous learning

As the team gains feedback whether negative or positive, it is important to embrace failure as well. Failure is inevitable when in the exploration and experimental phase. However, it is crucial to "get it out of the way" in the early phases to avoid BIG costly failures. As per the lean start up first principle which encourages the project teams to fail fast by focusing on customers. Instead of waiting in traditional Project Management to kick off the project, it is better to develop and build iteratively based on feedback and engagement with the customer [16]. The accepting failure mindset is seeing failure as being one step closer towards what the client wants. It is important to note this works effectively within an agile space.

Accept uncertainty and be open to risk

Contemporary projects are ambiguous innovative initiatives; therefore, the project outcome is not necessarily known. There are multiple unknowns which makes it difficult to determine what the user's actual needs are. This mindset leverages the ability of DT practitioner to make decisions based on the potential of a solution which results in risks such as failure and ambiguity. The complexity and iterations that will be required to devise a solution is unknown therefore adding time and cost risk. The holistic approach to comfortably embracing uncertainty and risk as a mindset is to view the problem as a whole which allows the team to create innovation that could be incremental in nature and ultimately be disruptive [21].

Modelling behaviour – selfless leadership, relentless optimism and creative confidence.

DT practitioners are to an extent responsible for leading their team in understanding, conceptualizing, engaging, and finding a solution to a problem. These responsibilities are all centred around maintaining a team momentum through collaboration of multiple disparate groups [28]. DT drives selfless empathetic behaviour. This behaviour is valuable in ensuring that there is fruitful conversations, steering away from conflicted ego driven conversations but rather ensuring that everyone has a say and are comfortable to engage [28].The application of this mindset is driven by firstly, sharing from a humility perspective highlights, failures, wins, and experiences by embracing the "Self-efficacy" concept by Bendura [21]. Importantly, the ability to show relentless optimism. As suggested by Kelley and Kelley [20] "urgent optimism is manifested by a designer's ability to "move forward", knowing they will not always be right but rather optimistic about their ability to experiment and conduct midcourse correction further down the road".

3.4 Design thinking tools and techniques with relation to DT phases

Empathize phase

(I) Empathy user interviews are conducted with the user to gain insights into their experience and usability of a solution [21].

(II) An Empathy map is a technique used to explore your users' feelings, believes and values [20].

(III) Personas are archetypical users that are created to represent a user type or user group. These personas include the characteristics of this fictional user such as age, occupation, ethnicity, education, life story, goals, skills aspiration [19].

Define phase

(I) The “How might we” techniques are a powerful tool used to translate the gathered insights in the empathy phase into understanding and framing a problem statement.

(II) The “How might we” techniques are a powerful tool used to translate the gathered insights in the empathy phase into understanding and framing a problem statement.

(III) Pain-storming is very much like brainstorming however it is aimed at uncovering what issues the user has[29].

Ideate Phase

(I)Brainstorming is a great way to generate ideas as a team. It leverages off the collective energy and creativity in the room. When ideas are being positioned, this may trigger more ideas, therefore the team feeds off each other [21].

(II) This technique is aimed at telling the story from a user point of view. It’s a visualization of how the user interacts with the solution. The story board is driven by the scenario that enables the team to come up with ideas to solve the problems [13].

(III) The SCAMPER method is based on asking 7 questions that trigger the thought process into ideating mode [30].

Prototype Phase

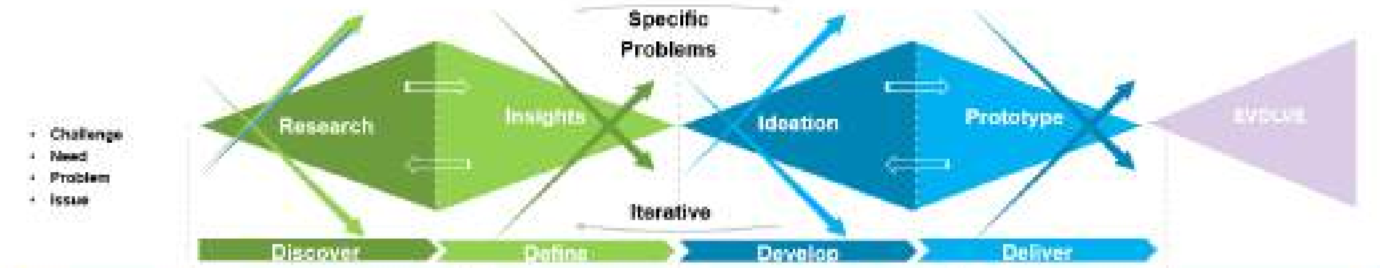
Paper prototyping is more of a low fidelity prototyping method and at a high level it is focused on user experience rather than the interaction with the functionality [24]. Wizard of Oz ‘WoZ’ is a simulation that is human operated instead of an actual built and constructed robotic process.

Test Phase

(I)The concept testing method is used as the “initial” testing. It is usually used to test the first prototype which is likely the low fidelity prototypes[25].

(II) A/B testing: This technique is ideal for any stage of the process whether it be low or high-fidelity prototype testing. It is used to compare two different possible prototypes [10]. (III) Usability is aimed at determining how easy it is for the user to use the prototype. The team gives the prototype to the user and observes how the user interacts with this prototype [21].

Summarized process of synthesis of DT models and PM traditional delivery model



Project Management Process	Initiation and Planning	Execution	Execution	Monitoring and control	Close out and lessons Learned
Design thinking Process	Empathy	Define	Ideate and Prototyping	Testing	Iterate the DT process
Design Thinking Mindset	Empathize Collaboration	Collaboration Empathise	• Experimental • Embrace fear • Embrace continuous learning • Open to risks	• Collaboration • Empathise • Open to feedback	• Experimental
Design thinking Tools and Techniques	• User interviews • Empathy Mapping • Personas • Field Research • Journey maps	• How might we • Why-How Laddering • Point of View (POV) • Rainstorms • Fact, Action, Gasss (FAG)	**Ideate** Brainstorming, Mind Mapping, Concept Map, Sketch Storm, Story Board, Scamper **Prototyping** Story boarding, Sketching, Wizard of Oz, Paper interfaces, Lego prototypes, Role playing, Physical models, User driven protypes	• Concept Testing • A/B testing • Usability testing • First click testing • Tree testing	Iterate and use other methods to reach a higher innovation

GOLDEN THREAD EMPATHY

Figure 2: Merging design thinking process, mindset and tools and techniques with Project Management methodology

3. DISCUSSION AND CONCLUSION

The results of the study are derived by reviewing 29 resources of which 4 were online websites and blogs, 23 are journals and 2 are books.

The findings reveal that DT simultaneously addresses the (1) desirability of the solution, (2) its technical feasibility and its (3) viability. DT is an essential discipline to adopt in any space that requires problem solving especially ambiguous complex wicked problems. The emergent insights in the research emphasize that the DT process drives (1) understanding of the problem, (2) understanding and providing the solution (3) testing the solution in the real world and (4) continuous improvement that could possibly lead to disruptive innovation. The paper highlights the benefits that can be harnessed by closely coupling the DT methodology with the PM methodology. The key benefits of DT were identified and synthesized with the aim to explain and translate the possible benefits of DT within the project management context. The synthesis also revealed that DT goes beyond enhancing the existing project management methodology, DT can mitigate the frustrations that are common in project management.

The application of DT in project management is explained. The DT process, the mindset and tools are explained in detail in this paper, not only from a DT perspective but also combined with the existing PM methodology to map and interlink the respective disciplines. There are many commonalities between DT and PM. These synergies that already exist make it easier to slowly transition the team and organization into a design thinking delivery method. The last figure (Figure 2) displayed above provides a view of how DT and PM can be streamlined into a working process without disturbing the existing flow of a PMO.

Innovation and creativity is the catalyst to wicked, ambiguous and complex projects. Multiple organizations are dependent on the Business and PMO to deliver innovative solutions for them to remain competitive. DT is one of the answers to ensure that projects that are delivered are innovative, the delivery teams are inspired, and user is central. The heart of design thinking is without a doubt “Empathy”. Empathy informs the process, the tools and the mindset. It was the most prevalent concept identified in this review study.

A recommendation would be to expand on this study by investigating design thinking in the banking industry. FinTech’s are the future and design thinking is key to propelling traditional banking into the fintech space without disturbing the legacy products, but rather allowing these traditional products to be phased out in time.

4. REFERENCES

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IMPLEMENTING A KAIZEN PROGRAMME TO IMPROVE PRODUCTIVITY AT A CLOTHING MANUFACTURER IN GAUTENG

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ABSTRACT

This paper reports on the implementation of a Kaizen programme to improve productivity at a clothing manufacturer. It emanated from a referral by the Productivity and Training Institute for the National Bargaining Council for Clothing Manufacturing. The manufacturer faced closure early in 2021 and significant challenges with load shedding and water supply. The primary objective was to achieve more efficient operations and become competitive to ensure its sustainability. The programme included capacity building, workflow analysis, the application of 5S principles, quality improvement and compilation of standard times via time study for its operations. Results over a six-month period indicated marked improvements with, for example, efficiency improving by 118% and reducing rework by 80%, whilst improving employment by 117%. The kaizen programme assisted in creating a foundation for continuous improvement by improving processes and creating productivity awareness amongst employees. Further industrial engineering interventions are planned towards improving processes and enhancing productivity.

Keywords: Kaizen, clothing, productivity, sustainability, operations.

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1 INTRODUCTION

The advent of the Covid-19 pandemic has had devastating effects not only on the livelihoods of the South African population but also on the manufacturing landscape with many organisations struggling to sustain itself. Organisational sustainability is a principle of improving social, environmental, and economic performance in business operations and is paramount in these fluctuating economic times [1]. Mass layoffs and closures had occurred with most businesses seeking funding through the Coronavirus Aid [2]. Company A, on which this paper is based was not spared.

As a member of Proudly South Africa [3], Company A was established more than 25 years ago and has a reputable track-record based in Gauteng. It was taken over by new owners in January 2019 as an ongoing concern with 37 employees. Company A produces exceptional high-quality, specifically tailored clothing ranges, from scrubs to other corporate wear that are professionally executed with well-crafted durable material. The company operated as a subcontractor in the corporate uniform sector and operated very informally without proper infrastructure for administration, finance, and the technical aspects of the company. Van Keuren [4] defines a subcontractor as a person or company which is hired by the primary contractor to conduct specific jobs as part of a larger project. It had two contracts in place that barely brought in a profit and during the onset of Covid-19 they lost both contracts.

Company A was at the brink of closure early in 2021 with only 17 employees and decided to venture into manufacturing fashion clothing on a sub contractual basis. Entrance into this sector was disastrous as they could not improve quality or enhance productivity on the new product, and it became another loss-making exercise. To prevent closure, the company adopted an industrial engineering approach to manufacturing with the aim to reduce rework rate 80% or higher and increase productivity by a minimum of 50%. The company joined Productivity SA's six-month Kaizen Program in 2022 and used their productivity consultant to facilitate the implementation [5]. The primary objective was to achieve more efficient operations and become competitive to ensure its sustainability. The research methodology consisted of Kaizen and 5S principles to effect process improvements towards improving productivity. The programme consisted of four interventions, namely, 5S in the factory and storerooms, improvement in quality control, visual management, and the compilation of standard minute values via the use of time studies.

The aim was to change the approach to manufacturing using work study initiatives on the factory floor to one of continuous improvement and to expand further. Company A faced major challenges, including load-shedding and water supply. This resulted in rushed production and making the implementation of the Kaizen Program difficult to execute within the required time constraints. Concurrently, the company experienced major quality and output challenges resulting in the signing of an Aftercare Programme with Productivity SA on 19 May 2022, providing an additional six months for implementation.

The essential contribution of this paper is the evaluation of processes at Company A to improve productivity, reduce waste and create a productivity awareness amongst employees.

2 PROBLEMS INVESTIGATED AND THE RESEARCH OBJECTIVES

2.1 Problem investigated

The manufacturer faced closure early in 2021 and significant challenges with load shedding and water supply. Company A also experienced major quality and output challenges. Some of the challenges that contributed to lower productivity and rejects entailed high incidence of sewing waiting time due to insufficient throughput, lack of end-to-end planning and monitoring, insufficient skilled workers in critical areas of production and no clear guidelines of management authority and accountability.

2.2 Research objective

The primary objective was to achieve more efficient operations and become competitive to ensure its sustainability.

3 LITERATURE REVIEW

3.1 Reasons for partnering with Productivity South Africa

Productivity SA is established in terms of section 31 (1) of the Employment services Act, No. 4 of 2014 as a juristic person with a mandate to promote employment growth and productivity thereby contributing to South Africa's socio-economic development and competitiveness. Productivity SA is managed in accordance with the Public Finance Management Act (PFMA). The mandate of Productivity SA is to enhance the productive capacity of all South Africans [5].

Company A functioned as a sub-contractor for a total of four companies operating within the corporate clothing sector on an infrastructure that had no formal administration, finance, or technical ability. Out of the four clients, two clients were not profitable as the income derived was minimal, and due to the onset of the Covid-19 pandemic, were lost. In addition, one client had to shut down its business operations and the remaining client decided to relocate to Lesotho for increased cost efficiency. In January 2019, it was sold as an ongoing concern with a staff compliment of 37.

Although there was sufficient work available within this sector, items were priced extremely low, and clients were much stricter on delivery and quality. The result was not as hoped for, as Company A could not achieve the required quality and productivity on the new products. Due to the failure of this exercise, it was decided to seek the root-causes of their losses and hence the Productivity SA Kaizen intervention. On 26 October 2021, the company signed a six-month Kaizen Programme with 17 employees (10 males and 7 females) as referred by the Director of Productivity and Training Institute at the National Bargaining Council for Clothing Manufacturing Industry (NBCCMI) [6]. The main reason for joining the Kaizen Programme was to increase productivity, to reduce waste and bringing awareness of productivity to key employees. The Kaizen approach is appropriately applied for solving the problems because Kaizen functions to tidy up all company activities slowly but with definite results [7]. A. The following steps were taken to execute Kaizen Programme within the company.

Figure 1: Steps to execute the Kaizen programme

3.2 Kaizen defined

Kaizen is a Japanese philosophy that focuses on continuous improvement in all aspects of life. The word "kaizen" is derived from two Japanese words: "kai," which means change, and "zen," which means good. The concept of Kaizen is often associated with the Japanese manufacturing industry when Japanese companies were seeking to improve their production processes and quality standards.

Kaizen also refers to the continuous and gradual development of increasing value, intensification, and improvement [8]. The idea behind Kaizen is to continually make small improvements in all areas of an organisation, from the production process to employee training, with the goal of achieving greater efficiency and effectiveness. Rather than trying to achieve large, sweeping changes all at once, Kaizen emphasizes the importance of making small, incremental improvements over time. These small improvements can lead to significant gains in productivity, quality, and customer satisfaction. Kaizen involves a continuous cycle of improvement that includes four steps, namely:

- ***Plan:*** Identify areas that need improvement and develop a plan to address them.
- ***Do:*** Implement the plan, making small changes to the process or system.
- ***Check:*** Measure the results of the changes and compare them to the previous performance.
- ***Act:*** If the results are positive, incorporate the changes into the process or system. If the results are not positive, repeat the cycle with a new plan.

These are referred to as the PDCA cycle. Kaizen is not just a business philosophy; it is also a way of life that can be applied to personal goals and habits. By making small, incremental improvements in our daily lives, we can achieve our goals and become more efficient and effective in everything we do. Daniel [9] adds that Kaizen speaks to the creation of continuous improvement based on the idea that small, but ongoing positive changes can realize noteworthy improvements. Kaizen is based on cooperation and commitment and stands in contrast to approaches that use radical or top-down changes to achieve transformation. A must mention is that Kaizen is core to lean manufacturing and the Toyota Way. Figure 2 shows that Kaizen includes seven steps, from identifying problems to finding solutions, testing them out, analysing the results and then doing it all again, [9]

Figure 2: Kaizen Seven Steps

3.3. Capacity building

Capacity building refers to the process of developing and enhancing the abilities, knowledge, skills, and resources at an individual and organisational level, to effectively achieve their goals and fulfil their potential [10]. It involves empowering people to develop their strengths, acquire new capabilities, and adapt to changing circumstances. Capacity building plays a crucial role in driving sustainable development, fostering resilience, and promoting positive change.

The key components of capacity building are Education and Training, Skills Development, Institutional Strengthening and Collaboration and Networking. The benefits of capacity building are Improved Performance, Adaptability and Resilience, Empowerment and Confidence and Sustainable Development. Capacity building is a transformative process that strengthens individuals and organisations, enabling them to reach their full potential and contribute to positive change. There was a need to build capacity by upskilling employees as well [11]. Company A saw the need to increase capacity to full orders and increase profitability. They utilised this to promote improved performance and empowerment of employees.

3.4. Workflow analysis

Shepard [12], states that workflow analysis is an innovative way of looking at your processes and improving them. By examining a company's workflows, it assists to improve operational efficiency. It identifies areas of process improvement, such as redundant tasks or processes, inefficient workplace layouts, and bottlenecks in the workflow. It is a series of tasks and the people and resources needed to complete these tasks, [13]. Company A conducted workflow analysis systematically to examine and evaluate their processes, to identify areas of improvement and optimise efficiency. It included flow process charts of the current processes, identifying possible bottlenecks or inefficiencies, and the developing proposed or improved processes to streamline and enhance productivity.

3.5. The application of 5S principles

The American Society for Quality [14] defines 5S as a lean methodology that results in a workplace that is clean, uncluttered, safe, and well organised to help reduce waste and optimize productivity. It is designed to help build a quality work environment, both physically and mentally. The 5S philosophy applies in any work area suited for visual control and lean production. The 5S condition of a work area is critical to employees and is the basis of customers' first impressions.

Table 1: The 5S's

Japanese	Translated	English	Definition
Seiri	Organise	Sort	Eliminate whatever is not needed by separating needed tools, parts, and instructions from
Seiton	Orderliness	Set in order	Organise whatever remains by neatly arranging and identifying parts and tools for ease of use.
Seiso	Cleanliness	Shine	Clean the work area by conducting a cleanup campaign.
Seiketsu	Standardise	Standardise	Schedule regular cleaning and maintenance by conducting *seiri*, *seiton*, and *seiso* daily.
Shitsuke	Discipline	Sustain	Make 5S a way of life by forming the habit of always following the first four S's.

Company A initiated a Kaizen Team to be trained by Productivity SA. The training focused on placing everything where it belongs and ensuring proper housekeeping, which would make it easier for employees to conduct their daily activities without the loss of time or the risk of injury. The Kaizen team was trained on 5S principles during the Kaizen training. During process flow observation and analysis, the team identified various 5S opportunities. A total of six Productivity Champions (who were regarded as the Kaizen Team) representing were trained in the following as displayed in Table 2:

Table 2: Training interventions

Best Operating Practices	5S and 7 Wastes
• Value versus Waste. • Kaizen Toolkits. • Basic Kaizen Tools: • 5S & 7 wastes. • Visual management. • How does a production operation work? • The Level of improvement in • a company. • Identifying and eliminating waste.	***5S Principles:*** Creating a clean and organised workplace for a more efficient working environment. ***7 Types of Waste:*** Understanding activities that cause inefficiencies and increase operational costs.

3.6. Work study

Work study as the systematic examination of the methods of carrying out activities to improve the effective use of resources and to set up standards of performance for the activities being carried out [15]. Work study consists of two techniques, namely, method study and work measurement. These two techniques are used to examine work in any place where work is conducted with the aim of enhancing productivity. It is systematic and follows a set procedure and investigates all the factors which effect the efficiency and economy of the situations being reviewed to effect improvements, [16].

3.6.1. Method study

Method study is the first technique of Work study and is concerned with investigating the methods of working and subjecting them to systematic and critical examination to improve and make it more efficient. IMS [17] states that method study was initially designed for the analysis and improvement of repetitive manual work. Method study can be defined as the systematic recording and critical examination of the existing and proposed methods of doing work, as a means of developing and applying easier and more effective methods and reducing costs, [16]). Slack, Brandon-Jones, Johnston, Singh, and Phihlela [18] add that method study investigates and improves the methods and activities of jobs. Seminal works by work study expert, Kanawaty [15], states that method study can also be seen as the systematic recording and critical examination of the factors and resources involved in an operation to develop a more efficient method and to reduce costs. It can be seen from the above definitions that method study offers a systematic approach to problem solving. Company A used method study to review current processes and then to come up with improved processes. The objective is to make the work method or process more effective and to eliminate unnecessary and inefficient operations and movements.

3.6.2. Work measurement

Stevenson [19] defines work measurement as the length of time that it should take to complete a job. Work measurement is the second technique of the concept work study. Work measurement is mostly concerned with the investigation and reduction of any ineffective time associated with a job or operation. Work measurement has been widely used as a method for measuring actual working time using time study, [20]. The IMS [17] states that work measurement is the process of establishing the time that a given task would take when performed by a qualified worker working at a defined level of performance. Kanawaty [15] defines work measurement as the application of techniques designed to establish the time for a qualified worker to carry out a task at a defined rate of working. Time study is the most commonly used direct work measurement technique to measure work and determine standard times for operations. Company A conducted time studies to determine time for their operations.

4 RESEARCH METHODOLOGY

Kaizen and 5S principles were used as the research methodology to effect process improvements towards improving productivity. It describes actions and solutions implemented towards improving the efficiency in the operational processes. Kaizen can bring many benefits to an organisation, such as improving quality and increasing productivity and efficiency by standardising processes, eliminating waste, and optimising resources.

5 FINDINGS AND RESULTS

5.1 Baseline assessment

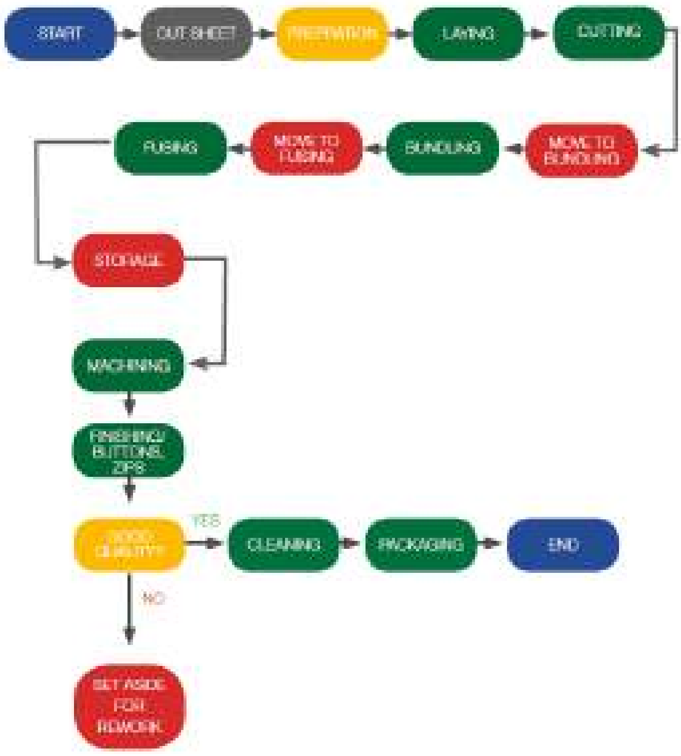
Discussions were held with Productivity SA, the Kaizen Team, and the management of Company A, where an overview and understanding of critical problems experienced in an organisation were illustrated. In addition, it provided an excellent opportunity to mutually uncover, gather and analyse data to better identify improvement opportunities. During the capacity building, the team highlighted issues related to unrealistic set targets applied across the board to all styles of items created, which was unrealistic. This was confirmed by management indicating that the company struggled to meet its daily targets. Furthermore, quality checking was a cause for concern as this was only conducted at the end of the production process, resulting in rejects and subsequent alterations required. By analysing historical data, the problems experienced are contextualised in the table below:

Table 3: Problems experienced

Month Targets- Units/	Targets- Units/Hour	Actual Production Units/hour	Rework %
January 2022	45	30	37.8%
February 2022	45	32	32.5%
March 2022	45	30	26.8%
Average:	**45**	**30.67**	**32.37**

5.2. Process flow analysis

The diagram below illustrates the process map of manufacturing garments.



Key: *Non-value add but Necessary - Wasteful Activity - Value Add activity*

Figure 3: Process flow analysis

5.3 Root causes

The root causes of issues taking place in the process was analysed as depicted in Table 4 below.

Table 4: Root causes

Problems in the process	Causes
Repetitive motions/movements. Time lost waiting and looking for material.	Poor workplace organisation and controlling movement of machines to create space.
Reworks	Lack of QC personnel during the process.
Difficulty in meeting targets due to complexity of product styles	Lack of standard production times for different styles. Sampling is done but no record of time it should take to complete, which will help in determining standard times. Lack of visual management to monitor progress which may help fast track production.

5.4 Kaizen implementation action plan

Table 5: Action Plan

Intervention	Action	Status
1	5S in garment and cotton storeroom and factory	Continuous
2	QC personnel/QC during process	Done
3	Visual performance scoreboards	Done
4	Sampling and setting time standards for different styles. Method study	Done

5.5 Intervention 1 – 5S in factory and storerooms

The main aim of 5S was to eliminate waste of movement of the cutter to the bundling station which is located at the front end from the cutting table. Other aims included reducing time spent searching for the right cotton colours and garment which is sometimes scattered or hidden in the boxes or in and around the office.

Figure 4: Before and after interventions

5.6. Intervention 2 – Improvement in quality control

As noted in the process flow, Company A only inspected quality at the end of the process thus relying on the supervisor to monitor quality and tracking production times. The company now employs two quality control personnel to oversee and solve quality issues, resulting in increased quality checkpoints and a reduction in reworks.

5.7 Intervention 3 – Visual management

The company implemented a visual scoreboard where teams record their hourly output, helping the teams to increase their speed when recognising that they are behind their targets. These are temporarily manual as management has plans to improve this with digital boards.

5.8 Intervention 4 – Standard minute values – via Time study

Company A made use of standard times (also referred to as Standard Minute Value or SMV) and implemented by the previous owners who were not constrained by resources or technical capabilities. Neither were there an issue of creating and producing several types of products, for example, school uniforms, all of which contributed towards setting incorrect targets.

The main goal of the time study was to enable the setting of realistic targets, increasing output rates and cost effectiveness. The company utilised the services of an external consultant to conduct time and method studies of different operations within the factory, largely focusing on the machining of clothes. This facilitated an increased production output.

5.9 Tangible results

Due to successful implementation of industrial engineering techniques, Company A can boast the following achievements:

A sales turnover of R5 200 000.00 by end of February. A 118% efficiency improvement rate due to implementing the VPM board, standard minute values for all clothing cycles, and change in layout/reduction of non-value adding activities / 5S.

An 80% improvement in quality (less rework) rate due to VPM monitoring of actual versus target results, thus planning executed more accurately, training of employees on quality assurance, employing two Quality Officers, and increased quality check points.

Finally, an 118% employment improvement was realised, that is, from 17 to 37 employees.

6 MANAGERIAL IMPLICATIONS

One of the challenges, namely, the lack of guidelines of management authority and accountability alluded to in the problem statement was addressed by the facilitator. It was agreed that these interventions would need to be addressed by management to ensure that there are set guidelines and the level of accountability to ensure operational efficiency. The outcomes from the interventions of the study will encourage Company A's management to monitor the interventions with regular routine checks, [15]. It would also facilitate the skilling of employees and the subsequent implementation of a method study investigation to improve methods of working. It would also ensure that proper standard minute values are compiled for processes by a trained work study officer. Further to this it would assist management in ensuring that set targets for outputs are realistic and achievable. Employees would be more aware of productivity and the need to ensure that targets are met.

7 CONCLUSIONS AND RECOMMENDATIONS

The following note-worthy conclusions were drawn from the intervention:

Company A has made significant improvements in their Kaizen application which assisted in creating a foundation for continuous improvement by initially creating productivity awareness to key employees. This was followed by critical analysis of processes. Through effective questioning, the analysis revealed several gaps in processes such as the basis for target setting, control systems in place to ensure quality and maximum production and the general organisation of the factory.

To close these gaps, the Kaizen team worked on 5S where they removed the unnecessary items from the factory and re-organised some of the machinery and equipment. This allowed for the efficient flow of work and the removal of potential injury threats. The company went further to develop new standard minutes values for assorted styles and method studies were done to simplify machining methods such as handling of garments which resulted in reduction of wasted time thereby improving output rate. Employees were trained on quality and two quality controllers were hired; inspection points were increased thus decreasing the rate of reworks significantly. The agreed performance measures are reflected in Table 6 below.

Table 6: Performance measures

Objective	Activity	Indicators	Baseline	Target	Actual May 22	Actual Jun 22	Actual Jul 22	Actual Aug 22	Impact
Improve factory organisation.	5S implementation	Factory organisation							Improved waste and costs.
Remove non-value adding activities.	Rearrange machinery/ move the bundling station closer to cutting m/c.	N/A							Improved flow.
Measurement criteria aligned to strategic goals.	Key Performance Indicators – Kaizen.	Efficiency/ output rate	32/hr	80/hr	36/hr	60/hr	65/hr	70/hr	80% increase in output.
		Waste/ Rework	37%	5%	18%	9%	4.7%	3.2%	28% reduction of rework.

The intervention was limited to six-months which affected further improvements to enhance productivity. Time constraints also prevented the facilitator from carrying out many observations during time studies. Facilitator was restricted to learning the processes and then improving them. The scale of the Covid-19 pandemic disruption also significantly affected manufacturing companies and the intervention suffered due to this, [21].

As a result of the implementation of their productivity initiatives over the period October 2021 to June 2022 improved line output resulted in an increase from 32 garments per hour to 60 garments per hour and improvement of 87% on like-for-like styles. Reduction of rework rate on their new product reduced from 38% to 8%. Absenteeism decreased from 23.5% to 1.6%. Turnover increased from 5.2 million rand in the last financial year to a projected turnover of 13.4 million rand by February 2023 and employees increased from 17 to 67 employees and improvement of 295%. In the next two to four months, they plan to invest in another sewing line of 22 machines which will create, and additional staff compliment of 25 team members.

The kaizen programme assisted in creating a foundation for continuous improvement by improving processes and creating productivity awareness amongst employees. Further industrial engineering interventions are planned towards improving processes and enhancing productivity.

The interventions allowed Company A to enter the annual Productivity Annual Awards for organisations who have shown significant productivity improvements. Company A won the Gold Award in the emerging business sector.

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AN E-WASTE MANAGEMENT FRAMEWORK TO IMPROVE E-WASTE RECYCLING

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ABSTRACT

The world is undergoing a paradigm shift towards environmental stewardship and sustainable source management. Almost one billion electronic devices will be discarded within the next five years and as a result, e-waste is becoming an increasing challenge for the environment. E-waste recycling also presents many opportunities including reducing the quantity of new mineral resources that need to be mined and creating job opportunities. One of the challenges in South Africa is maintaining collection rates of e-waste to provide recycling facilities with sufficient materials to be sustainable. To interrogate this problem, this study presents a current state-, consumer-, and root cause analysis based on survey and interview data with e-waste institutions, consumers, and recycling facilities. This data and literature were used to develop a framework that can be used to improve awareness and collection effectiveness to address the identified problem.

Keywords: e-waste, recycling, framework

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1 INTRODUCTION

1.1 Background to the problem

E-waste is anything that runs on electricity that has been discarded, damaged, or permanently stored. When electronic products reach End-of-life (EoL), they become e-waste [1]. E-waste includes consumer electronics, white goods, and informative and communication technologies (ICT) [2].

E-waste is one of the fastest-growing waste streams globally, with 60 million tons having been produced in 2016 alone [3]. E-waste recycling can have positive benefits for the economy as it creates a market for recovered products, makes post-consumer waste accessible, and allows valuable metals to be extracted. The recycling industry creates 296 more jobs for every 10 000 tons of disposed e-waste [4]. Recycling and reuse also save energy compared to mining raw materials [4]. However, e-waste recycling is often unregulated and conducted in scrap yards, especially in developing countries [5]. “Backyard operations” can lead to toxic waste at landfills that release hazardous chemicals into the air [6] and can cause environmental pollution. This emphasises the need for formal and managed e-waste recycling activities.

E-waste recycling schemes successfully implemented in developed countries are often not as successful in developing countries that lack sufficient resources [7]. The research of Mmereki [7] shows that developing countries such as South Africa and China are faced with the problem of e-waste increasing by 200-400% from 2007 to 2020. Also, the e-waste management system of developing countries is not as organised. Little consideration is given to e-waste quantification and information is invisible to statistics. Therefore, establishing baseline levels of information where informed policy and management decisions can be made is required to achieve sustainable development targets [7]. The African continent lacks legal e-waste frameworks and proper management [8]. There is often careless enforcement of e-waste management regulations [8]. The lack of general awareness within the community is also emphasized [9].

Currently, e-waste recycling is small compared to general recycling with only 12% of e-waste being recycled, compared to 63% for tin-plate steel cans and 52% for paper [10]. Unfortunately, many recycling facilities regard e-waste recycling as a secondary activity. The reason for this is that at present, e-waste recycling cannot be a self-sustaining business, due to the low volumes of e-waste received from consumers [11]. The success of the formal e-waste sector is limited by the volumes of e-waste released into the e-waste management system [11]. E-waste recycling facilities need a consistent supply of e-waste to function successfully and sustainably. E-waste recycling operations currently function at 20-50% capacity while 70% or higher is needed for sustainability [1].

1.2 Purpose of this study

A significant problem of the e-waste management system is the inadequate amount of e-waste released into the system due to a lack of recycling from households and consumers. Therefore, the study focuses on factors that influence the availability of e-waste as a resource for sustainable recycling business operations, and consequently, the improvement of the e-waste management system.

This study aims to develop a preliminary framework that can be used to create the foundation for sustainable e-waste recycling by summarising the correct approach towards e-waste recycling, emphasizing the importance of increased e-waste awareness, and highlighting channels and activities to progress e-waste collection.

The objectives of the study are to:

- Understand the reason for low e-waste availability within the current e-waste management system of South Africa
- Analyse and determine the interrelationship between the main reasons for low e-waste availability through a root cause and inter-relationship analysis
- Develop an e-waste framework to guide sustainable e-waste management and address low e-waste availability

1.3 Contribution of the study

This study contributes towards setting up a system to increase e-waste collection and add to future sustainability research. The focus is on more established collection logistics, a more convenient e-waste recycling system for consumers, and creating awareness.

2 LITERATURE

This literature explores factors that affect e-waste recycling, including consumer behaviour and awareness, collection strategies, and legislation.

2.1 Consumer behaviour, awareness, and motivational factors

A recurring problem in developing and developed countries is the lack of awareness from consumers. It has been shown that there is a positive correlation between e-waste awareness and higher collection and recycling rates [13]. A study in China found that environmental awareness had the largest positive impact on e-waste recycling behaviours [14]. Awareness creation should include effects on human health, environmental hazards, proper disposal, e-waste management, recycling convenience [15], and relevant legislation [16].

However, awareness is often an insufficient motivator for shifting e-waste recycling behaviours [14]. In 2017 a survey was conducted to understand the behaviour and attitudes of consumers in Johannesburg [10]. When asked, 96% of consumers believed the environment has been negatively affected by e-waste, but only 56% considered their homes environmentally friendly [10]. In Malaysia, Afroz [17] found that although 59% of households were aware of the effects of e-waste, but only a few recycled their e-waste.

In addition to awareness, promoting moral norms and giving consumers access to more convenient e-waste recycling channels are essential motivators to increase e-waste recycling [15][18]. Saphores [20] found that although consumers may be aware of e-waste, 73.1% were often not aware of the location of recycling centres. Consumers are also more willing to recycle if they feel moral responsibility and social pressure [20].

2.2 Collection strategies

E-waste collection is one of the biggest problems identified for inadequate recycling volumes [11]. Many types of collection strategies influence the success of e-waste recycling. There are formal and informal collectors and consumer responsibility strategies to collect e-waste, with collection barriers that must be overcome [11].

The primary modes of collection are door-to-door pick-up, permanent drop-off facilities, or drop-off events. These collections can be done through informal and formal channels [12]. Formal collectors are legal collectors of e-waste who follow the appropriate channels as required by law [11].

Salhofer [20] explain that informal collectors are known as waste pickers. They are unlicensed collectors of waste from landfills, shopping malls, or refuse bins. Lundgren [21] stipulates that the informal sector is typically unregulated, involves low earnings, and is undertaken by individuals or groups using basic technology. The informal sector work in a legal grey zone where activities are prohibited but accepted, creating challenges for the formal sector [22]. Informal collectors have, however, become important in bridging the service component in the value chain. The government cannot compete with the door-to-door collection of informal collectors. There exist opportunities to integrate the informal sector into formal processes to develop a sustainable green economy and e-waste system [23].

2.3 Legislation and Policies

Extended Producer Responsibility (EPR) is an environmental protection strategy that places the financial and physical responsibility of managing and recycling e-waste on the producer for the product's entire life cycle [8]. Four vital principles for an EPR approach are source reduction, waste prevention, environmentally compatible product design, and circular economy for sustainable development [8]. Better e-waste designs are more sustainable, less expensive, easier to process, and 20 times more environmentally friendly [24]. Informing the public on how and where to dispose of e-waste safely is also a part of EPR [25]. The Advanced Recycling Fee (ARF) is an important part of EPR as it assists with financing [9]. ARF is collected from consumers on every purchase of new electronic appliances. The fee is equivalent to the difference between the total system cost and the total claimed value of e-waste [3] [9].

Implementing EPR can have many challenges in developing countries. Most of these relate to a lack of economic and infrastructural capabilities to adopt this model [9]. Challenges further include a lack of formal treatment facilities, illegal imports, the informal sector, and risks for the reuse market [9] [24].

Many countries have different policies and obligations. The similarities between successful systems, though, are the policies created explicitly for e-waste management and the enforcement thereof. In many developed countries, EPR forms a core part of the legislative strategy. This is true for countries such as Switzerland [9] and Germany [26]. The policies of Switzerland cover all aspects of the e-waste management system from collection to disposal [9]. Developing countries need clear and defined roles from the government [9]. The e-waste system will not be successful if all responsibility falls only on manufacturers and consumers.

3 METHODOLOGY

To achieve the objectives of this project, a structured approach was followed to assist with decision-making and problem-solving. During the first phase of the project – requirements – the necessary background of e-waste recycling was obtained. This covered aspects of reverse logistics, collection, and legislation. The overall need for the system was also identified. From there, various existing internal expertise was used. Existing internal expertise is data collected from e-waste recyclers through interviews. More data collection was done through qualitative measures such as primary data collection and secondary research. Primary data refers to the survey conducted with consumers. Secondary research entailed desktop research of the e-waste industry. A root cause analysis could then be done to define the problem.

Various tools led to a broad understanding of the whole system, how factors influence each other, and how to approach the problem. The literature study was further used in this approach – researching various sources applicable to the South African context.

Once the needed research was completed, this knowledge could be transferred into concept designs. These designs included potential solutions that are all applicable to the South African context. After evaluating these designs and comparing them to the purpose and objectives, a final integrated design was chosen. The final design is explained in detail. The final design integrated knowledge obtained from the research, consumers, stakeholders, and e-waste experts. Lastly, to conclude the project, the recommendations and future work opportunities were set up.

3.1 Stakeholder interviews

Semi-structured interviews were conducted with 22 stakeholders, as seen in Figure 1, to understand their perceptions and experience of the current state of e-waste recycling. The stakeholders were from e-waste institutions and recycling facilities, schools and universities, service delivery enterprises, malls and retail stores, petrol stations, and municipalities.

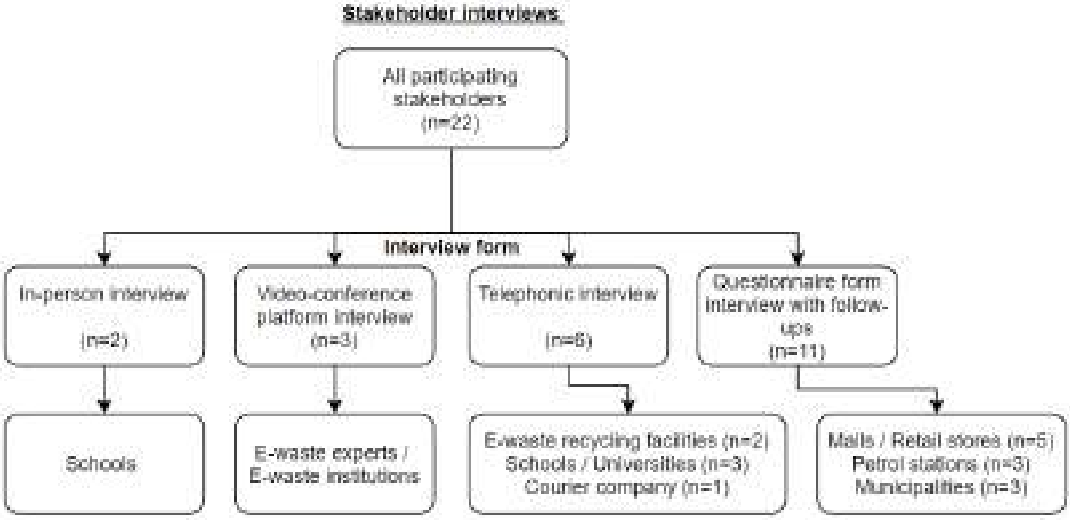

Figure 1: Stakeholder interviews breakdown

3.2 Consumer survey

To explore consumer perceptions, recycling behaviours and preferences, a consumer survey was conducted. The questions were set up to determine consumers' knowledge of e-waste, which recycling methods they would prefer, and more importantly, support.

To collect the survey data, an online link was shared on social media platforms to reach consumers in South Africa. Responses were accepted for the survey over a period of 3 weeks. A total of 360 responses were received.

3.3 Data analysis

The data from the interviews were used in conjunction with literature to conduct root cause analysis and identify the main issues affecting the e-waste management system in South Africa. The consumer survey was used to explore consumer perceptions and behaviours concerning emerging issues. Both data sources were then used to construct a framework that could be used to guide e-waste development and increase e-waste collection.

4 RESULTS AND ANALYSIS

The stakeholder interviews focused on the formal e-waste sector, while the survey focused on consumers. This was done so that the input from both stakeholders can be integrated into concept solutions on how to increase e-waste collection.

4.1 Stakeholder interviews

The interviews identified existing processes, how they work, and the focal points of e-waste recycling facilities. The interviews highlighted problems that the participants have (crime, costly legislation, not enough e-waste), what they would want to improve upon (lack of awareness from consumers, collection points), and future considerations (security, theft, motivation to recycle).

4.2 Consumer survey data results

Firstly, when asked if the survey respondents know what e-waste recycling is and how unsafe it can be, only 19% said yes, 57% are aware of some information, and 24% has no knowledge. Fortunately, 82% of the respondents are willing to recycle. Respondents who indicated, 'it depends' on would want to ensure that the recycling facilities' process is up to standard and that recycling is convenient and accessible.

Respondents were asked about their preferences for different types of existing collection schemes in South Africa. Interestingly, the highest choice of 60% was un-incentivised drop-off bins. Incentivised drop-off had a 48% preference. When asked if the respondents have used any of the schemes, 83% of consumers indicated that they had not.

The respondents were then asked if they would support other types of collection schemes. The highest voted scheme was e-waste events and campaigns with 67%, and another 18% said yes if it is interesting. Furthermore, 97% of the respondents indicated that they would be willing to recycle if they were equipped with enough information and similarly, 95% of consumers would be willing to drop off their e-waste at bins in convenient and well-known places.

4.3 Root cause and Inter-relationship analysis

The data from the stakeholder interviews and consumer survey were used in conjunction with literature to identify and analyse the root causes that affect the sustainability of e-waste recycling and the low availability of e-waste in the e-waste management system.

4.3.1 Root cause analysis

The identified root causes were classified into six categories and are presented in a Fishbone Diagram in Figure 2. These six categories are 1) legislation, 2) environment, 3) consumers, 4) labour force, 5) material, and 6) system.

There is a general lack of e-waste-specific legislation and implementation which then constrains formal e-waste recyclers. South Africa also faces contextual challenges such as a lack of infrastructure, development, and collaboration. There is also a shortage of specialised and skilled labour. All of these challenges are enhanced by formal and informal e-waste sector rivalry, the effort associated with recycling, and the lack of awareness, motivations, and standard procedures in place for consumers to be a part of e-waste recycling.

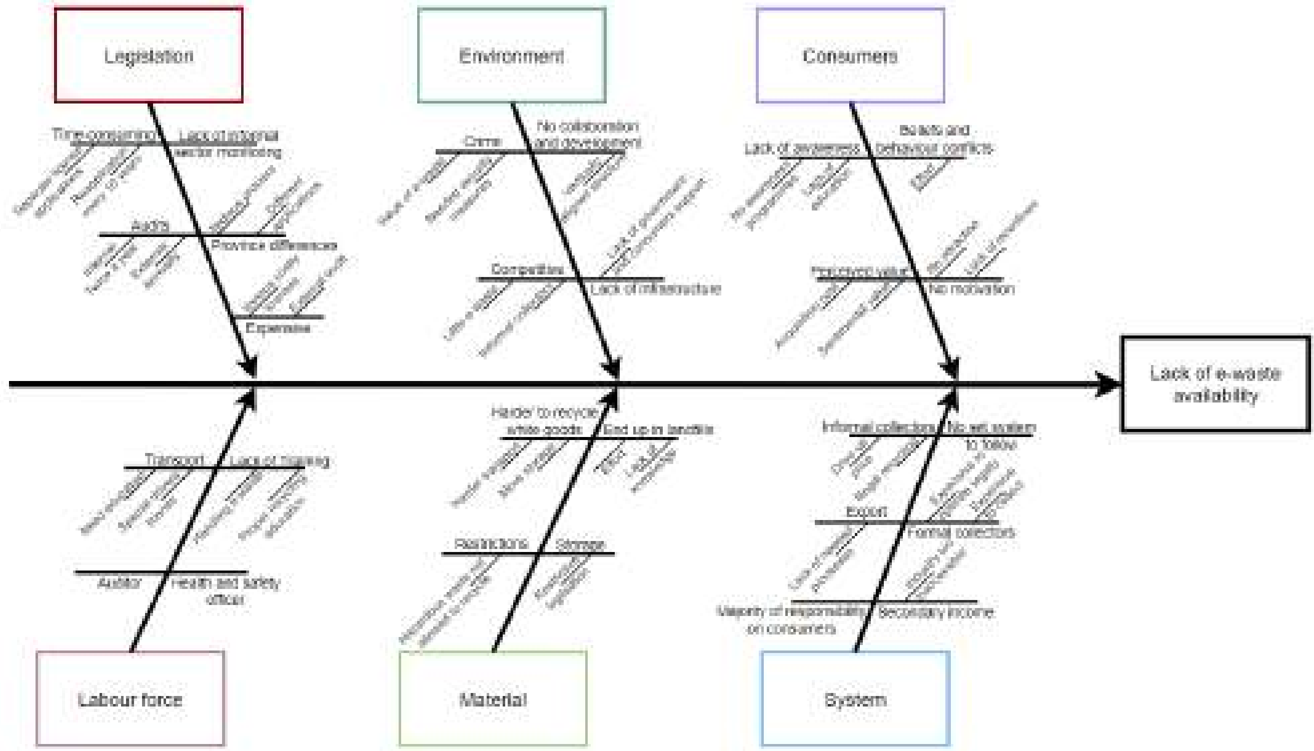

Figure 2: Fishbone diagram for lack of e-waste availability

4.3.2 Inter-relationship analysis

Figure 3 represents the interconnectedness of the factors that influence low e-waste availability. To determine the links, all the factors that influence each other were connected. In the industry environment, competition is linked to the formal and informal e-waste sectors as they compete for e-waste. The system is governed by legislation, also recycling facilities need to export e-waste due to the lack of processing infrastructure in South Africa where e-waste recycling is mainly a secondary source of income. Informal collectors are also linked to the lack of monitoring of the informal sector. There is a lack of awareness among consumers because there is no set system for all parties. There are also internal links – the perceived value of e-waste is much higher as consumers do not know how much e-waste is worth. No motivation is linked to contradicting beliefs and behaviour, and the latter is again linked to a lack of awareness. Legislation is not linked to other elements but influences most factors. Lastly, material handling and human resources are regulated through legislation. These connections highlight the importance of considering the impact of all factors when developing solutions.

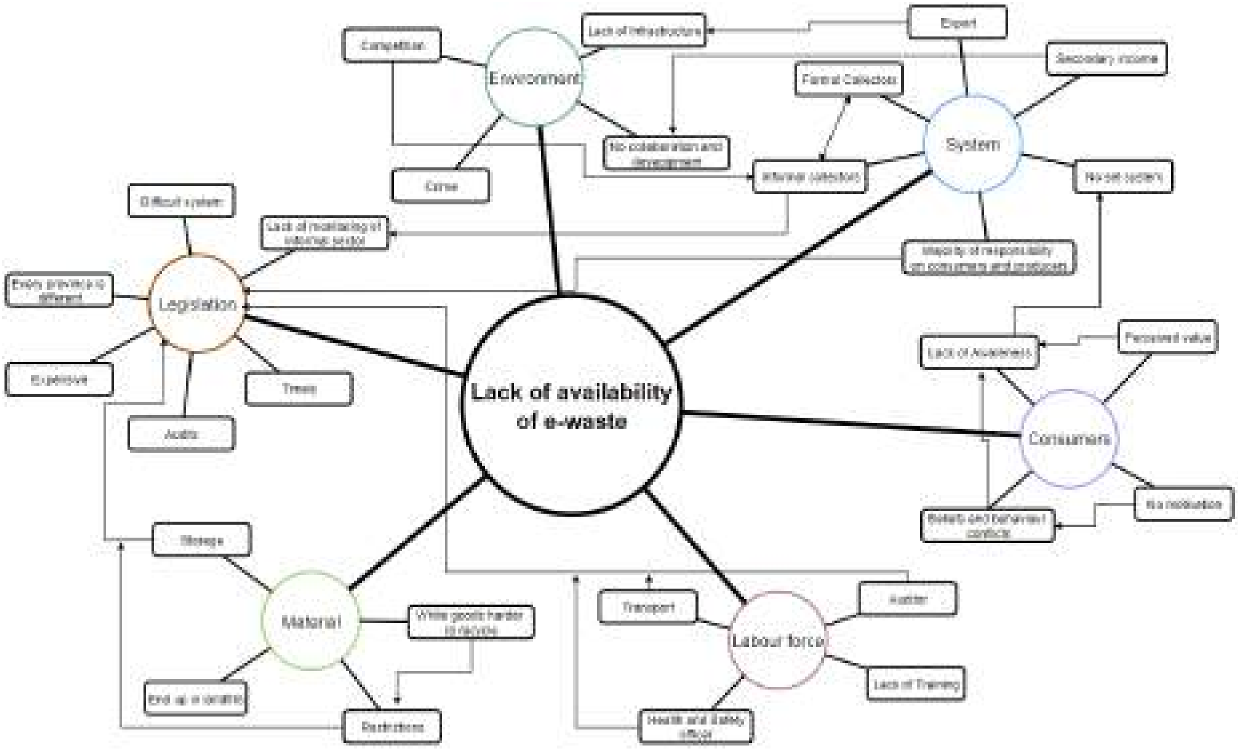

Figure 3: Interrelationship diagram showing interdependencies between factors

5 FRAMEWORK DEVELOPMENT

5.1 Framework overview

The framework was developed using the interview and survey data and literature of this study. Figure 4 displays the major components within the framework. Based on the needs identified through the root cause analysis, the main focus of this study is the e-waste management system, creating awareness, establishing partnerships, and collection strategies. These four components create the foundational solutions needed to progress sustainable e-waste recycling in South Africa. Informal sector formalisation and the logistics framework link to collection strategies as they are additional methods to explore for increased e-waste collection. Through this, the informal sector will act as a partner in collecting e-waste, while logistics focuses on route optimisation and using third parties to collect e-waste.

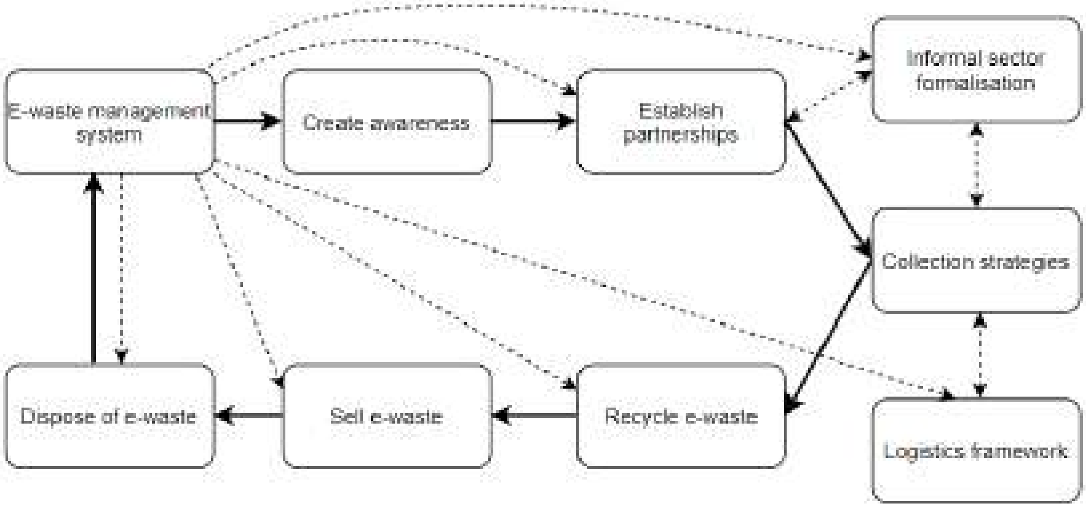

Figure 4: High-level e-waste recycling framework

Figure 5 links to Figure 4 but further represents an implementation timeline that suggests the order in which elements should be implemented due to their interconnected nature. Detailed explanations of all the elements within Figure 5 are explained in the following section. It is important to note that this framework is based on the existing e-waste management system and elements that are already in place, but the effectiveness and efficiency need to be improved for it to work optimally. Therefore, the order of the timeline may not be logical compared to a newly developed framework. Time of implementation is also a factor. The system needs to be improved as soon as possible without unnecessary delay.

Based on the current system, awareness campaigns and e-waste events are needed to first inform consumers about e-waste. Collection strategies must then be in place to support consumer recycling. The correct legislation is also needed to ensure the correct channels and processes are followed and enforced but has a much longer development and implementation timeline. Then forming partnerships, formalising the informal sector, and setting up logistics require the foundational elements to be in place first.

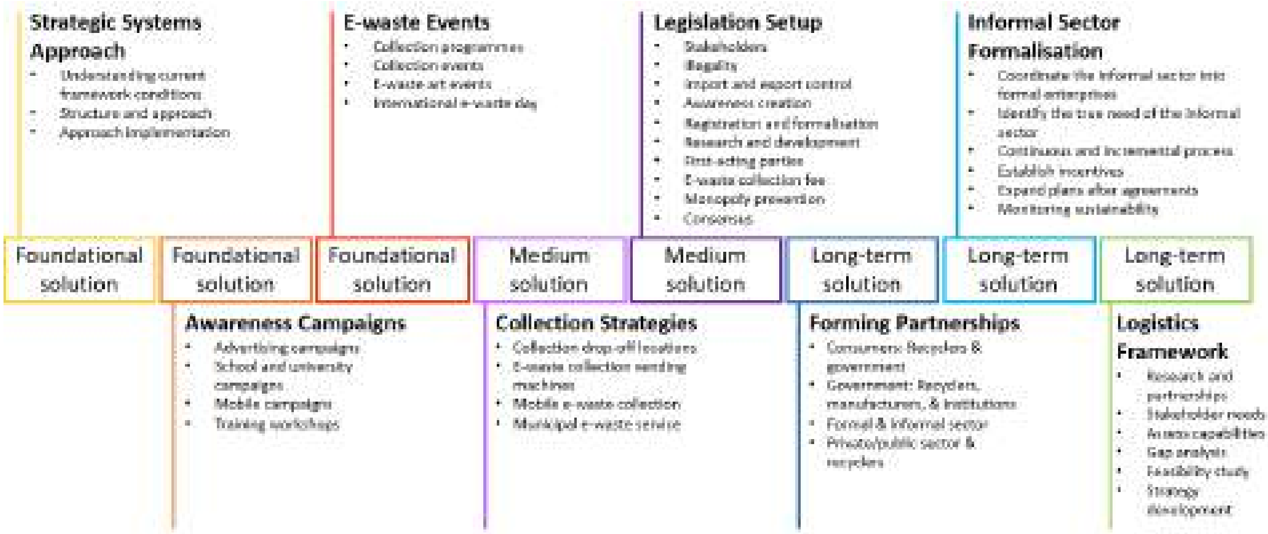

Figure 5: High-level e-waste recycling framework implementation timeline

5.2 High-level e-waste recycling framework detail

Within this framework, only the foundational solutions are discussed. To be able to implement medium to long-term solutions sustainably, the foundation of e-waste management must be set up correctly. For this, the correct strategic approach is needed to plan details of the e-waste management system, awareness campaigns are needed to emphasize the importance of e-waste recycling, and e-waste events create easily accessible channels to motivate e-waste collection and recycling. The following sections will discuss these.

5.2.1 Strategic system approach

For a sustainable e-waste management system, certain main services must be delivered. This includes e-waste collection, recovery of valuable secondary materials, and separation and safe disposal of e-waste [27]. The goal should be to prevent illegal dumping and recycling, divert e-waste from municipal waste streams, and recover e-waste discarded at landfills or incinerators. The fundamental factors are to create awareness among stakeholders, organize events, develop collection strategies, adopt policies, establish networks, assign responsibilities and improve communication between stakeholders [28]. To that end, it is necessary to know the amount and type of material received, how it arrives at facilities and how it is processed, the output type and conditions of different materials and components, activities in disposal and recycling, and any information concerning research, education, innovation, and outreach [28].

Based on the research of Torres [29], Puja [30], and Schluep [31], key steps have been identified for sustainable e-waste management with special relevance to developing countries. These steps include:

1. Identify e-waste production sources and account for the management of volumes
2. Understand the current e-waste conditions in the region
3. Structure an approach with a focus on:
   - Policies and regulations
   - Business and financial management
   - Training and skill improvement
   - Continuous monitoring and control
   - Marketing and awareness creation
4. Implement the approach according to:
   - Available time
   - Roles and responsibilities
   - Existing and new partnerships
   - Open communication and coordination
5. Continuously focus on recycling, repair, and reuse and improve technology for more efficient e-waste management

5.2.1.1 Understanding the Current Framework Conditions

The local, regional, and national conditions regarding e-waste must be understood. This is done through thorough country assessments [31]. The country assessment looks at various developed and developing countries that have well-established or similar e-waste management systems to South Africa. The success and failures of these countries are lessons that can be applied to South Africa [31]. Data can be collected through literature, statistical data, meetings, and field investigation. These assessments usually deliver stakeholder interactions, possible partnerships, e-waste flow, and hotspots to address a sustainable e-waste management system [31].

5.2.1.2 Structure and Approach

After the current framework and landscape have been explored, a structure and approach for implementation can be devised. The following five areas are the focal points in the structure. Marketing and awareness creation is explained in more depth later as it acts as a foundational solution.

Policy and Legislation Construction

To improve e-waste management in developing countries, thorough legislative frameworks must be constructed without conflicting objectives [5].

Business and Financial Management

Without effective management, the e-waste system will not be able to generate enough income to be sustainable. This framework includes establishing a process that will accommodate negotiations for stakeholders, identifying institutions for responsibility allocation, and developing a system to ensure long-term financial sustainability [31].

Training and Skill Improvement

These activities aim to develop an efficient e-waste sector. The best techniques and practices must be tested and documented and applied based on established international initiatives [31]. Control and monitoring mechanisms, such as reports, audits, and PROs, are needed to track e-waste flow within the system [26]. Lastly, skills and capacities can be improved through employee training and infrastructure development of recycling facilities [26].

Continuous Monitoring and Control

There are various activities to ensure continuous improvement and compliance within the e-waste system. These activities include establishing an auditing process and technical standards, continuously collecting data for monitoring, a mechanism to update the data continuously, and using the data for informed decision-making and improvement [31].

Marketing and Raising Awareness

These activities include using appropriate means to make information available and urging stakeholders towards a sustainable system through personalized solutions [31].

5.2.1.3 Approach Implementation

The implementation can be divided into different timeframes – immediate actions, medium-term, and long-term solutions. The exact timeframe will depend on the entities implementing the operations and their resources.

Roles and Responsibilities of different Stakeholders

Chaudhary & Vrat [26] and Torres [29] describe the stakeholders' roles and responsibilities within the e-waste system. The first is Producers. As producers have comprehensive management, the required responsibilities, not enforced by legislation, are proper disposal of e-waste, establishing an accessible collection system, creating awareness, and designing environmentally friendly electronics. It is also important that producers are transparent and indicate where harmful substances are and how to remove them. In the same way, recyclers and disposers have required responsibilities to manage e-waste and disposal of e-waste remains. Retailers should take back electronics and create awareness. Distributors can also be included in this category. The responsibility of distributors is to set up designated collection points and encourage recycling.

Support Framework

There are successful legislation and initiatives in place in developed countries such as Switzerland and Europe. Switzerland has encouraged and supported developing countries for the past 15 years [32]. International organisations can be approached to help advise the set-up of legislation and recycling policies, increase expertise in business and finance and improve technology and skills. Sound advice and support are needed to establish a successful e-waste system [27].

Local partnerships are also important, as mentioned in the following sections. Partnerships should be given enough time to get organised, establish themselves in a new environment, establish their structures and framework, and find momentum. The partnerships must be transparent to prevent miscommunication and conflict. A separate institutional framework can also be constructed to accommodate negotiations among all stakeholders.

5.2.2 Awareness Campaigns

Based on the consumer survey, most consumers do not know what e-waste recycling is, the dangers and benefits thereof, or how to be a part of it. There are various schemes in which awareness can be created. Advertising, campaigning at schools and universities, competitions, mobile campaigns, conferences, workshops, and information sharing through leaflets or social media. There are, however, factors to consider when creating these campaigns. Private and public partnerships are crucial for funding and sustainability, the content must appeal to all stakeholders, including the government, and communication between stakeholders is also crucial for effective implementation.

5.2.2.1 Advertising Campaigns

Through television, radio, blogs, newspapers, influential people, and public companies, numerous users are reached and systematically influenced to recycle their e-waste. Advertisements promoted on these platforms should focus on the most essential information that can be transferred shortly and effectively. This includes what e-waste is, the dangers, how and where to recycle, and further contact information to obtain more knowledge. Sharing footage of e-waste activities will also greatly influence electronics users to see first-hand what it entails. This creates transparency between relationships and the urge to support these activities.

5.2.2.2 School and University Campaigns

The youth is the future and needs to be educated on such a cause. This can be done through shows, talks, performances and competitions at these institutions. Students could also be provided with the opportunity for e-waste training programmes and visits to recycling facilities to intrigue their minds further. Campaigns at schools and universities must consist of some key aspects – education, entertainment, motivation, moral responsibility, and reward.

5.2.2.3 Mobile Campaigns

School campaigns are unfortunately not always practical for rural areas. Furthermore, recycling facilities are almost non-existent in rural areas. A mobile campaign can be used to address these challenges using a mobile vehicle that addresses education needs and can collect e-waste simultaneously. Through a mobile campaign, awareness can be created when travelling to different locations. The mobile vehicle is also installed with the correct equipment to transport e-waste.

5.2.2.4 Training Workshops

Training workshop entails investing in the community by developing the skills of the informal sector, the community, or students. Participants can be taught the dangers and value of e-waste, and environmentally friendly techniques to dispose of, refurbish, recondition, dismantle, and recycle e-waste. Training should include professional, certified training, varying in length and complexity.

5.2.3 E-waste events

E-waste events are closely linked to creating awareness. Numerous types of events are used to create awareness and educate consumers.

5.2.3.1 Collection Programmes

A collection programme refers to e-waste being collected over a medium-term period. The programme may be implemented for all electronic users and households willing to recycle and may be a public-private initiative. Thus, the public may be able to dispose of their e-waste at selected drop-off sites or events. This collection program launches as an official event for consumers to take notice of and be informed. People are more likely to partake in such events if it is well-known, there is peer pressure from other participants, and if people are contributing towards a bigger goal.

5.2.3.2 Collection Events

Like collection programmes, collection events are also focused on collecting e-waste, emphasising education, and creating positive associations with e-waste recycling. The focus of these events will convey information to consumers and answer any questions. However, these events also focus on entertainment. Hosting these events during holidays and over the weekend will increase participation as people can participate more easily. Marketing and advertising at schools, online, and through print will also attract more people. After e-waste has been collected at these events, the partnering recycling company will collect it. These companies can also be active at the events themselves and further educate consumers.

5.2.3.3 E-waste Art Events

Another event that has proven to be successful is an e-waste art gallery. Sculptures are created by art students at Universities using e-waste obtained from recycling facilities. The sculptures make visible the growing problem of e-waste. The main attraction is the art, but to create e-waste awareness, the audience is also educated. Bins will also be provided for consumers to dispose of their e-waste.

5.2.3.4 International E-waste Day

International e-waste day is a new initiative that took place for the first time in 2017. It is coordinated by the International Telecommunication Union (ITU), in collaboration with the WEEE Forum. The purpose is to motivate all countries to partake in the initiative. To be successfully implemented in developing countries, it is recommended that all stakeholders come together to coordinate activities. The ITU provides support and advice for countries who wish to be involved.

5.2.4 Collection Strategies

Once awareness has been created, there will be more success in collecting e-waste. E-waste events are already a step towards collecting e-waste but if e-waste volumes are to increase significantly, more formalised and established collection strategies need to be developed. The collection strategies recommended as part of this survey emerge from best practices and the consumer survey that was conducted. The strategies include a range of solutions that cater for a variety of consumer needs including drop-off bins, vending machines, mobile collection and municipal collection services. Consumers refer to households, public and private companies, institutions, and the government.

5.2.4.1 Drop-off Bins

The strategic placement of e-waste drop-off bins is based on the principles of consumer behaviour and motivation. The survey results and research analysis indicated that ease and convenience of recycling are the biggest factors for increased recycling rates. Apart from e-waste bins at schools and other community centres, street bins can be placed throughout communities. Even though these bins are secure and hard to break open, consumers must not be in danger of theft when visiting the bins. The most preferred locations based on the consumer survey were schools, malls, and petrol stations. Bins can be fitted with sensors that alert recycling facilities when bins are full to optimise transport planning.

5.2.4.2 Collection vending machines

Collection Vending Machines (CVMs) are a convenient and safe way to collect smaller and more valuable electronic devices. These can be placed in malls and can evaluate e-waste and reimburse consumers for disposing of e-waste [33]. CVMs can also use sensors to track how full the bins are, notifying recyclers when they are full. Based on this data and disposal rate, decisions can also be made to determine how many CVMs are needed at which malls, which CVMs per location are being used more, and how to use this data to increase the e-waste disposal rate.

5.2.4.3 Delivery Service Enterprise Collection

Another convenient way that e-waste can be collected directly from households is through delivery service enterprises. Using interactive online maps for household collection requests and without much deviation from scheduled routes, e-waste could be collected from households. The e-waste can then be delivered to recycling facilities or collected at delivery service enterprises. Local authorities or recycling facilities should provide incentives for these enterprises and the terms of the partnership should be mutually beneficial. Due to social responsibility and high perceived quality, being a part of a sustainable and green movement already creates positive publicity and marketing [34].

5.2.4.4 Municipal E-waste Service

The last collection strategy is to use the current municipal waste service to collect e-waste. Only 7% of South African e-waste is intercepted before entering landfills [2]. As indicated by one of the e-waste experts from the interviews, in the future e-waste will also be prohibited from entering landfills. This can be difficult to control in developing countries and can increase illegal dumping. Using the municipal waste service to separate the e-waste from general waste before dumping and creating a landfill collection site can address this. However, trust in municipal systems can be a challenge. The consumer survey indicated that 44.41% of consumers would be willing to use the municipal collection service, but concerns were raised about being continuously disappointed by municipal services.

5.3 Framework validation

To validate the proposed framework, four e-waste experts were consulted for evaluation purposes. The experts have experience and field knowledge about e-waste recycling in South Africa. The feedback was positive and confirmed the accuracy of the identified key factors and the suitability of the proposed solutions. Several insights and recommendations were made by the experts which have been incorporated into the final framework. Further insights highlighted that:

- Education and creating awareness are a long and continuous process that should incorporate numerous stakeholders
- Labour and logistics costs are the most expensive costs to consider
- Formalisation of the informal sector holds great potential for e-waste collection

6 CONCLUSIONS AND RECOMMENDATIONS

A comprehensive analysis of the e-waste system revealed numerous factors that contribute to the e-waste low e-waste collection rates in South Africa. This analysis included thorough research on the overall e-waste industry – locally and internationally, stakeholder interviews, and a consumer survey. It was found that the main cause of low levels of e-waste in the recycling system is due to a lack of awareness, education, and collection strategies available. To address this problem, research, and requirements from e-waste recycling stakeholders led to solutions that focus on creating awareness, educating consumers, and providing easy and convenient collection strategies.

The results and analysis show that there exist opportunities to increase the flow of e-waste volumes from consumers to the formal e-waste recycling sector through various solution strategies. To fully utilise the potential of this increased e-waste flow, it is recommended that the timeline suggested by the high-level e-waste recycling framework be followed. The foundational solutions must be implemented first to create a stable starting point for further e-waste management strategies to build on. Without fully understanding the components of the strategic systematic approach and creating e-waste awareness, e-waste events will not have the same success rate. It is then recommended to implement the medium-term solution for more long-term success possibilities. More established collection strategies with supporting legislation enhance the opportunity for increased e-waste collection.

Finally, long-term solutions are needed to create a sustainable e-waste management system. Forming transparent and long-term partnerships between various stakeholders within the e-waste management system is the key to a coherent and well-functioning system. A partnership between the formal and informal e-waste recycling sectors is crucial as an informal sector formalisation framework is a potential collection resource that needs to be utilised, especially in a developing country such as South Africa. From there, a logistics framework can be set up that includes optimised transportation routes, collection routes, gap analysis, feasibility studies, and software systems.

Further recommended research can be explored to increase e-waste recycling rates and include:

- Set up an e-waste recycling regulatory framework
- Explore options on how to set up a record-keeping system that can be implemented within the informal e-waste sector
- Compare solid waste legislation and e-waste legislation to identify which laws can be amended and applied to the e-waste management system and assess the effectiveness of e-waste legislation
- Determine how the formal and informal e-waste sectors can be integrated into a reverse logistics model to deliver an optimal and flexible route collection system
- Determine the deep social aspects and crucial social factors of the two e-waste recycling sectors (formal and informal) working together

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FROM CONDITION MONITORING TECHNOLOGIES TO CONDITION ASSESSMENT SYSTEMS – SOME INSIGHTS FROM INDUSTRY PRACTICES

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ABSTRACT

Condition monitoring and condition assessment form the basis of informed decision-making for process optimization and effective management of industrial assets such as equipment, machinery, facilities and infrastructure. Various methods/techniques are used to capture and analyze data and information associated with engineered assets utilized in industrial operations. For pragmatic reasons, condition monitoring tends to be limited to the technical dimension of condition assessment. This limitation often results in narrowly-informed decisions, ineffective actions, suboptimal interventions, and poor asset management performance. Curiosity questions the extent to which acclaimed 4IR technologies are currently applied to *monitor* and *assess* the performance of engineered assets in real time. This article explores the claims based on recent case studies of actual industry practices in existing mining and coal-fired power generation facilities. The discourse further explains the dyadic relationship between condition monitoring and condition assessment in the context of long-lived engineered assets.

Keywords: Condition Monitoring, Condition Assessment, Asset Performance, Engineering Management

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1 INTRODUCTION

There is perpetual need to continuously obtain and keep track of accurate, authentic, relevant, and valid data and information to control and optimize processes, and concurrently, to indicate the condition of equipment, machinery, and infrastructural systems that facilitate all aspects of human endeavor in all sectors of governance, commerce, industry and society. The need to track rapid changes in process conditions concurrently with changes in the condition of operational equipment and machinery in conventional fossil fuel power generation and mining has become paramount given the increasing concerns to mitigate the effects of climate change. Techniques such as visual inspections, non-destructive testing, photographic and optical imaging, as well as the sensing of a variety of parameters (e.g., pressure, temperature, flow, pH, dissolved oxygen, dielectric polarization) that generally represent physical phenomena are typically used to obtain data and information to control and optimize processes as well as to determine the condition of operating equipment and machinery, either in real-time, or at specified intervals/periods in time.

The techniques are increasingly embedding intelligent/smart sensing to provide multiple criteria data and information for real-time monitoring, tracking and assessment of the condition of engineered assets, particularly in power generation and mining operations. In theory, it is desirable to obtain the widest range of data and information so as to monitor and track in real-time, the rapidity of changes happening internally within operating engineered assets as well as changes induced/imposed by events taking place within the operational environment. In practice, the process of acquiring, manipulating, analyzing and utilizing such 'big data' can be burdensome. However, it is envisioned that capabilities inherent in 4IR technologies such as IoT, distributed ledgers (i.e., blockchain), sophisticated artificial intelligence algorithms (e.g., deep learning, natural language processing), augmented, virtual and extended reality imaging and mapping, across digital age platforms (e.g., RAMI 4.0[†]) enable and facilitate digitalization of the dyadic processes of condition monitoring and condition assessment.

On the one hand, researchers, original equipment manufacturers, suppliers, vendors and systems integrators are forging ahead and making available technologically advanced devices and systems that can be applied for the linked purposes of (i) control and optimization, and (ii) condition monitoring and performance assessments of engineered assets. On the other hand, the challenges of (i) introducing and integrating new technologies, coupled with (ii) upgrading and retrofitting existing equipment, machinery and infrastructure, together with (iii) updating/upgrading legacy systems and work procedures, to (iv) transforming attitudes and behaviours, are not trivial pursuits for owners and users (e.g., operators of equipment and machinery) especially in asset and energy intensive power generation and mining. The question arises as to the extent to which actual industry practice is keeping pace with claims of advances in condition monitoring technologies and condition assessment systems. This paper, which is the third in the series, explores this question. The discourse is based on further observations of actual practice in some existing industrial sites and operations. The earlier papers reported on recent case studies conducted in 2020 and 2021 on condition assessments of railway infrastructure, primary healthcare, high schools and municipal waste water treatment facilities. In addition to the 2020/21 case studies (see [1], and [2]), the views expressed here are based on case studies conducted in 2022 regarding actual industry practice

[†] *RAMI 4.0 – Reference Architectural Model for Industry 4.0 (IEC PAS 63088)*

of condition monitoring and performance assessment of equipment and machinery in three upstream mining operations and a power generation facility.

This paper is structed as follows. Section 2 of this paper contains a brief discourse on the dyadic relationship between condition monitoring and condition assessment given that, in practical situations, there tends to be an implicit requirement to do both simultaneously. Examples of current industry practice of condition monitoring are briefly described in sections 3 and 4. The concluding remarks in Section 5 highlight some insights distilled from the case studies.

2 CONDITION MONITORING AND CONDITION ASSESSMENT

There is abundant literature and discourse on methods and techniques for detecting the incidence of degradation mechanisms, particularly in static equipment and rotating machinery deployed in industrial plant operations (re: [3]). For brevity, the references [4] [5] [6] [7] [8] [9] are cited in this paper given that there are several academic journals as well as a myriad of trade magazines devoted to the subject matter of condition monitoring technologies. In manufacturing and processing operations, condition monitoring technologies are typically deployed and utilized to facilitate control and optimization of industrial processes as well as to initiate maintenance interventions. Thus, a customary motivation and justification for investing in and applying the condition monitoring technologies is to determine or ascertain "asset health" – which, in a sense, is a curious colloquial! A more pragmatic motivation is to detect abnormal deviation, incipient defect(s), and to track the rate of degradation as trigger and leading indicator of one or more failure modes intrinsic to an item of equipment or machinery [10]. Extant literature indicate how condition monitoring technologies are customarily applied to facilitate the planning and execution of appropriate maintenance interventions. Hence, the terminology that has become widely associated with the application of condition monitoring technologies is 'predictive maintenance.'

Although the reliability-centered maintenance philosophy is well established in terms of failure modes analyses, however, condition monitoring tends to be narrowly focused on the observation and tracking of the signals pertaining to particular failure modes that are intrinsic to an item of equipment, machinery or engineered structure. The process requires that an item of equipment or machinery be resolved into its components, so as to apply the sensing and monitoring method that is most sensitive to the changes experienced by the respective component. For example, the blades, bearings, and shaft are components (i.e., failure modes) of the rotor of a wind turbine. Ultrasound sensing can be used to monitor blade changes while vibration sensing can be applied to monitor changes induced in the bearings and the shaft. A similar resolution can be applied to the drive train, generator, transformer, tower, etc. From a management viewpoint, monitoring the condition of a wind turbine ([11], [12], [13]) can be quite onerous for an operator/maintainer of a renewal energy power station. Similarly, condition monitoring represents a daunting challenge that confronts the operator of a steam turbine in a coal-fired power station or an operator of earth moving machinery in mining.

With condition monitoring technologies installed, it is not surprising that business managers often ask whether an asset (e.g., equipment, machinery, facility or infrastructure) is in a 'good' or a 'bad' condition! Technical personnel focused on condition monitoring technologies ponder to provide credible and satisfactory answer to what is, essentially, a condition assessment question. The implied question is more about assurance that the asset has technical integrity to function, that is, to deliver the required services at specified or desired level(s) performance in terms of economic, environment, social, and governance metrics.

Interestingly, the term condition assessment is more commonly discussed in the context of facilities and infrastructure, somewhat muting the fact that equipment and machinery inherently form part of facilities and infrastructure. Condition assessment tends to focus on issues such as technical integrity/safety, cost, ergonomics, impact on environment, *et ceterra* (see, for example, [14] [15] [16] [17] [18] and [19]). The reality is that condition monitoring feeds into condition assessment, that is, data and information derived from various monitoring technologies are typically collated to form the inputs for condition or performance assessment. This means that condition assessment is typically conducted at higher levels in the hierarchy of assets, whereas condition monitoring takes place at lower levels of the hierarchy of engineered assets (see illustration in Figure 1). Obviously, the requirement to demonstrate compliance to statutory regulations is a primary reason to monitor relevant parameters and to conduct safety condition assessment at the appropriate level of the asset hierarchy.

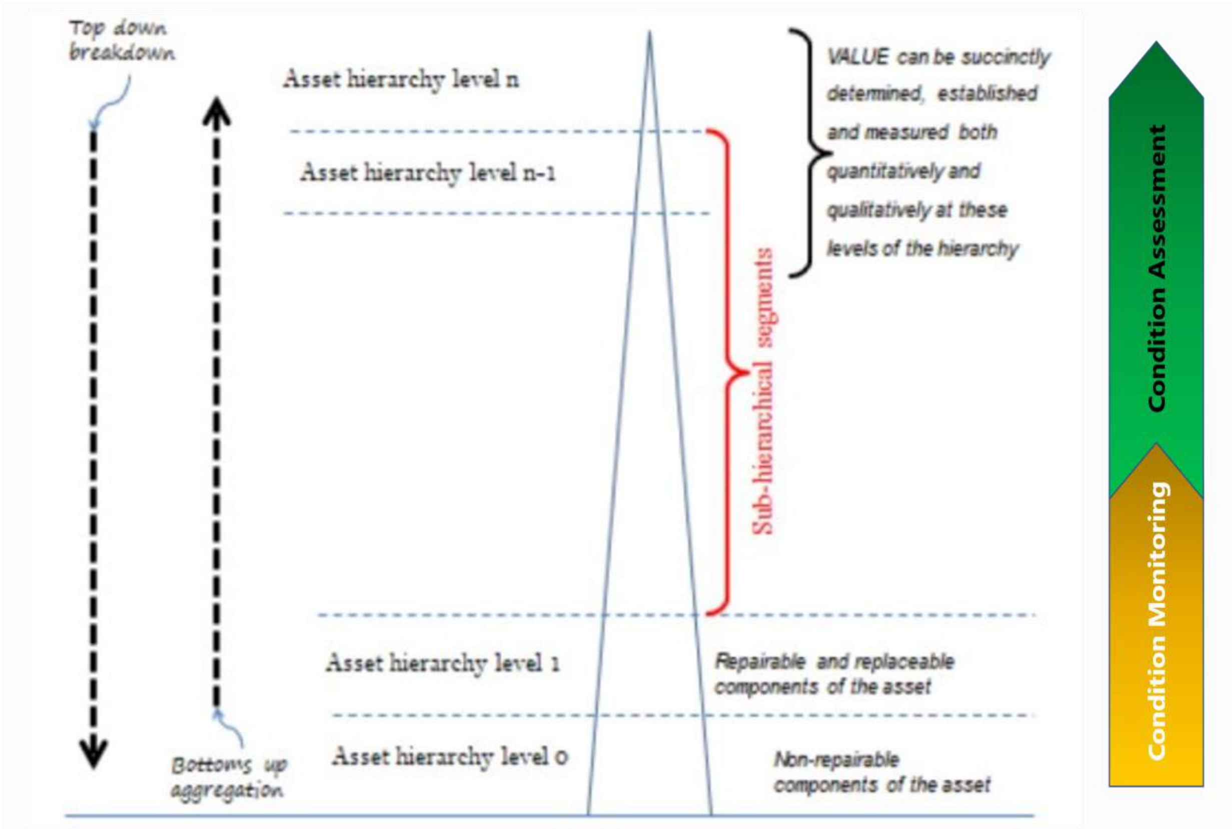

Figure 1. Asset hierarchy - condition monitoring feeds into condition assessment (re: [19])

Considering that an item of equipment or machinery cannot be dissociated from the economic, socio-technical and the natural environments, then condition assessment should be performed according to five dimensions – (i) functional, (ii) technical, (iii) economic/financial, (iv) environmental/ecological, and (v) socio-political [20]. The resulting dimensional metrics may then be aggregated to determine the condition as assessed at the particular instance, which means that a condition assessment is only valid within a stipulated time period ([1]).

The dyadic relationship between condition monitoring and condition assessment is often a source of confusion between business managers and technical personnel. Furthermore, the dyad seems to exacerbate the choice and scope of technologies that should be acquired and implemented by users in order to achieve the business objectives of effectively managing assets during the utilization stage. The remainder of this paper discusses two case studies that highlight some challenges confronting asset owners/users concerning investments in condition monitoring technologies and condition assessment systems.

3 CASE STUDY 1 – CONDITION MONITORING AND CONDITION ASSESSMENT IN CONVENTIONAL MINING OPERATIONS

This first case study examined condition monitoring and condition assessment practices in conventional mining operations in South Africa. Part of the motivation was to understand the extent to which condition monitoring technologies are applied in practice to facilitate predictive maintenance of equipment and machinery at three similar mining operations of a particular company. In this regard, conventional mining refers to manual labour-intensive, low mechanized mining operations that still prevail at many mine sites. In underground 'breast' mining, handheld pneumatic/hydraulic drills are used to charge explosives into ore containing rock. Handheld drills are typically used to install bolts that support the roof of the mining area. Other equipment/machinery utilized for both surface and underground mining operations include, for example, chainsaws, chairlifts, compressors, pressure vessels, ventilation fans, rail locomotives and wagons; facilities such as conveyor belt systems, dewatering pump stations, electrical substations, hoist systems, piping systems, refrigeration systems; structures such as silos; and railway infrastructure.

For this case study, secondary data and information were obtained from three separate mines operated by a major mining firm. Noting that most of the equipment and machines operating at the three mines are long-lived, the historical records of maintenance interventions showed that condition monitoring by technical personnel involved visual inspections for visible defects, functional testing of equipment/machinery, electrical and temperature measurements, noise and vibration observations. It was surprising to observe that an operator or maintainer 'listens' to the equipment so as to establish whether the noise/vibration level is abnormal; an operator/maintainer uses a thermometer to measure and report the temperature. Other observations included locomotive braking system tests conducted at scheduled intervals, and ultrasonic measurements of silo wall thickness.

Thus, condition monitoring, i.e., the aforementioned observations/measurements are carried out only during scheduled inspections either by inhouse or third-party personnel. Based on some of the data accessed for the rock winder machine, 43% of the condition monitoring routines occurred on a daily basis, 46% weekly, 5% quarterly, 2% annually/biannually, and less than 1% on a monthly, 2-yearly, and 5-yearly basis. Across all the primary mining equipment, 62% of scheduled condition monitoring tasks were visual inspections, 21% were functional tests, while 17% were manual measurements of temperature, pressure and other parameters.

Curiously, these manual condition monitoring inspections conducted by inhouse technical personnel prevailed at the respective mining operations during the period of the case study. However, technically-skewed condition assessments were mostly conducted by third-party inspectors as stipulated by legislation, for example, thickness testing and structural assessment of the silos. Other condition assessments were carried out by supplier/vendor representatives as prescribed by original equipment manufacturers, sometimes together with inhouse technical personnel where the assessment is necessitated by the occurrence of an event. It is remarkable that within the period covered in the historical records examined, the data showed that condition monitoring activities occurred 98% of time while condition assessment activities occurred less often at 2%.

Perhaps, in recognition of, and to keep track of rapidly evolving technologies, a topical issue gleaned from the annual reports of the case study mining firm is the desire to increase mechanization, especially to mitigate safety risks, firstly to humans and secondly, to machinery, equipment and structures. Implementation of mechanization requires changes in the existing mine layouts, further complicated by life-of-mine considerations and applicable industrial relations regulations. The suggestion from the case study is that mining firms apparently commence mechanization by investing in, deploying, and utilizing technologies that enable the mine operators to, at least demonstrate compliance with health and safety regulations and statutes. This requires the installation of condition monitoring devices especially on existing equipment, machines, facilities and structures that are deemed to pose the highest risk to safety. The aim seems to be to provide the required level of technical integrity assurance to be granted the necessary operational permits.

4 CASE STUDY 2 – MULTI-SENSOR CONDITION MONITORING OF STEAM TURBINE GENERATOR

Improving the energy efficiency of operational machinery provides an interim approach in the chain of activities that are geared towards mitigating environmental impacts of existing fossil power generation facilities. Condition monitoring technologies are typically deployed and utilized to provide data and information that facilitate energy efficiency improvement interventions. The first motivation for this case study was to observe how condition monitoring is actually practiced in an existing power generation facility, especially on the unit operation that converts mechanical energy to electrical power. The second motivation was to examine how the condition monitoring parameters changed following the implementation of predictive maintenance intervention on a steam turbine generator. A third motivation was to build a business case for investment towards automation of condition monitoring and condition assessments.

At the case study power plant, the installed condition monitoring sensors and corresponding signals associated with the steam turbine generators are logged into a data historian once every 5 minutes. The record of condition monitoring signals captured between 1st and 31st July 2022 for just one turbine were examined because there was maintenance intervention on the particular machine during this period. For brevity, there are at least 36 condition monitoring signals on each of the 6 steam turbines (i.e., over 200 process measurements) at the coal-fired power generation facility. As shown in Figure 2, the signals arise from the sensing of stator, rotor bearing, steam and lubricant temperatures, rotor and shaft assembly vibrations, generator speed, and steam flow; as well as the electrical output signals. Interestingly, the maintenance intervention which occurred around 18 July 2022 seemingly triggered by an abnormal signal level on, at least, one of the monitored parameters. It is quite a challenge to discern the effect of the maintenance intervention just by looking at the signals; it is even more tasking to state the operational condition, or the actual business performance of the steam turbine without collating, incorporating and analysing all relevant data and information from the disparate sources.

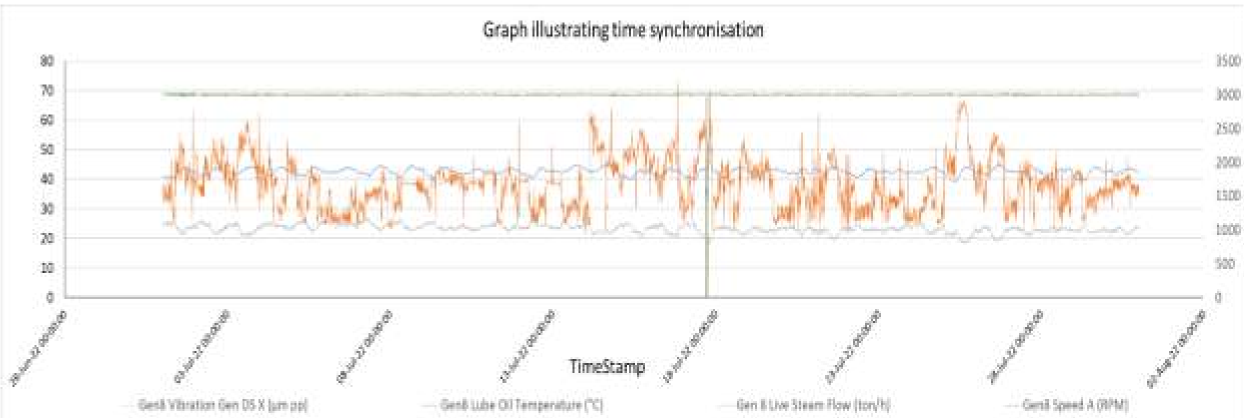

Figure 2. Some condition monitoring signals observed during case study 2

During the period of the case study, it was observed that the operators and maintainers at the facility had become accustomed to attending to the process control alarms. Further discussions with technical personnel indicated that it was customary to respond to the alarms as the trigger to initiate so called 'condition-based' maintenance interventions. Nuisance alarms accentuated the tendency to rely often on the tacit knowledge, gut feel, and wit of experienced personnel in order to initiate predictive maintenance interventions.

Technical personnel commented that it was an exasperating chore to track multi-sensor signals arising from physical phenomena (i.e., technical data), to collate associated economic/financial plus environmental/ecological and socio-political data and information, then to analyse the agglomerated changes in real-time so as to discern the aggregated change in condition. By custom, technical personnel have been trained and certified to operate, and to trouble-shoot in the event of a soft or hard failure of equipment/machinery, then to repair or replace as applicable and necessary. Furthermore, technical personnel were expected to maintain safe operation of equipment/machinery; operators and maintainers were normally held responsible and accountable for the quality of technical data regarding equipment/machinery. An overriding sentiment expressed during the case study was that operators and maintainers characteristically choose to be pragmatic. Thus, to minimize the uncertainty created by sophisticated condition monitoring technologies, operators and maintainers were generally reluctant to deviate from the scheduled maintenance tasks recommended by OEMs/suppliers/vendors.

5 CONCLUDING REMARKS

Whilst it is reasonable that there will a lag between developers and users of technologies, however, the case studies briefly described here also point to some kind of mismatch and/or disconnect between the unbridled excitement and enthusiasm often expressed by proponents of rapidly evolving technology systems on the one hand, and on the other hand, the apparent apathy and reluctance of users to invest in, implement and deploy, and utilize sophisticated monitoring technologies and performance assessment systems. The profusion of suppliers coupled to continual re-branding of rapidly evolving technologies and systems can be confusing to users. Asset owners, especially in energy intensive power generation and mining, have to contend with long-lived large equipment, machinery and infrastructure that are installed both under and above ground. Thus, it is not surprising that investments in rapidly evolving condition monitoring technologies and condition assessment systems may be more readily justified on the basis of obsolescence supported by real evidence of improvements in asset performance.

Rapidly evolving technologies and systems not only impose changes in ICT infrastructure, but also, such technologies and systems tend to revolutionise organisational culture, especially the procedures and tasks performed by technical personnel. Furthermore, the onerous tasks of condition monitoring and assessment actually demands cross-, multi- and trans-disciplinary skills and competences. Investment in rapidly advancing condition monitoring technologies also requires corresponding human capacity development and behavioural change to successfully deploy and utilize such technologies to deliver improved business performance - see, for example, references [21] [22] [23]. These references more or less surmise the need for rapid transformations in education, training, certification, skills, responsibilities, roles, accountabilities, reward and recognition for technical personnel in order to keep pace with the unstoppable waves of rapidly evolving technologies and systems that facilitate modelling, monitoring, and management of cyber physical assets.

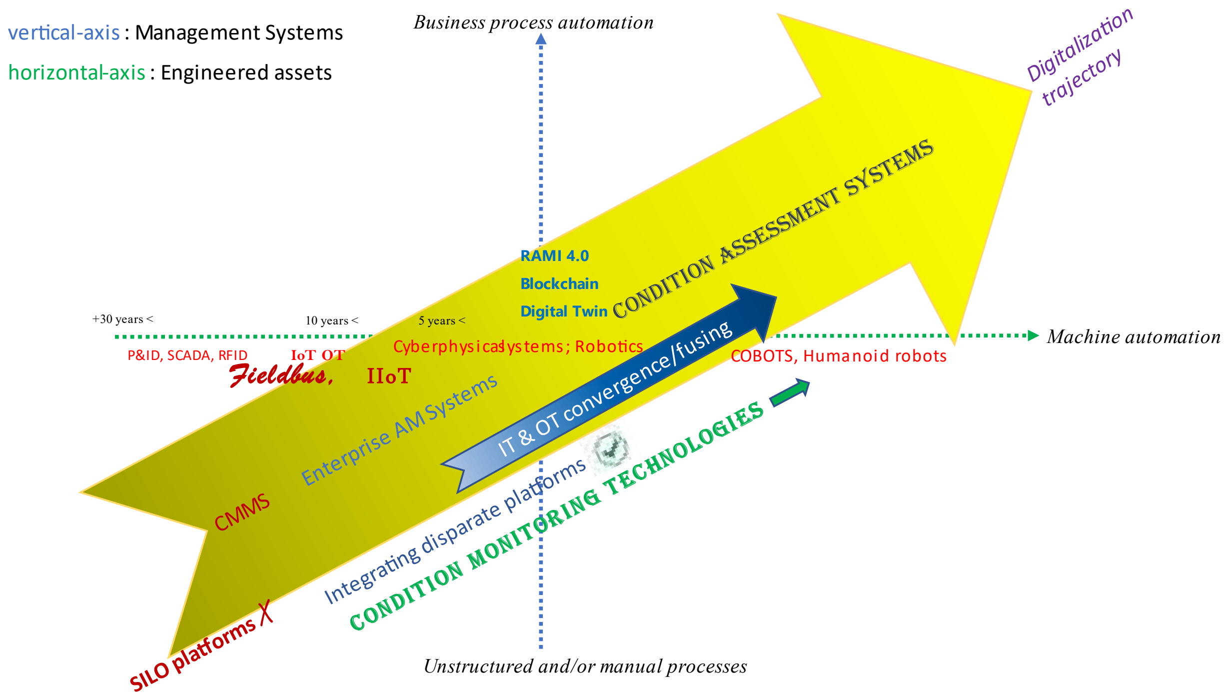

Figure 3. A foresight model – from condition monitoring technologies to condition assessment systems

Perhaps, a primary challenge for both developers (i.e., researchers, original equipment manufacturers, suppliers, vendors and systems integrators) and users is to resolve the customary, and sometimes, muted differentiations between operational technology (OT), and information and communications technology (ICT) systems (re: [24]). OT systems tend to be more focused on work attitudes, behaviours and outcomes embedded in organizational business processes, whereas ICT systems have been traditionally deployed to facilitate data and information capture, storage, retrieval, transmission, exchange, and communication. Given the rapid convergence and fusing of ICT and OT systems within the context of 4IR, this paper postulates the foresight model illustrated in Figure 3 as a way to evolve technical capabilities along the digitalization trajectory imposed by rapidly evolving 4IR technologies and platforms.

It is anticipated that mining and fossil power generation businesses that operate and maintain existing long-lived equipment, machinery, facilities and infrastructure may follow a similar foresight approach towards integrating rapidly advancing condition monitoring technologies into condition assessment systems. At least, the trajectory of the dyadic condition monitoring and condition assessment skills and competences should co-evolve with the rapidity of the technologies and systems. In addition to safety, economics, and environmental impact considerations, investments in condition monitoring and assessment technologies and systems may also be motivated on the need to augment and complement technical skills of operators and maintainers of equipment, machinery, facilities and infrastructure in asset-intensive business organisations.

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ANALYZING THE DIFFUSION OF E-COMMERCE TOOLS SUPPORTING THE E-AGRICULTURE SUPPLY CHAIN. A SOUTH AFRICAN PERSPECTIVE

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ABSTRACT

The purpose of this study, is to develop a system dynamics model to assess the policies for the adaptation of e-commerce tools enabling the South African agriculture supply chain operation. A Bass paradigm for technology innovation diffusion was modelled using Vensim software. The research found out that the degree of consistency and effectiveness of a mobile phone service propels diffusion among the farmers who in turn encourage distributors to adopt it. This research contributes by emphasizing the need to evaluate how information technology can benefit the e-agriculture supply chain. The research offers a way to communicate the factors that impact e-agriculture supply chain services.

Keywords: agriculture, diffusion, e-commerce, e-agriculture

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1 INTRODUCTION

E-commerce is rapidly developing and has reached almost every business sector. Agriculture has been regarded as promising because of its high amount of segmentation. E-commerce is defined by Turban, King, Liang, and Turban [1] as "the process of buying, selling, transferring, or exchanging products, services, and/or information via computer networks, primarily the Internet and intranets." According to the Organization for Economic Cooperation and Development [2], Small businesses can profit from e-commerce adoption by gaining access to overseas markets. However, Zhu and Kraemer [3] suggest that the extent to which e-commerce advantages are realized depends on an organization's level of e-commerce utilization. According to Smith [4], e-commerce in South Africa is continuing to develop. Such development is due to increased internet-based buying via mobile devices and international purchases as South African customers prefer a wider range of items at the best possible costs.

The adoption of future internet technologies appears to significantly impact the agriculture industry [5]. Internet access, in particular for commercial purposes, is promising for farmers [6]. Farmers may increase farm revenue and performance by using the Internet to minimize transaction costs [6]. In this regard, the Internet makes it easier to obtain pricing and product information and communicate with a wider range of suppliers and customers [7].

Many developing countries use e-agriculture to encourage the integration of technology with multimedia, knowledge, and culture, with the goal of enhancing communication and learning processes between different agricultural parties locally, regionally, and globally [7]. According to Food and Agriculture Organization (FAO) [8], major components of e-Agriculture include support for standards and norms, technical assistance, education, capacity building, and extension. Mobile agriculture, often referred to as M-Agriculture, is a subset of e-agriculture. It involves the use of mobile devices such as cell phones, tablets, and other handheld communication or computer devices to provide agricultural services and information [9]. Through the application of mobile technologies, Mobile Agriculture assists players along the agricultural value chain [10].

Considering the fact that supply chains in developing countries are not as advanced as those in rich nations, there are significant challenges to overcome in agriculture e-commerce. These challenges are often aggravated by the absence of efficient economic and physical infrastructure in rural areas and urban areas. Since e-agriculture platforms have limited availability in these remote regions, it is necessary to introduce innovative approaches suitable for environments with limited resources and underdeveloped infrastructures. One potential solution lies in the utilization of mobile tools.

This research focuses on assessing the policies for adopting e-commerce tools to facilitate the operational efficiency of the agriculture supply chain in South Africa, specifically in the context of fresh food. Given the complex nature of the agriculture supply chain, a systems dynamic approach is proposed in this study to analyse its various links and gain a deeper understanding of the underlying causal factors. The study considers the actor within the fresh food supply chain, situated in the Greater Sekhukhune District of the Limpopo province in South Africa. The simulation model's outcomes highlight the factors that influence the adoption of e-commerce tools and enable the formulation of policies to promote the widespread adoption of e-commerce tools within the agriculture supply chain.

2 LITERATURE REVIEW

2.1 E-agriculture

E-agriculture is an emerging field that aims to promote agricultural and rural development using advanced information and communication technologies (ICT) [10]. ICT refers to a broad variety of technologies, including devices, networks, mobile services, and applications [11].

Innovative Internet-era tools, sensors, and classic communication aids such as landline telephones, TVs, radios, and satellites are examples of these techniques [11]. As new ICT applications are implemented in the agriculture industry, the scope of e-agriculture grows [12]. E-agricultural, in particular, include the idea, design, development, testing, and implementation of novel ICT solutions in rural regions, with a major focus on agriculture. This includes developing standards, norms, procedures, and tools, as well as developing human and institutional skills and providing policy support [8].

2.2 E-commerce

The internet has developed business operations, allowing companies to function 24/7 and enabling customers to shop at any time without visiting physical stores [13]. Nowadays, global online businesses have expanded and include various services like online shopping, cleaning services, food delivery, and more [13]. The remarkable growth of the e-commerce industry is largely attributed to the widespread adoption of smartphones by consumers. A key factor driving e-commerce is the availability of digital payment solutions, which can be facilitated through mobile services. Mobile money accounted for 79% of the value of e-commerce transactions in 2018 [14]. Mobile operators play crucial in the e-commerce sector, particularly as mobile e-commerce continues to rise. The potential success of e-commerce in the agricultural sector holds great promise despite the challenges it may face [15]. By using online platforms, farmers can sell their products directly to buyers, eliminating intermediaries and potentially obtaining better prices. Additionally, this direct approach ensures that fresher produce reaches consumers on time, resulting in less food wastage [14].

2.3 The role of mobile service in supply chains

In supply chain management. Nguyen et al. [16] highlight the significance of mobile devices in providing order fulfilment options for customers and retailers from a business application perspective. Cagliano [17] [18] reported on studies on the supply chain of mobile applications. Cagliano [18] highlighted service reliability and efficiency as critical drivers of smartphone adoption in the e-grocery supply chain. Cagliano [17] created a simulation model of system dynamics to depict and explain the causes and effects of time-dependent connections facilitated by mobile technologies. The findings provide light on how the use of mobile tools might improve supply chains. In the agriculture supply chain, Tembo [19] indicated that mobile services could be used in every step of the agriculture supply chain. It contributes to improved communication patterns, coordination of cooperative activities, and organizational structures through its capacity to store, process, transfer information, and accelerate administrative activities [20].

2.4 Bass diffusion model.

Bass [21] created the Bass diffusion model in 1969 to predict sales and the diffusion of new technologies. This model effectively addresses the "startup problem" encountered in other innovation diffusion models and has since become widely used in marketing and technology management [22]. The Bass diffusion model describes how technology innovation can be accelerated using external means [23]. This concept assumes that the potential consumers of new technology will become aware of it by means of an external source. The sources of adoption are commonly referred to as advertising and word of mouth [23]. The former refers to the process of attracting potential adopters through advertisements, while the latter refers to the process of being infected by word of mouth [24]. The Bass diffusion model assumes that the likelihood of making an adoption decision remains constant as a result of a potential adopter's contact to adopters or advertisements. It also assumes that all potential adopters will eventually adopt the technology, and once adopted, users do not discontinue its usage [21].

3 METHODOLOGY

The study centres on the agricultural supply chain, where products experience varying demand fluctuations. Due to the uncertain demand nature, a dynamic simulation-based method is chosen, aligning with the belief that systems are highly interconnected and subject to change over time. This aligns with the systemic worldview emphasizing complexity, interdependence, and evolution in systems [22]. To examine the impact of e-commerce tools on the agricultural supply chain, a System Dynamics approach is adopted. This approach sees the system as a set of interrelated components, and feedback loops play a crucial role in shaping system behaviour [22]. This approach is chosen because it provides a holistic understanding of the dynamics involved, in line with the research approach that seeks to comprehend the complex nature of supply chain operations.

The study starts by constructing a causal loop diagram that describes relationships among key variables, such as agriculture supply chain participants' adoption, inventory management, user satisfaction, and revenue. This diagram transforms into a set of differential equations showing how each variable evolves over time. This approach of diagram-to-equations conversion captures the dynamic interactions and influences within the system, reflecting an approach that aims to capture close relationships and behaviour [22]. The model's calibration was executed using data sourced from the agricultural supply chain. Furthermore, sensitivity analysis was conducted by adjusting data under various scenarios, enabling the identification of the main variables influencing the population of supply chain participants. Through simulation experiments, the study delved into the factors influencing the adoption of e-commerce tools.

To collect the data, a combination of methods was employed to gather qualitative and quantitative information. Questionnaires were distributed to a total of 45 participants drawn from diverse groups in the agriculture supply chain: crop farmers, processors/distributors, and retailers. Additionally, market studies were conducted in the Greater Sekhukhune district. Discussions were held with representatives from a mobile service provider company, and historical data from the same company were utilized. The participants targeted for data collection included owners, managers, supervisors, and procurement specialists, given their direct involvement in day-to-day operations, decision-making, and projects. The gathered data were then translated into written form, contributing to the creation of a causal loop diagram. Moreover, numerical data were collected and integrated into a stock and flow model using the Vensim tool. This procedure captures both quantitative (numerical) and qualitative (written and mental) data. Sterman [22] classifies the system dynamics as qualitative and quantitative approaches. This is because system dynamics is based on qualitative information, which subsequently serves as the basis for the quantitative approach. Luna-Reyes & Anders [25] highlighted the importance of incorporating three types of data—numerical, written, and mental—to develop the structure and decision rules of System Dynamics (SD) models. Numerical data refers to information presented in the form of time series and cross-sectional databases [25]. These data sets provide quantitative measurements and statistical figures that help quantify various aspects of the system under study. Written data encompasses a wide range of textual sources, including organizational operation documents, archive documents, and minutes of meetings [25]. These written sources offer valuable insights into the operational procedures, policies, and historical records of the system. Mental data represents the knowledge and understanding embedded in people's minds [25]. It includes their perceptions, beliefs, mental models, and tacit knowledge about how the system operates and how decisions are made within it. Gathering this type of data often involves interviews, questionnaires, surveys, and discussions with individuals who possess expertise or experience related to the system being modelled [25]. The comprehensive data collection aligns with the approach to encompass a broad spectrum of insights for modelling.

The research's timeframe scope encompassed a multi-stage process. Initially, the model construction and calibration stages were executed over a two-year timeframe, equivalent to 104 weeks. This facilitated the baseline simulation and formed the foundation for subsequent analyses. Within this time frame, three distinct scenarios were generated by adjusting influential factors in the model. These scenarios allowed for an assessment of user growth patterns under varying conditions. This sequential approach ensured a comprehensive evaluation of the effects of e-commerce tools over different time periods and circumstances.

4 SIMULATION MODEL

The model was developed using Vensim software. The model focuses on the adoption of e-commerce tools enabling the South African agriculture supply chain operation. The model builds on work conducted by Cagliano [18]. The system dynamics model is designed with several interconnected sub-models that focus on different aspects of the overall system. These sub-models include:

- Diffusion sub-model - this sub-model examines the adoption of the base application among retailers, processors, and farmers.
- Inventory management sub-model - this sub-model focuses on inventory management within the system. It helps analyse how inventory levels impact the overall functioning of the system.
- User satisfaction sub-model - this sub-model evaluates the satisfaction levels of users within the system, including retailers, processors, and farmers.
- Revenue sub-model - this sub-model focuses on the revenue generated by the service provider company. It considers factors pricing, it helps analyse the growth potential of the service provider company.

By incorporating these interconnected sub-models, the system dynamics model defines feedback loops that describe the relationship between the new mobile service's diffusion and the supply chain processes.

The supply chain participants include individuals who use mobile services to place orders upstream as well as deliver products downstream. There are several feedback loops between variables in the system dynamics model. The number of retailers who use the mobile service grows, which increases the order rate to the distributors or processors, and how effective these companies are in completing the enhanced orders impact retailer's satisfaction. Satisfaction, as a result, impacts the expansion of the population of adopting retailers via imitation and the "word of mouth" effect. The more farmers adopt the services, the more products are available to processors, and the more satisfied processors are. As a result of the relationship between these two supply chain tiers, the number of adopting farmers grows.

4.1 The dynamics of Retailer diffusion

The Bass Diffusion Models from Sterman's [23] Business Dynamics was used to develop a retailer's diffusion model. The model represents the adoption of mobile services by the potential retailers. The retailers adopting the mobile service, as measured by the "Retailer Service Adoption Rate" reduces the Potential Retailers and this as a result increases Retailers which shows the number of Retailers adopting the mobile service. Retailers enter the supply chain through advertising or word of mouth. In this model, advertising is done by service providers who have adopted mobile services. Adopting retailer use word of mouth to imitate members of the same supply chain level. Retailers base their satisfaction and service adoption decisions on the degree of service attained by their adopting counterparts. This model is similar to the one that represent the mobile service adoption by the processors and the farmers.

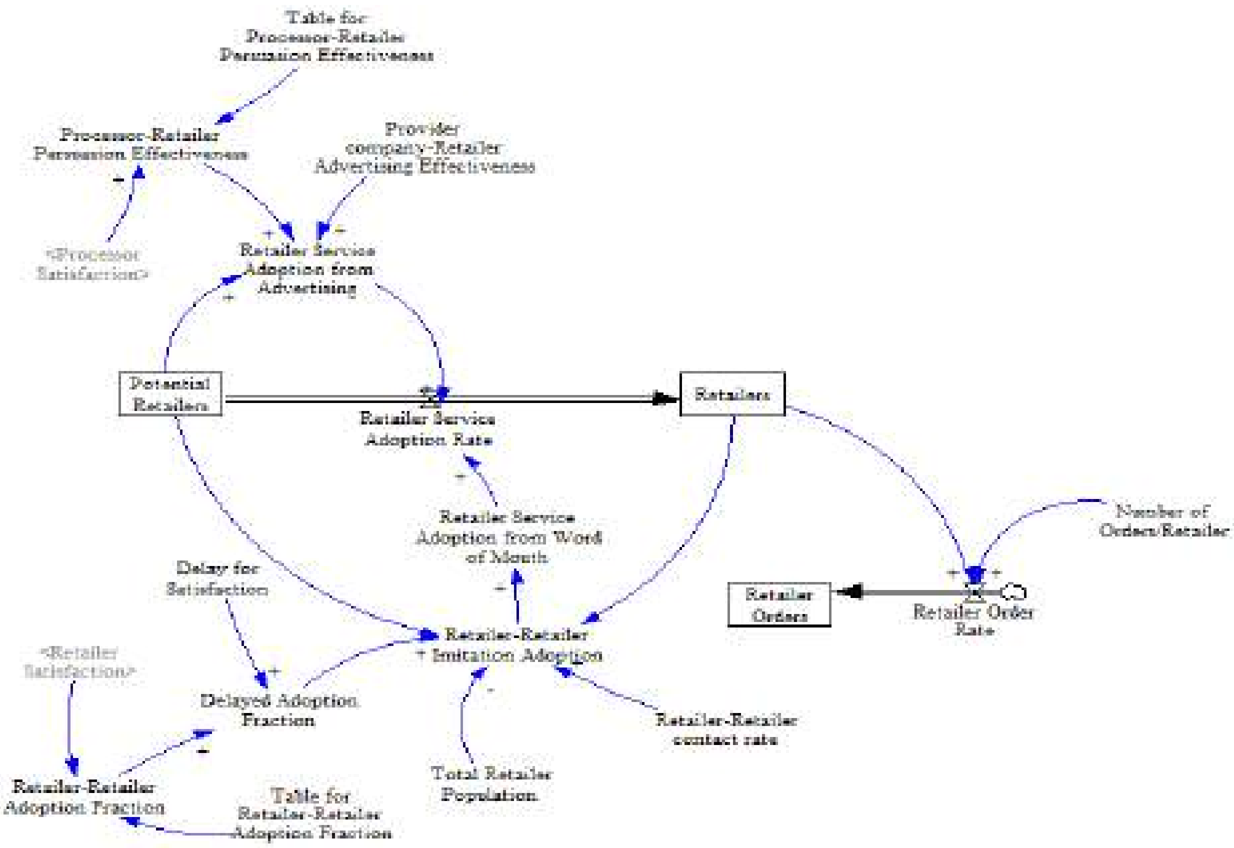

Figure 4.1: Retailer diffusion

4.2 The dynamics of processor inventory

The processor inventory sub model is based on Sterman's manufacturing supply chain model [23]. The stock variable "Single Processor Inventory" is increased by the supply of orders from the Farmer received by each processor ("Single Processor Receiving Rate") and decreased by the orders dispatched to retailers ("Single Retailer Shipping Rate"). The retailer order drives both the shipment rate, which is determined by the number of orders on hand, and the orders to the farmer.

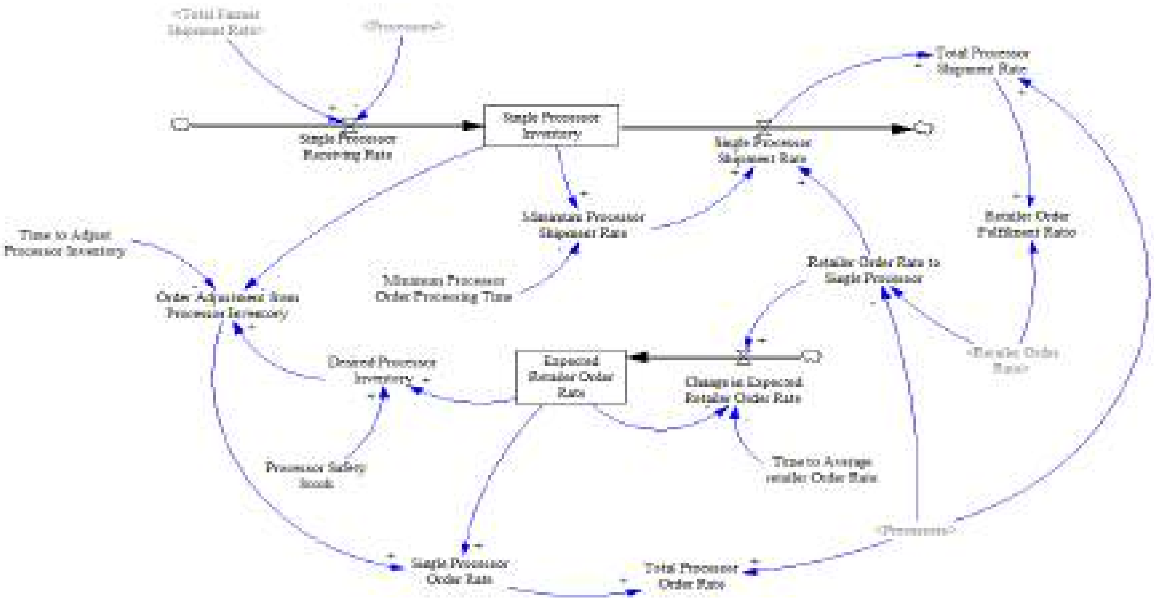

Figure 4.2: Processor inventory

4.3 The dynamics of retailer satisfaction

Zeithaml, Berry, & Parasuraman [26] proposed that customer satisfaction is primarily influenced by two factors: the sensitivity to pricing of the service and the level of service provided. The "Retailer Sensitiveness to Pricing" variable assesses the price expectations of retailers compared to the actual price. The Receiving Unit Fee refers to the amount paid by users for placing and receiving orders through the mobile service. The WebApp Unit Price represents the cost of downloading the application that facilitates communication with the mobile service. The "Retailer Receiving Service Level" variable measures the quality of service experienced by retailers when placing orders and receiving items via the mobile service. This variable is determined by the "Retailer Order Fulfilment Ratio." Additionally, the efficiency of order receipt using the mobile service is evaluated through the "Retailer Receiving Timeliness and Efficiency" measure.

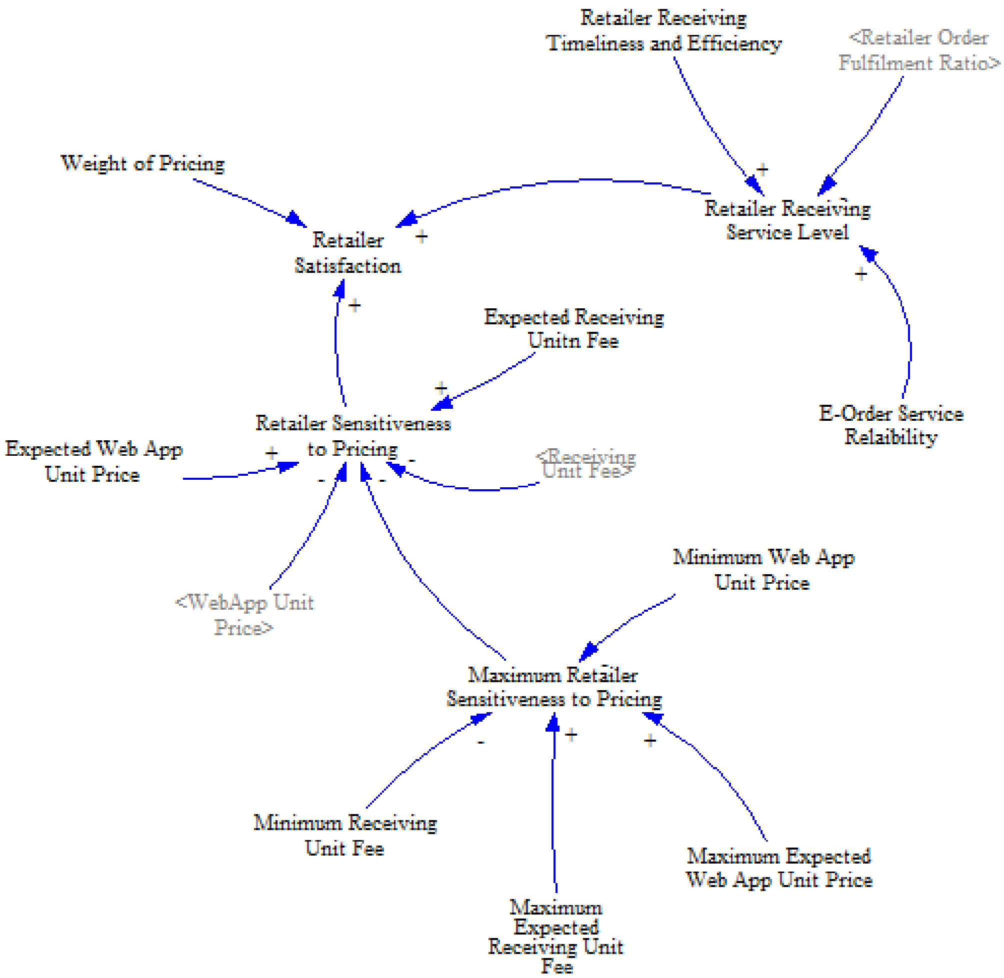

Figure 4.3: Retailer satisfaction

4.4 The dynamics of processor satisfaction and farmer satisfaction

Processor satisfaction and farmer satisfaction are assessed in a manner similar to retailer satisfaction. Sensitiveness to Pricing involves assessing the expected price to be paid with the actual price. The service level evaluates the quality of service experienced by processors and farmers when placing orders and receiving items through the mobile service. This measure is determined by the "Retailer Order Fulfilment Ratio."

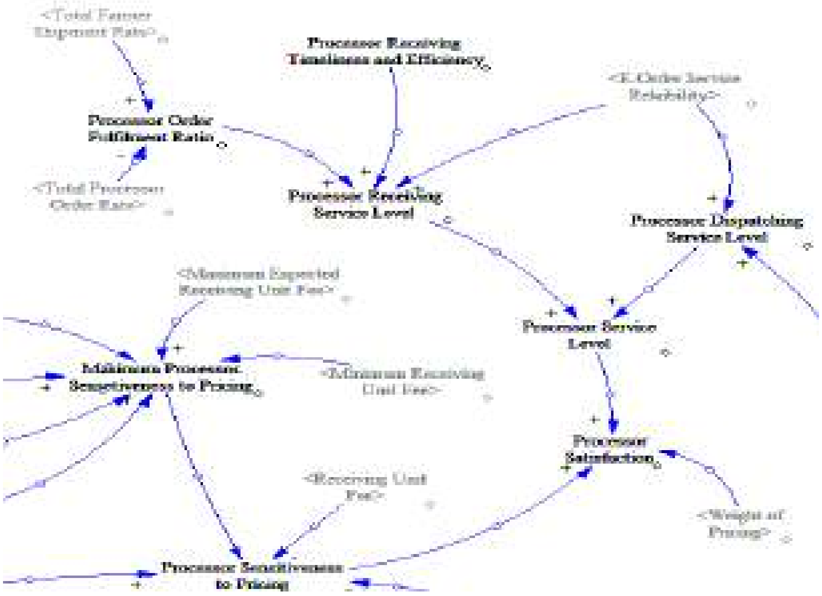

Figure 4.4: Process satisfaction

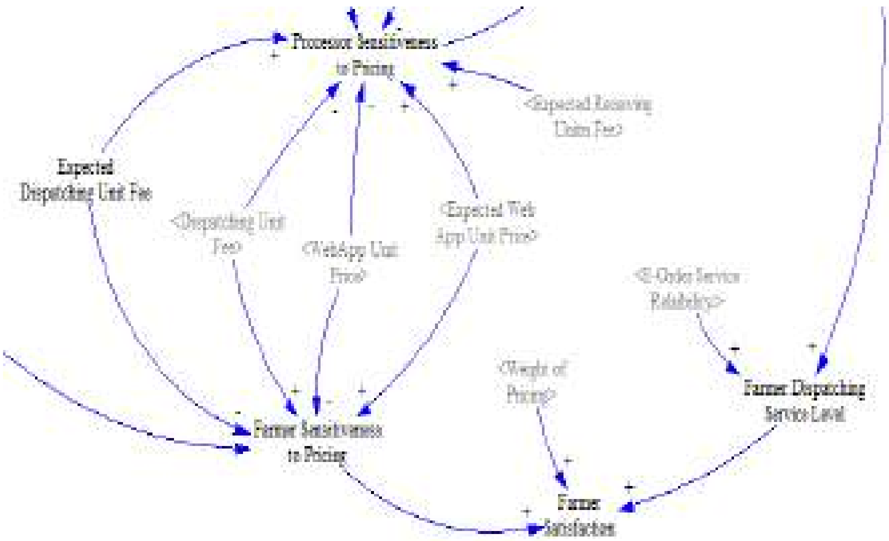

Figure 4.5: Farmer satisfaction

4.5 The dynamics of revenue growth.

The revenue growth sub-model evaluates the income generated by the adoption of the mobile service for the Provider Company. The total revenue is calculated by combining the revenue derived from supporting order receiving and dispatching operations with the revenue generated from the sale of WebApp packages that integrate customers' mobile phones with the mobile service. The "WebApp Unit Price" represents the cost of downloading the application that facilitates communication with the mobile service. The "Subtotal Revenue" refers to the aggregate value of the revenues obtained from order receiving and dispatching activities conducted through the mobile service

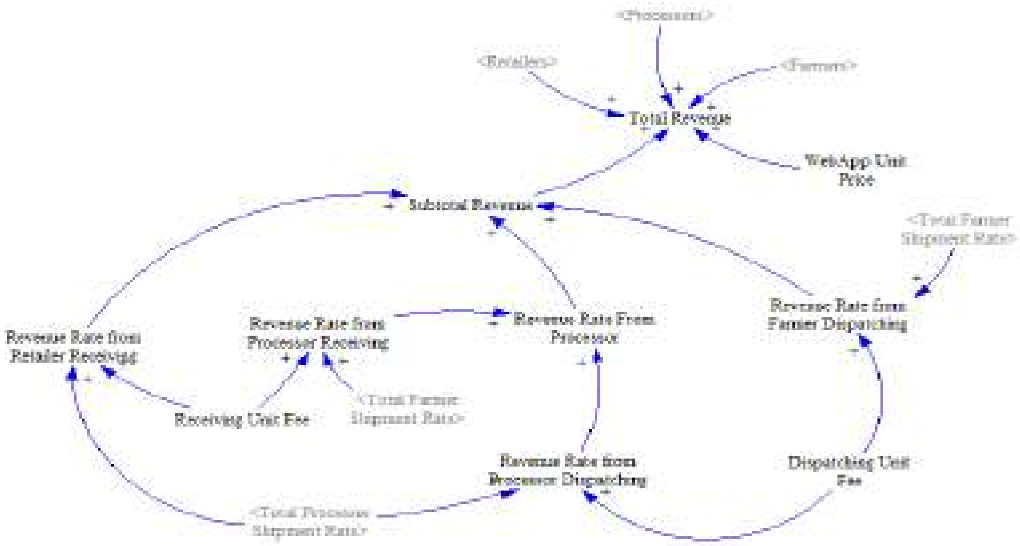

Figure 4.6: Revenue growth

5 ANALYSIS OF THE MODEL RESULTS

The purpose of this study is to assess policies for the adaptation of e-commerce tools that enable agricultural supply chain operations. Three scenarios were created by adjusting the levels of the influencing factors of the model to assess user growth in three different conditions: scenario 1 (25%), scenario 2 (50%) and scenario 3 (75%). The influencing factors include the effectiveness and reliability of mobile services, service pricing and advertising effectiveness. The base case of the model will be described as a reference point for assessing the behavioural reactions in subsequent simulations. Following that, the scenarios are examined to provide understanding and of how the model might be used to assess the adoption of mobile services.

In the base case simulation, the mobile service is adopted by the entire population of retailers in approximately 20,357 weeks. For processors, the adoption time is estimated to be around 43.75 weeks, while farmers are expected to adopt the service in about 18.625 weeks. To assess the mobile service user growth on the effectiveness and reliability parameters, the “Retailer Receiving Timeliness and Efficiency”, “E-order Service Reliability”, “Info Routing Service Reliability”, and “Processor Receiving Timeliness and Efficiency”, were adjusted according to the scenario conditions discussed above. Table 5.1 displays the results of the simulation conducted for three different scenarios related to the adoption of mobile services by the entire population of participants in the agriculture supply chain. The results shows that the population growth of retailers, processors, and farmers is influenced by the changes in service efficiency and reliability. As shown in Figure 5.1, the confidence limits for retailer, processor, and farmer population growth are detached from the line associated with the base case. This means that variability of efficiency and reliability has a significant impact on these adoption dynamics.

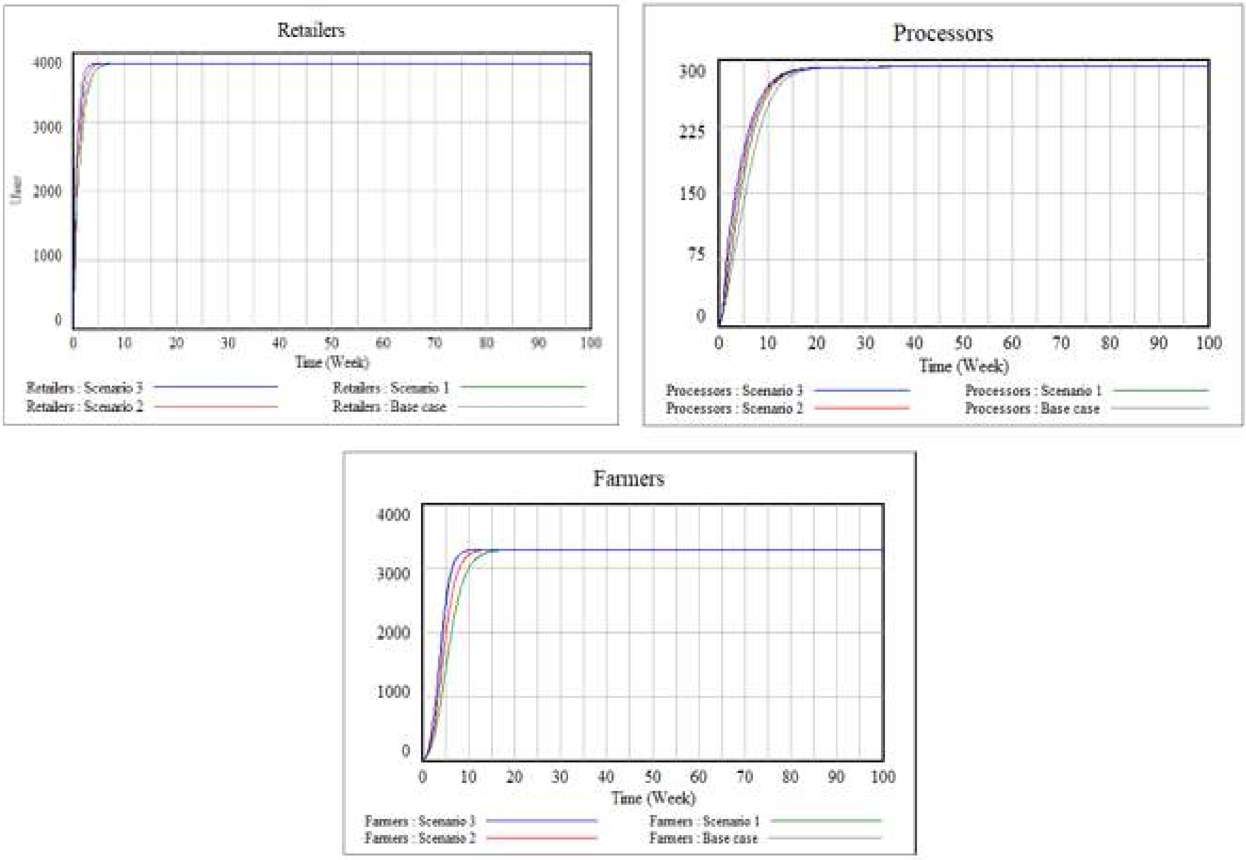

Figure 5.1 User growth on effectiveness and reliability parameters.

Table 5.1 User growth on effectiveness and reliability.

Scenario	Retailer (Weeks)	Processor (weeks)	Farmer (weeks)
Base	20.375	43.750	18.625
Scenario 1	14.625	42.625	26.000
Scenario 2	10.625	41.875	34.875
Scenario 3	8.000	41.500	18.625

“Dispatching Unit Fee”, “Receiving Unit Fee” and the “WebApp Unit Price” were adjusted to assess population growth in relation to the service pricing. The results in Figure 5.2 and Table 5.2 shows that the farmer is relatively not influenced by the changes in service pricing. The confidence limits for the farmer population growth are closer to the base case line. This means that the farmer population is not affected by the variation in the fees. In contrast, the confidence limits for to both retailer and process population growths are detached from the base case line, this means that variability has a significant influence on these two adoption trends.

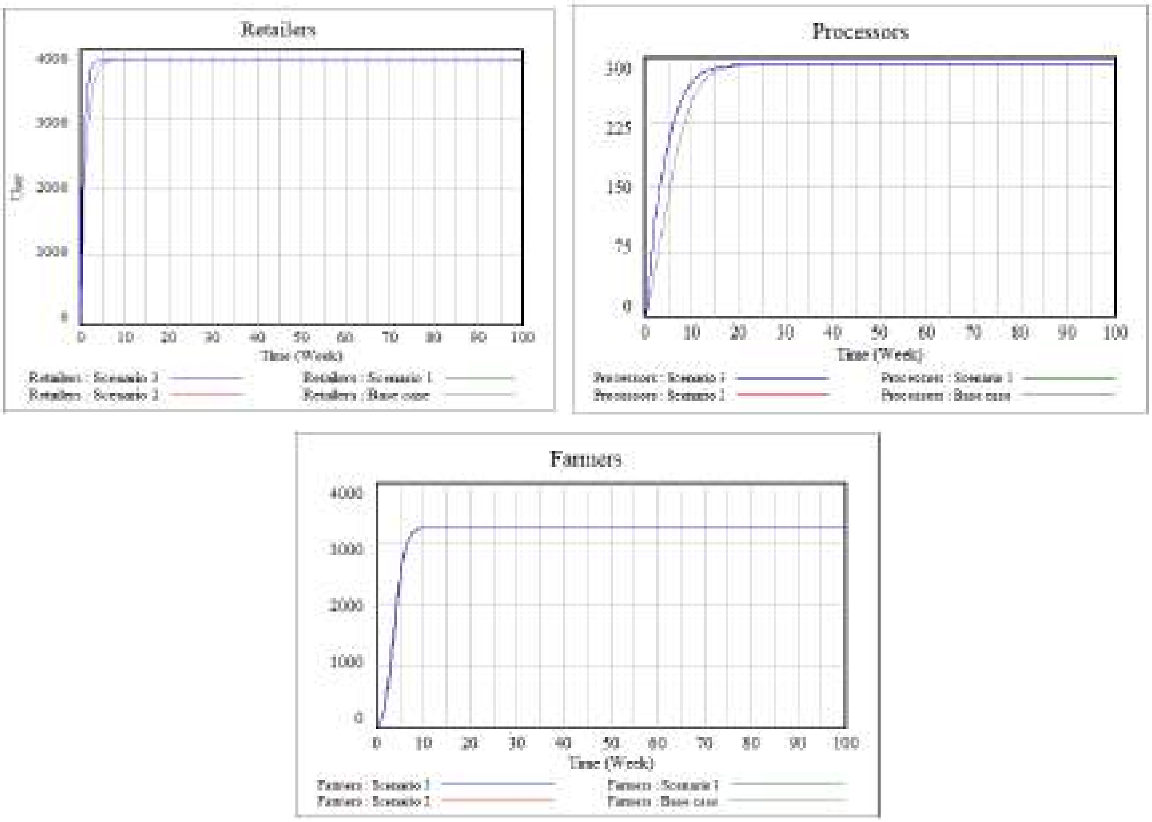

Figure 5.2 User growth on pricing parameters.

Table 5.2 User growth on pricing.

Scenario	Retailer (Weeks)	Processor (Weeks)	Farmer (Weeks)
Base	20.375	43.750	18.625
Scenario 1	7.625	41.250	20.500
Scenario 2	7.625	41.375	20.250
Scenario 3	7.625	41.375	20.000

To assess the population growth in relation to the advertising effectiveness, the “Provider Company-Retailer Advertising Effectiveness”, “Provider Company-Processor Advertising Effectiveness” and “Provider Company-Farmer Advertising Effectiveness” parameters were used to assess the advertising effectiveness for the retailer, processor, and farmers. Figure 5.3 depicts that the confidence limits associated with the population growth for retailers, processor and farmers are closer to the base case line, thus, the “Provider Company -Retailer Advertising Effectiveness”, “Provider Company -Processor Advertising Effectiveness” and “Provider Company -Farmer Advertising Effectiveness” have the less impact in the population growth of the agriculture supply chain participants.

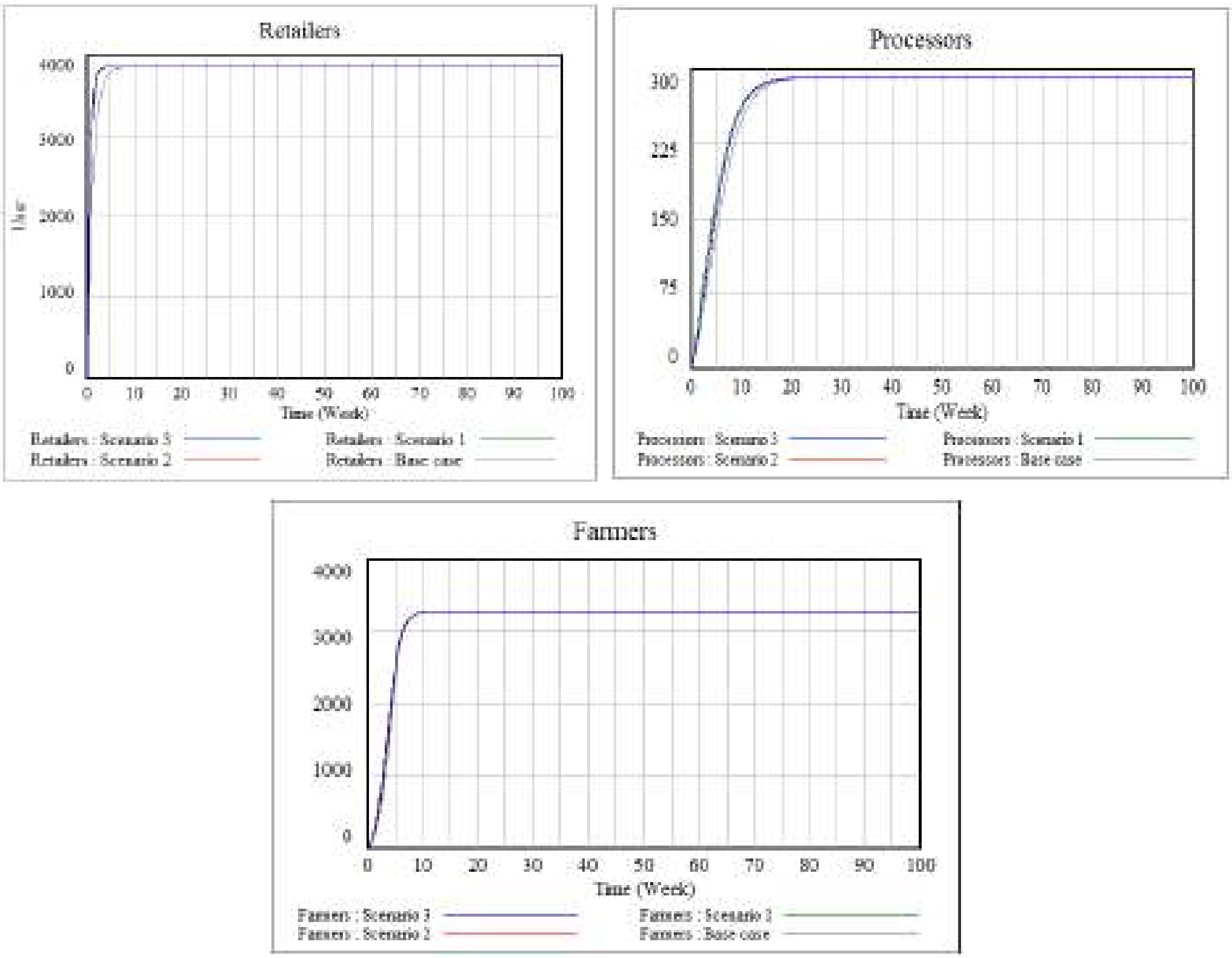

Figure 5.3 User growth on the advertising effectiveness parameters.

Table 5.3 User growth on the advertising effectiveness

Scenario	Retailer (Weeks)	Processor Weeks)	Farmer (Weeks)
Base	20.375	43.750	18.625
Scenario 1	9.250	41.750	20.250
Scenario 2	8.125	41.625	20.000
Scenario 3	7.750	41.125	19.875

6 DISCUSSION

6.1 Effectiveness and Reliability Parameters (Scenarios 1, 2, and 3)

This part analysed how changes in the effectiveness and reliability of mobile services influence the adoption of these services across the agricultural supply chain. The findings suggest that variations in service efficiency and reliability have a significant impact on adoption dynamics. Specifically:

- In Scenario 1 (25% effectiveness and reliability), all segments experience shorter adoption times compared to the base case, indicating that improvements in these parameters expedite adoption.

- In Scenario 2 (50% effectiveness and reliability), the adoption time further decreases for all segments, indicating a stronger effect of increased efficiency and reliability.
- In Scenario 3 (75% effectiveness and reliability), adoption times continue to decrease, showing that higher levels of effectiveness and reliability lead to faster adoption.

6.2 Pricing Parameters (Scenarios 1, 2, and 3)

This part examined how changes in service pricing influence the adoption of e-commerce tools. The results show that pricing has a varying impact on different segments. For farmers, changes in pricing do not significantly affect adoption, as indicated by confidence limits closer to the base case line. This suggests that farmers might be less sensitive to pricing changes. However, for both retailers and processors, adoption trends are affected by variations in pricing. Confidence limits are detached from the base case line, indicating that pricing has a notable influence on these segments.

6.3 Advertising Effectiveness Parameters (Scenarios 1, 2, and 3)

This part examined how changes in advertising effectiveness influence adoption rates. The findings suggest that advertising effectiveness has a comparatively smaller impact on adoption across the segments. In all three scenarios, confidence limits for retailers, processors, and farmers are relatively closer to the base case line. This indicates that changes in advertising effectiveness have a less pronounced influence on adoption dynamics compared to other factors.

Overall, the results of this research support the previous study conducted by Cagliano [18]. This previous study also confirms that the key factors influencing smartphone adoption in the e-grocery supply chain are service reliability and efficiency.

7 CONCLUSION

The primary objective of this study was to assess the policies aimed at adapting e-commerce tools within the agriculture supply chain in South Africa. A System Dynamics model was developed using Vensim, and the simulation was conducted over a two-year period. To assess the impact of the policies, key variables were adjusted and compared to the base case simulation. The results indicate that pricing and advertising have a minimum effect on the adoption of e-commerce tools. However, factors such as consistency, reliability, and efficiency significantly influence the adoption of e-commerce tools, particularly mobile phone services, which drive diffusion among farmers and subsequently encourage distributors to adopt them. This study provides valuable insights into the potential benefits of information technology in the e-agriculture supply chain and evaluates the various factors that can impact the adoption of mobile services. Furthermore, it emphasizes the importance of effectively communicating the factors that affect the delivery of e-agriculture supply chain services

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UNDERGROUND DIESEL SPILLAGES: A ROOT CAUSE ANALYSIS

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ABSTRACT

Several methodologies have been developed to manage diesel in open-cast mining due to its high usage and the constantly increasing diesel prices in South Africa. Although the use of diesel-powered equipment in underground mines has also increased over the years, its management has not garnered comparable attention. This study aims to adapt a recently devised diesel management tool, originally designed for open-cast mining, for application within the underground mining context. The tool employs the Data-Information-Knowledge-Wisdom (DIKW) hierarchy to make decisions and gain insights to minimise waste. The adapted methodology on a mine case study identifies diesel spillages and highlights that power failures due to loadshedding are the biggest contributor to these diesel spillages. A root cause analysis was employed to determine relevant system failures, followed by the identification of practical solutions to eliminate such spillages and allow the mine to adapt to the new normal, with a potential of saving exceeding R3.2 million.

Keywords: underground mine, automation, SCADA alarms, loadshedding, spillages, diesel management, root cause analysis.

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1 BACKGROUND AND LITERATURE

The fundamental foundation underpinning the growth of South Africa's economy and society resides in its abundant mineral resources. South Africa (SA) is rich in diverse minerals, such as platinum and gold. The methods of obtaining mineral resources include open-cast and underground mining, the choice of which depends on the mining depth [1].

Similar to open-cast mines, trackless underground mines rely extensively on diesel usage for material loading and transportation. The mechanization of underground mines is trending as a result of the increasing global demand for mineral resources [1]. Although mechanized mines offer heightened efficiency [2], their operation is costly.These encompass various operational expenses such as labour, maintenance, repair, and diesel consumption [3]. Diesel-powered equipment in underground settings includes drill rigs, loaders, and dump trucks. The appropriate management of diesel is a priority in all industrial companies that utilise diesel, including underground mines [4].

Diesel prices in SA, however, have increased tremendously over the years and are expected to further increase. According to the South African Petroleum Industry Association (SAPIA), fuel prices increased by approximately 65% from January 2020 to December 2022. The cost of haulage operations in mines is on the rise due to longer haulage routes [3]. This is forcing supervisors to seek more effective ways to operate mines, which includes diesel usage management. A comprehensive literature review was undertaken to pinpoint studies centered around the underground mining milieu, geared towards curbing diesel consumption and minimizing wastage, ultimately decreasing operational expenditures

The assessed studies were appraised through the lens of the following research inquiries:

- Did the study consider diesel management within the underground mining context?
- Did the study consider energy manaegment the underground mining environment, including diesel/fuel management?
- Did the study emphasize diesel particulate matter (DPM)?
- Did the study emphasize optimization of diesel-using equipment?

The literature summary is presented in Table 1. The table reveals that extensive research has been conducted on the underground mining environment. However, these studies do not primarily focus on diesel usage and storage. Motlogelwa and Minnitt [6] focused on diesel management, but not on underground mining. Meanwhile, other studies [7-11] focused on improving underground air quality conditions by monitoring DPM and the technologies employed to manage it. DPMs are harmful gases that are formed when diesel is combusted in diesel-powered equipment. The literature indicates that the majority of investigations are geared towards the management and reduction of DPMs due to their risk to human health [5].

Some studies [12-14] focused on optimising energy consumption in underground mines. However, none of these studies focused on diesel energy management. Lastly, some studies [1-3] focused on optimising the use of diesel equipment in underground mines by considering equipment lifespan, equipment replacement strategies, optimal operational sequence, and anticipated travel times. These insights assist managers in effectively repairing and maintaining diesel-powered equipment in underground mines. The headings in Table 1 correspond to the previously outlined research enquiries.

Table 1: Literature summary.

Reference	Underground	Diesel management	Energy management (electrical)	Diesel particulate matter	Equipment optimisation
[6]					
[7]					
[8]					
[9]					
[10]					
[11]					
[12]					
[13]					
[14]					
[3]					
[1]					

	Not within scope of reference
	Within scope of reference

From Table 1, it is evident that there is a notable lack of research dedicated to diesel consumption management in underground mines. No studies thus far have developed methodologies to manage and reduce diesel usage in underground mines. Given the escalating trajectory of fuel prices, effective diesel management is paramount in the underground mining environment. Previous work [15] implemented the Data-Information-Knowledge-Wisdom (DIKW) hierarchy to assist with meaningful decision-making to manage diesel in open-cast mining.

The objectives of the present paper are:

- To develop a procedure for the management of diesel consumption and the identification of wastage within underground mines by adapting the aforementioned DIKW framework.
- To identify the root causes of wastages within a selected case study mine.

2 METHODOLOGY

Several methodologies have been developed to manage diesel in open-cast mines owing to their high diesel usage and the constantly increasing diesel prices. Although diesel-powered equipment usage in underground mines has also increased over the years, its management has not received the same attention. Figure 1 summarises the four pillars of the DIKW hierarchy and the respective phases developed for open-cast mines in the preceding study [15].

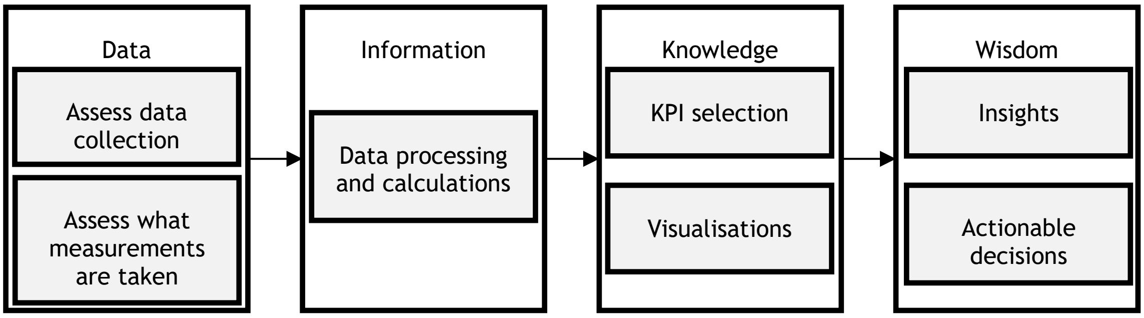


Figure 1: DIKW method for open cast mining diesel management (adapted from [15]).

Previous studies indicate that the DIKW hierarchy is capable of identifying diesel wastages and theft in an open cast mining environment [15]. It is also a good diagnostic solution to assist companies in decision-making. The method, however, does not determine the cause of failure or inefficiencies in a step-by-step approach. The present study seeks to evaluate the feasibility of applying the DIKW hierarchy to the underground mining environment and further expanding on the previous work byemploying root cause analysis.

Root cause analysis (RCA) is the process of determining the root causes of problems to identify appropriate solutions [16]. RCA can be performed with a collection of principles, techniques, and methodologies which can be leveraged to identify the underlying causes of an incident. Adding the RCA step to the DIKW hierarchy will assist mine management staff to systematically solve underlying issues rather than simply reacting to results from DIKW. In this paper, the DIKW hierarchy is extended as shown in Figure 2.

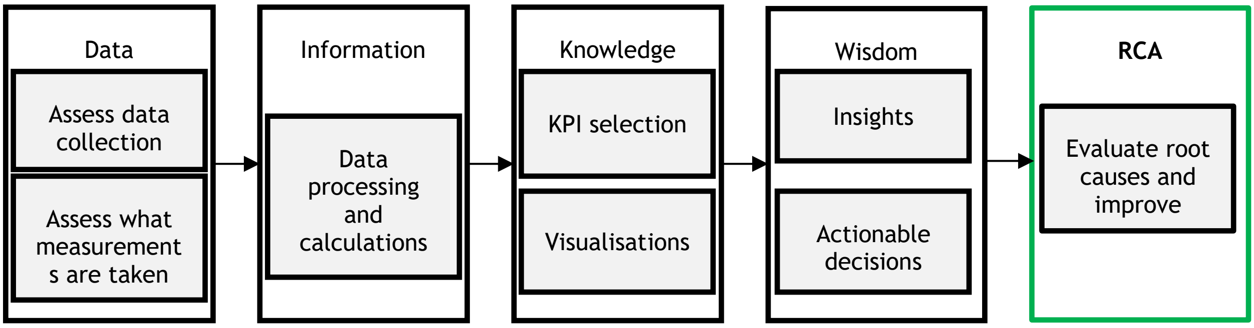


Figure 2: Expanded DIKW-RCA method for underground mining diesel management.

3 RESULTS AND FINDINGS

The approach described in Figure 2 was applied to a selected case study encompassing an underground mine. This section proceeds to elaborate on the implementation of this methodology, detailing the progressive steps and execution thereof. The case study mine is located in the Free State province of South Africa. Operating as a trackless mine, it relies on substantial volumes of diesel to carry out its activities, such as exploration, loading, and transportation of ore material.

In the previous study [15] the application of DIKW was divided into two domains: the data domain and the analysis domain. This study adheres to the same principle where the data domain is discussed as the first pillar (Data), and the analysis domain is discussed as the last three pillars (Information, Knowledge, and Wisdom). The domain that was newly added in this study is the RCA domain, aimed at determining the root causes after the initial findings, as shown in Figure 2.

3.1 Data domain

The data pillar of the DIKW hierarchy is divided into two sections, namely: assessing existing data collection methods and assessing available measurements.

3.1.1 Assess data collection methods

Due to the nature of underground mines and reduced accessibility, data is collected using various methods. Remote communication technologies are used in mechanized mines to facilitate communication between the surface and the underground levels [17]. This system architecture involves inner control loops managed by a network of local programmable logic controllers (PLCs) and an outer control loop managed by a central supervisory, control, and data acquisition (SCADA) system. This ensures complete control and monitoring of the entire PLC network and is therefore a popular approach to data acquisition in underground mines [18,19].

In sections of the case study mine where a SCADA system was not available, data was captured utilising a mobile application by a diesel bay attendant and synchronised to a centralised online database. To ensure completeness and accuracy of the data, diesel attendants are also required to manually capture the data on diesel control sheets that are handwritten and can be used as backup.

3.1.2 Assess available measurements

Understanding the basic diesel distribution layout is the first step to evaluating the various data points available in the network.

Figure 3 indicates three devices that are used to capture data per shift and four sensors that run for 24 hours daily, as described below:

- Device 1 – measures the diesel delivered on the surface and the level of diesel in the tank.
- Device 2 – measures the diesel issued from an underground tank at level 263 to underground vehicles.
- Device 3 – measures the diesel issued from an underground tank at level 282 to underground vehicles.
- Sensor 1 – measures the diesel outflow from the surface tank to an underground tank at level 263.
- Sensor 2 – measures the level of diesel in an underground tank 1 (263 X/cut 8).
- Sensor 3 – measures the diesel outflow from tank 1 to tank 2 (L282 X/cut 19).
- Sensor 4 – measures the level of diesel in tank 2.

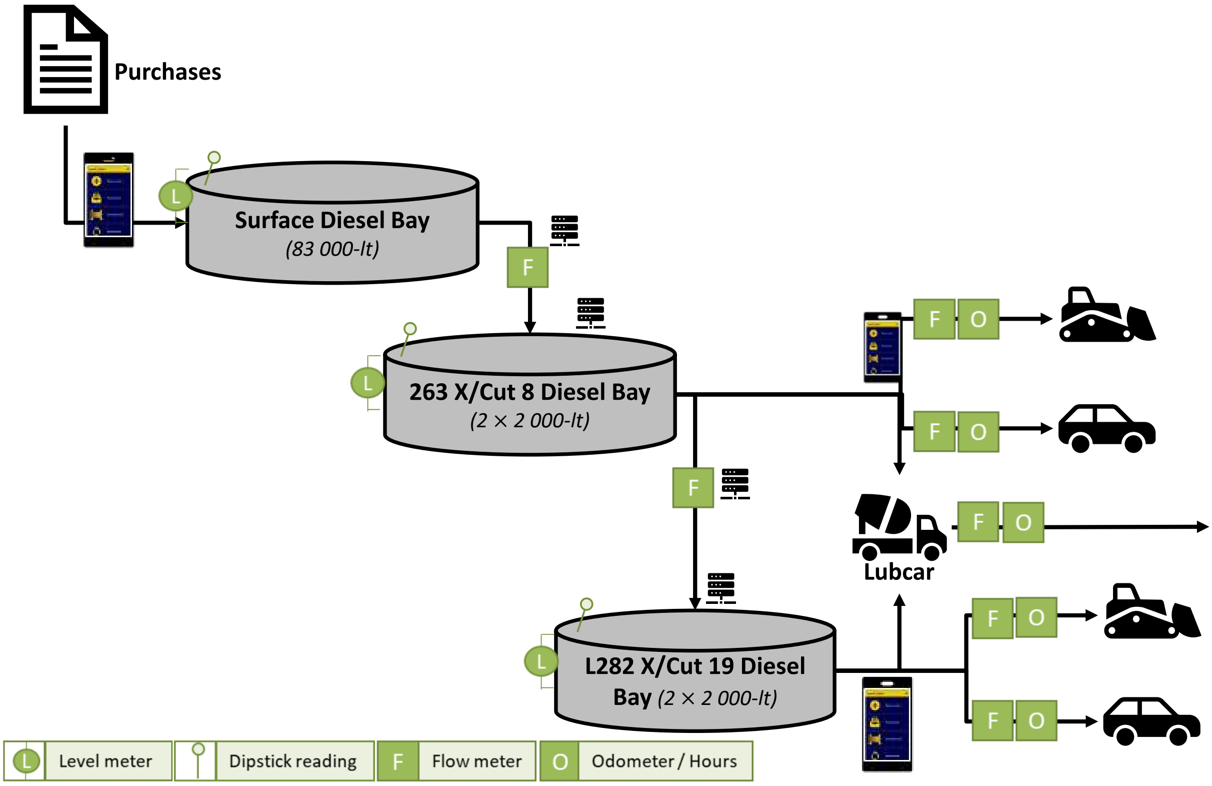


Figure 3: Diesel distribution layout and management at the case study mine.

3.2 Analysis domain

The second step of the DIKW hierarchy is to transform the acquired underground data into pertinent information. This process entailed contextualising the data to discern the significance of each individual data point. To proceed with converting tis information into knowledge, data profiles were constructed on Microsoft BI, as indicated in Figure 4. It is important to note that any data-management platform may be used to visualise the data, e.g. Microsoft Excel.

Figure 4 depicts the distribution of diesel underground at the case study mine. The dashboard allows managers and different stakeholders to understand and visualise their diesel consumption. The pie chart featured within the depiction indicates the type of vehicles utilised underground, as well as their consumption for a one-month timeframe. The chart offers management staff the insight to recognize their biggest consumers,as trucks followed by fermalUVs and loaders. This aligns with expectations, as these vehicles are used for primary activities in underground mines.

Figure 4 also shows the clustered bar chart, which indicates the amount of diesel issued per vehicle registration. This representation enables managers and stakeholders to visualise a specific vehicle's consumption, with the top vehicle being the highest consumer and the bottom being the lowest consumer.

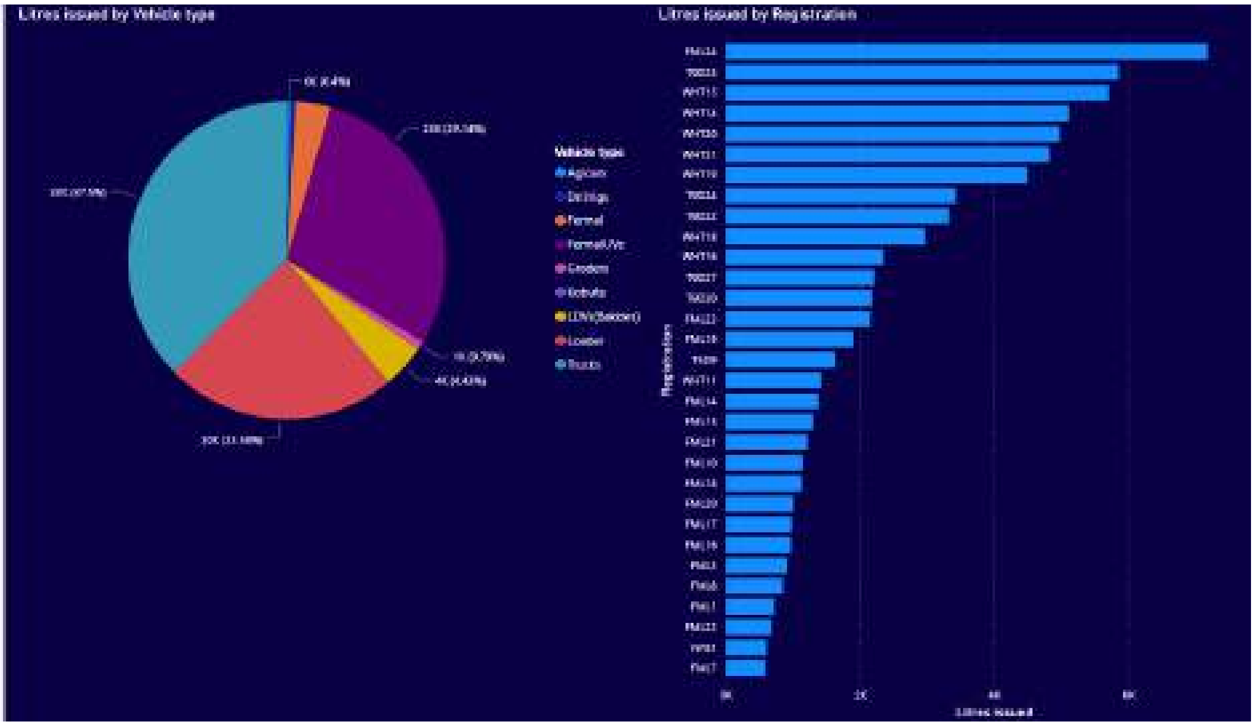


Figure 4: Underground diesel distribution Power BI dashboard for case study mine.

In underground mines, diesel is transferred from surface to underground through a pipeline, (as illustrate in Figure 3). Diesel is received and stored in the surface diesel tank, then transferred to level 263 (2 121 meters below surface) through a pipeline, into another storage tank. From here, the diesel is transferred to a lower level 282 (2 274 meters below surface), where it is stored for issuing at the diesel bays.

Visualising daily or monthly diesel balances can give a good indication of diesel amounts that were supplied, stored, and consumed. Using the DIKW hierarchy, Figure 5 was constructed on Power BI. Figure 5 indicates monthly balances of diesel underground, from the point of receipt to the point of use. From January 2022 until March 2023, diesel losses were noticed during every month, with the exception of two (May 2022 and August 2022).

Month [Year]	Opening (L)	Purchases (L)	Disposals (L)	Closing calc (L)	Closing (L) Actual	Losses [L]
Jan-22	54 479	135 495	101 013	88 961	67 232	21 729
Feb-22	67 232	75 978	85 938	57 272	27 752	29 520
Mar-22	27 752	110 037	103 870	33 919	29 688	4 231
Apr-22	29 688	113 882	102 102	41 468	33 494	7 974
May-22	33 494	75 908	96 827	12 575	12 575	0
Jun-22	12 575	147 586	95 319	64 842	47 212	17 630
Jul-22	47 212	110 126	93 196	64 142	51 528	12 614
Aug-22	51 528	77 488	102 295	26 721	26 721	0
Sep-22	26 721	114 750	99 064	42 407	22 192	20 215
Oct-22	22 192	148 270	109 284	61 178	43 092	18 086
Nov-22	43 092	106 086	97 314	51 864	18 977	32 887
Dec-22	18 977	92 739	64 274	47 442	44 506	2 936
Jan-23	44 506	75 902	73 612	46 796	28 531	18 265
Feb-23	28 531	69 428	73 849	24 110	18 188	5 922
Mar-23	18 188	140 766	86 144	72 810	67 935	4 875
Total losses [L]						196 884

Figure 5: Case study mine’s monthly diesel balances.

Utilising Figure 5, management staff gained *knowledge* of the problem and the *wisdom* to start with the investigation. Application of the DIKW hierarchy method resulted in the findings that frequent diesel spillages occur during diesel transfers from surface to underground. Inefficiencies in underground diesel usage was, therefore, successfully identified using the DIKW hierarchy.

As part of the *wisdom* pillar, managers must act to mitigate inefficiencies through investigations and ensure that the system’s performance improves (i.e., reduce spillages). However, it is evident that uncertainty is present given the longevity of the problem. A root cause analysis does not only resolve immediate and obvious symptoms of an issue [20], but also provides a root cause to the problem. In the next section, the DIKW is further expanded to include RCA as shown in Figure 2.

3.3 RCA domain

The purpose of RCA is to diagnose a problem, determine the underlying cause, and identify a solution. When the root causes of a problem are known, corrective action and preventive steps can be taken to ensure that the problem does not reoccur [20]. There are various methods for evaluating the root cause of a problem, for example ‘cause-and-effect analysis’, ‘Six sigma’, ‘fishbone diagrams’, ‘the 5 Whys method’, and ‘fault tree analysis’ (FTA), to name a few [20], [21]. The FTA is predominantly used in situations that involve failures and accidents [22].

3.3.1 RCA application to case study

After a site inspection at the case study mine, it was determined that the losses reflected by the DIKW hierarchy were a result of diesel spillages. However, there was no clear understanding of the causes. Consequently, an FTA was applied to determine the root causes of diesel spillages underground.

FTA is considered to be one of the simplest and most effective methods of improving system reliability [22]. By applying this method, an organisation can determine a logical relationship between the failure that has occurred and the causes that resulted in the failure. Figure 6 gives an overview of a general FTA procedure.

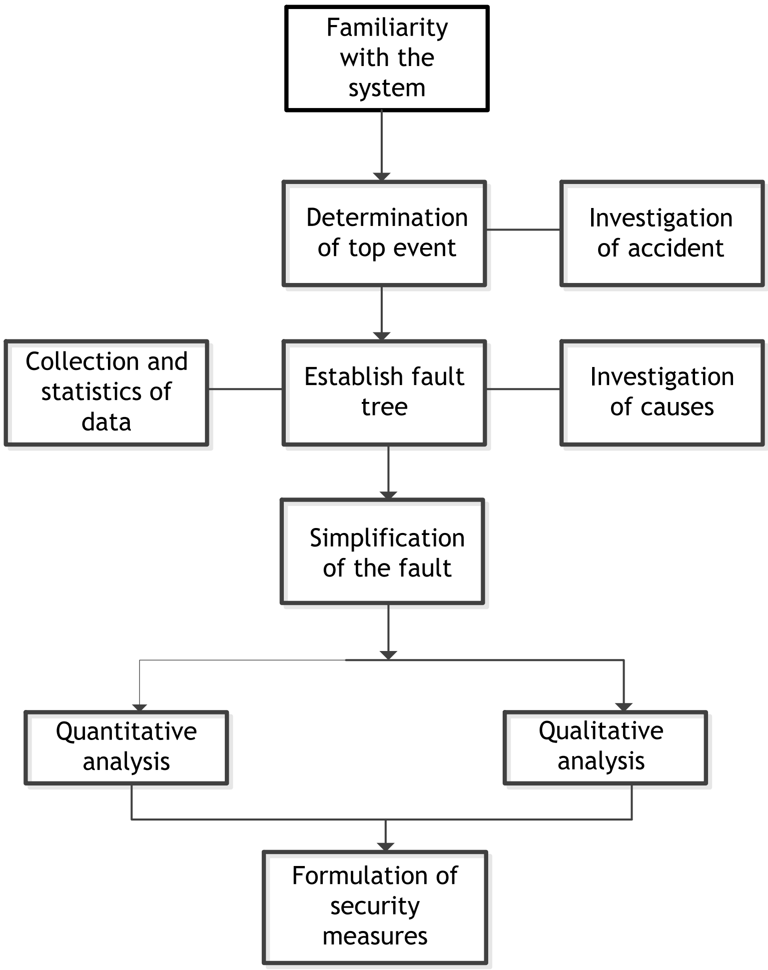
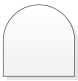
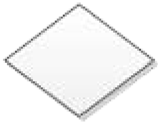
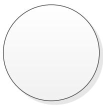


Figure 6: General procedure of an FTA (taken from [22]).

FTA is a top-down, step-by-step approach employed to determine the root cause of a problem. The starting point of the fault tree is the undesired event, also known as the top event. This event is followed by logically determining the immediate contributory fault conditions that resulted in the undesired event [22]. The contributory causes/faults are listed until primary causes are obtained. Table 2 summarises the typical components of a fault tree analysis.

Table 2: Components of fault tree analysis [23].

Symbol	Name	Description
	Event	Fault occurring from more basic events.
	AND gate	Logic gate where output exists only if all inputs exist (all inputs should be true).
	OR gate	Logic gate where output exists if anyone of the inputs exist.
	Undeveloped event	Event that could be further broken down but not pursued further [24].
	Basic event	Root cause or primary failure.

3.3.2 RCA results

Following a series of investigations and collaborations at the case study mine, a qualitative FTA was constructed, as presented in Figure 7. The figure indicates the undesired event (diesel spillages) as informed by the DIKW hierarchy, followed by possible causes and their associated sub-causes, ultimately culminating in the identification of the root cause(s).

The development of the FTA is an iterative process. It is important to ensure that the causes are exhaustive and unbiased. This was ensured through sustained communication between all relevant stakeholders. In the case study, the stakeholders encompassed the maintenance team, store coordinators oversseing diesel reception, instrumentation technicians, diesel bay attendants, engineers, and managers. To ensure exhaustive cause identification, the FTA was divided into distinct consultation- and auditing levels.

Level 1: This level was based on process knowledge and observation. Spillages can occur during two occasions: 1) During diesel transfer; and 2) At the point of storage. Consulted stakeholders were the store coordinators and engineers who approved the observation.

Level 2: At this level, the events identified in Level 1 were treated as the “effects”, and their causes were evaluated. Audits of transfer pipelines were executed with the support of the maintenance team and technicians. Two more causes were identified during the pipeline audit: 1) Pump failure; and 2) Pipeline damage. The latter is classified as an undeveloped event because, although it is a possible cause, it is not investigated further seeing as no damage was identified during the audit. Pump failure could, however, be explored further.

Diesel bay attendants are responsible for maintaining diesel storage. Investigations were conducted to further understand the possible causes of failures within diesel storage facilities. Two intermediate events were identified and agreed upon, namely tank maintenance and distribution failure. Both events could be further explored in Level 3 of the FTA.

Level 3: This level delved into the intermediate events in Level 2. Pump failure, according to the maintenance team and technicians, Indicated two potential causes: 1) Alert alarm flooding (where the pump is not stopped or detected), or 2) Mechanical failure of the pump. The latter is considered an undeveloped event after meticulous assessment of the pump mechanics, demonstrating proper functionality. Furthermore, a weekly pump evaluation schedule was established at the specific case study mine to ensure continued mechanical efficiency.

Three basic events were identified through the diesel bay inspection. These are classified as basic events, which are an integral part in spillage failures. No maintenance had been done on the storage tank over several years, and diesel bay attendants confirmed that management was not informed about the required maintenance.

Levels 4 to 6: Alert alarm flooding was further explored. This level encompassed collaboration with instrumentation technicians, control room operators, and engineers. From observation and consultation with control room operators, "alarm trigger" was confirmed as a fundamental event. Due to with the overwhelming volume of alarms, some alarm triggers were disregarded based on their perceived impact. Technicians and engineers agreed upon sensor malfunction as another cause, which was further explored. By the frequency of sensor inspection in the case study mine, sensor damage was marked as an undeveloped event.

Sensors require an electrical power source to operate. The time of spillages had a common pattern; it was noted that they mostly occurred during loadshedding. Further investigation indicated that the sensor registered as zero during loadshedding, triggering the pump to operate and transfer diesel to the underground level. The pump would persistently operate until control room operators manually intervened to halt its operation.

All causes were validated and endorsed by the consulted stakeholders at the case study mine.

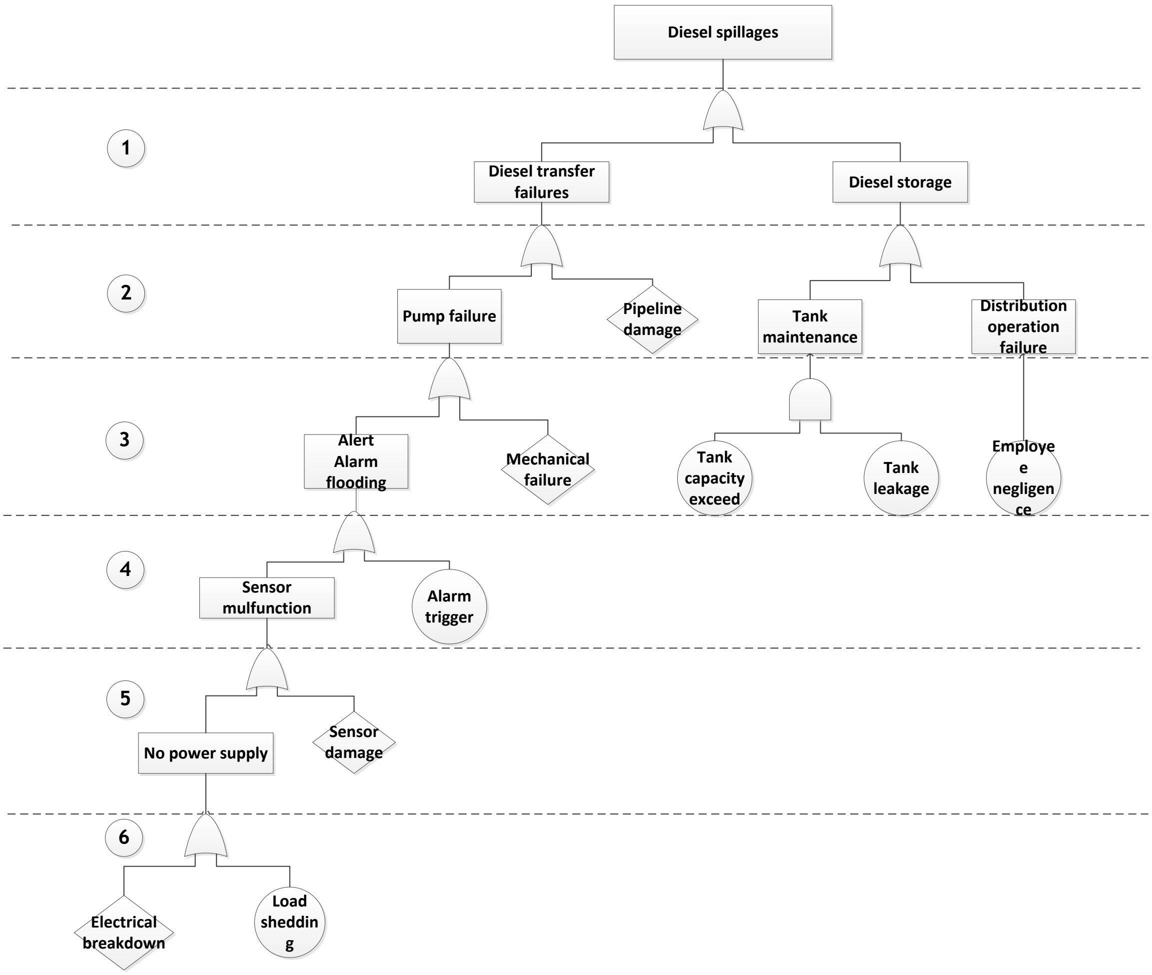


Figure 7: Fault tree graph for underground diesel spillages at case study mine.

As indicated by Figure 7, the basic events (root causes) were found to be loadshedding, alarm triggers, exceeded tank capacity, tank leakages, and employee negligence.

From Figure 7, managers were made aware of the root causes so as to identify direct solutions and make effective decisions. Table 3 summarises all the root causes identified and provides possible solutions for each cause.

Table 3: Possible mitigation strategies for diesel spillage

Root cause	Observation and possible mitigation plan
Loadshedding	**Observation:** Loadshedding resulting in no power supply is the main cause of sensor malfunction. During loadshedding, underground tank level sensors read zero, triggering the surface tank pump to start pumping diesel. If this is undetected due to alarm flooding, the pump will continue to run, resulting in higher volumes of diesel being wasted. **Mitigation:** Loadshedding is a frequent occurrence in South Africa and is predicted to continue. The best way to avoid power failures for sensors is to purchase and install uninterruptible power supply systems (UPS). These units are designed to supply electric power to devices during power outages, ensuring that sensors do not malfunction.

Root cause	Observation and possible mitigation plan
Alarm trigger	**Observation**: An alarm is an audible or visible means of indicating process deviation or abnormal conditions to the control room operator [25]. It is common to receive more than 2 000 alarms per day. Underground mines comprise of intricate systems with multiple alarms, in which can result in multiple triggered alarms (alarm flooding). This can ultimately overwhelm operators, which leads to many of these alarms being disregarded [26]. Diesel spillage alarms were often ignored in the case study mine as they are not perceived as immediate emergencies. **Mitigation**: An alarm management procedure using Engineering Equipment and Materials Users Association (EEMUA) guidelines should be developed [25], [26]. In this guideline, it is stated that all alarms are useful and should never be ignored. Management should ensure that there should be no alarm without a response and have a system in place to monitor these.
Tank capacity exceeded and tank leakage	**Observation:** These two basic events are linked: lack of maintenance and regular inspection results in diesel spillages. The case study mine was commissioned in 2002 and has been operational for over 20 years to date. The demand for diesel in this mine has increased over the years. However, the diesel storage capacity has been kept the same. **Mitigation**: Regular maintenance checks will enable managers to rapidly react to diesel leakages, resulting in minimised spillages. Increased diesel tank capacities will prolong the starting time of diesel spillages, allowing more time for control operators to react to the triggered alarm.
Employee negligence	**Observation:** Diesel bay attendants should ensure safe and efficient distribution, as well as diesel storage management. Attendants tend to focus solely on issuing diesel to different vehicles, while neglecting to assess the condition of the diesel bay. **Mitigation:** A procedure should be implemented to encourage diesel bay attendants to be more alert. Diesel bay attendants should not wait for control room operators to detect the alarm. Phones are made available underground and should be utilised to communicate failures with the control room.

3.3.3 Limitations and adaptability

Although RCA is a beneficial tool to identify systematic failures, it is limited by its requirement for an experienced team. Inexperienced individuals are often unable to identify all causes. Another limitation is hindsight bias towards one possible root cause. Operations can minimise these limitations by ensuring collaboration between teams and section experts.

In this study, the RCA is coupled with DIKW, which is a technique used for informed decision-making. Combining the two techniques ensures that the organisation is solving the identified problem and finding the root causes of a definite system problem. Although causes are identified, the RCA does not prioritise the causes. Therefore, this paper incorporates a priority matrix, which is discussed in the next section. The RCA method is a universal method that can be applied at any mine. The event sequence may vary, but the execution remains unchanged.

4 DISCUSSION

In the previous section, the root causes of diesel spillages in an underground mine were determined. These causes were identified to expand the DIKW hierarchy and enable management staff to manage underground diesel wastage more effectively. Upon identification of the root causes, a subsequent priority matrix is developed to prioritise solutions with the highest impact on the diesel-loss issues. In Figure 8, the second quadrant indicates the solutions that are high impact and easier to implement. These solutions can be implemented within a short timeframe.

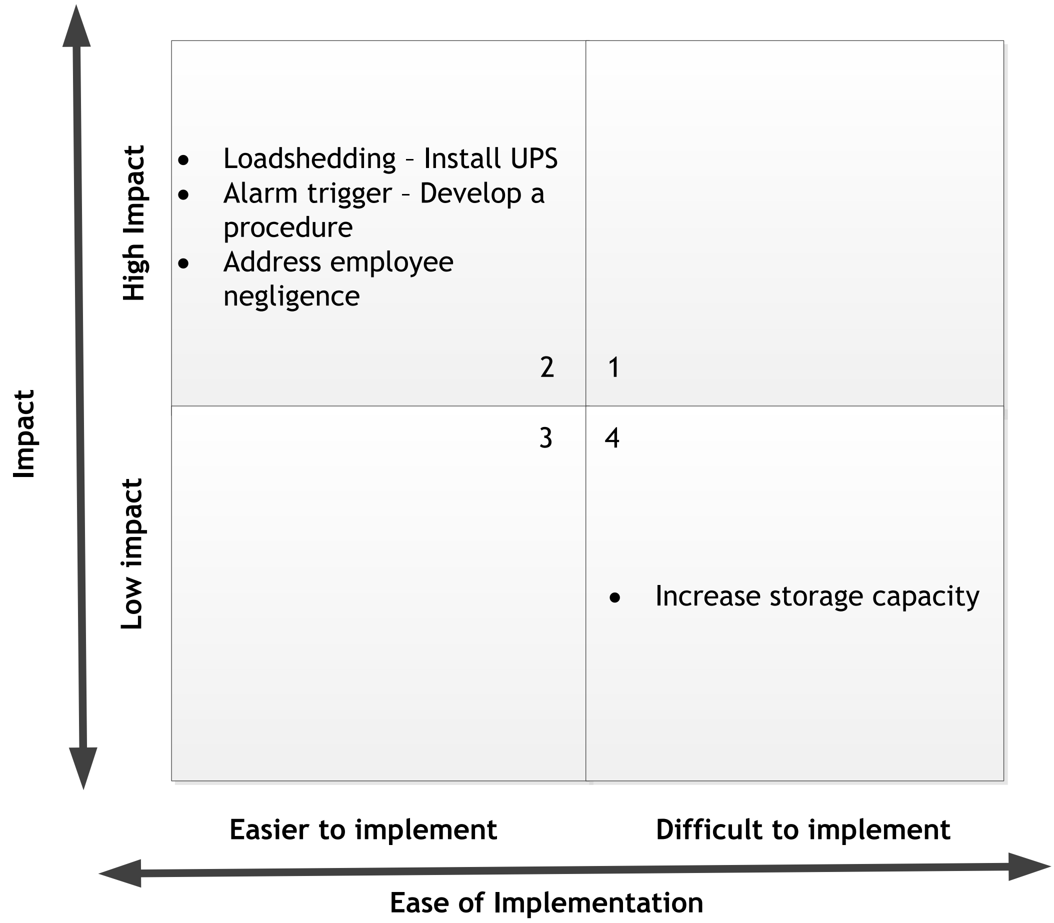


Figure 8: Priority matrix for solution implementation at case study mine.

The results show that increasing tank capacity has a minimal impact and is difficult to implement. It necessitates an appropriate budget for these tanks requires undergoing multiple approvals before execution. The operation would have to shut down for this to be implemented. Although the solution is not impossible to implement, it requires effort.

With this study's proposed approach, a total loss of 196 884 litres could have been avoided (monthly average spillage of 13 126 litres). For the case study mine presented, the mitigation strategies can result in an average diesel-saving cost of R269 079 per month, and an estimated R3.2 million per annum (at a diesel cost of R20.50 per litre[†]).

5 CONCLUSION

Over the years, diesel consumption within underground mines has steadily increased. However the corresponding management aspect has not received the requisite level of attention. Ample literature is available pertaining to the underground mining environment; nevertheless, no studies have primarily emphasized diesel consumption and wastage management. This study adapted the DIKW hierarchy framework to identify diesel wastages in a case study mine to assist management with enhanced decision-making. This study further expanded the DIKW hierarchy to include RCA, thereby producing a novel combination termed DIKW-RCA.

The methodology was applied to the case study mine to identify the causes of spillages in an underground mine. The method allowed management staff to not only diagnose the specific issues, but also to identify their root causes. The study provided decision-makers with mitigation strategies, which were subsequently subjected to a priority matrix to expedite the implementation process. Through the employment of this innovative methodology, diesel losses of a noteworthy 196 884 litres could have been avoided, resulting in a potential annual saving of approximately R3.2 million.

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TECHNOLOGY FORECASTING: A FUTURISTIC INNOVATIVE APPROACH FOR ORGANIZATIONAL SURVIVABILITY, RESILIENCE & COMPETITIVE ADVANTAGE; A LITERATURE REVIEW

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ABSTRACT

Over the years, technology has been a major force in changing people's lives. Yet, it's only in recent times that leaders within both public and private organizations have begun acknowledging the necessity of foreseeing technological change and its impact on their operations. Economic forecasts, market forecasts, financial forecasts, and even weather forecasts have become standard management tools. In this context, technology forecasting is now as embraced and valuable as any other analytical instrument. This paper focuses on the strategic innovation phenomena where technology forecasting plays a critical role in supporting organizational competitiveness and survivability. The paper explores some technological forecasting techniques that organizations can utilize to predict futuristic technological threats and opportunities. However, the application of these techniques will differ between organizations and industries; hence the intent of the paper is to give an insight view of each technique from which organizations and businesses can identify to help support strategic technology planning within their industry of operations.

Keywords: technology forecasting, competitive advantage, futuristic innovation, organizational survivability.

1 INTRODUCTION

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Technology forecasting is a field of research that aims to predict future trends and developments of new and emerging technologies [19]. The ability to forecast technology trends has become increasingly important in the current fast-paced technological environment. According to [14] accurate technology forecasting can help businesses, governments, and other organizations to stay ahead of the curve and make informed decisions about future investments and strategies. [17] analysed the origins and historical revolution of technology forecast which dates as far back as the 1930s leading up to World War II. The study showed that technology forecasting was a key factor in maintaining a sustainable military technological edge over rivals. Technological forecasting is evolving as an important driver for industry direction and technology development [20]. With the rapid development of globalization, the industrial paradigm has changed significantly with the advent of emerging technologies; hence technology forecasting is receiving more attention from governments and business circles [21]. According to [22] technology forecasting plays a crucial role in assisting decision-makers to identify and assess both opportunities and threats within a company's business operations industry. It also serves as a valuable tool in facilitating the planning process for new ventures, joint ventures, and strategic alliances. For business planning groups and R&D institutions, technology forecasts are essential not only for formulating business and technology strategies but also for determining the direction of resource allocation to R&D portfolios and new product development. Various methodologies for technology forecasting have been created and implemented across various industries and organizations, serving diverse objectives [22]. However, few studies have attempted to explore the overall impact of technology forecasts on business organizations [23-25], [26] suggests that technology like automation could “add significant value related to labor replacement,” allowing companies to understand customer preferences, improve operations through the use of predictive maintenance tools, reduce document production tasks, and find new ways to streamline and react instantly to weather changes affecting a company’s products.

According to [9] a crucial aspect of technology forecasting involves evaluating the influence of introducing new technologies on both the organization and its surrounding external context. Neglecting potential adverse effects could lead to catastrophic outcomes not only for the company itself but also for individuals who are not engaged in technology choices and are unlikely to reap any advantages from them. [10] explained that the process of technology forecasting is a tactic used by organizations to anticipate possible advancements in technology and make well-informed decisions based on such projections. [11] examined the process and cited that recognizing and examining patterns, scrutinizing data, and employing anticipatory models to predict forthcoming advancements in technology help guide an organization toward a plausible future. In the present-day fiercely competitive and quickly changing technological environment, technology forecasting serves as a valuable resource for companies to secure their continued survival, resilience, and competitive advantage [12]. By being forward-thinking about technological advancements, companies can proactively prepare for upcoming changes, create novel offerings, and maintain their competitive edge.

[13] highlighted that technology forecasting aims to enable individuals and organizations to make educated choices concerning investments, research, and development by providing valuable insights. Individuals and organizations can get ready for possible opportunities and difficulties in the future by forecasting technological advancements. According to [14] various means and procedures are employed in predicting technology, encompassing expert opinions, trend analysis, scenario development, and simulation models etc.

One industry that has witnessed the application of technology forecasting is the defence industry; the rise of various military technologies has continuously changed the battlefield. The management of military research and development has had a significant impact on the growth of technological forecasting as a substantial professional endeavours [15]. Technology forecasting can address both incremental changes to exploit current technologies and long-term changes to explore emerging technologies [15]. While technology forecasting cannot offer absolute certainty about the future outcome, it can provide valuable insights and prediction to assist individuals and organizations in making informed decisions [16]. Individuals and organizations can remain ahead of the game and be more prepared for the future by staying informed about new trends and advancements. In a rapidly changing technological landscape, organizations that embrace technology forecasting as a strategic tool can not only survive but also thrive by anticipating, embracing, and capitalizing on new opportunities while minimizing risks.

The research questions which led to the exploration of technology forecasting methods are:

- What are the various technology forecasting techniques?
- Does technology forecasting support competitive advantage?
- Are all technology predictions always, correct?
- Is technology forecasting embraced by a firm's management?
- Are all technological forecasting techniques applicable to all industries?

Identifying the right forecasting methods is crucial for informed decision-making, innovation, risk management, and maintaining a competitive edge in an increasingly dynamic and technology-driven world. They empower organizations to navigate change and uncertainty with confidence, ensuring their continued success [17]. And while technology forecasting is concerned mainly with predicting future developments and trends of advancements in various technological fields, it is also important to understand how these technologies impacts the environment [18]. The relevance of ecological models and technology forecasting share similarities, as both concepts address the complexity of future challenges and opportunities. This relationship lies in their shared contribution to understanding, anticipating, and addressing complex challenges and opportunities spanning the fields of ecology and technology. Integrating knowledge from both fields can lead to innovative, sustainable, and flexible solutions for the future. This paper makes a definite contribution to the field of Engineering Management by providing a comprehensive exploration of technology forecasting techniques and their applicability to different industries. It emphasizes the importance of technology forecasting in supporting organizational competitiveness and survival. Additionally, the paper highlights the historical evolution of technology forecasting and its significance in shaping industry direction and technological development. The relevant data for this study was acquired by employing various search engines to identify pertinent information. This information was then extracted by meticulously reviewing scholarly articles and reports released by reputable professional organizations. The selection process involved thoroughly perusing these publications to extract and reference the applicable information. The research questions were also answered by the study.

2 LITERATURE REVIEW

2.1. Technology Forecasting

Technology forecasting has emerged as a proactive approach that empowers organizations to navigate uncertainty and capitalize on emerging trends [1]. The rapid acceleration of technological development has given rise to forms of technology that were unthinkable a few decades ago [2]. This pace of technological growth has significantly shrunk both geographical and cultural distances with the advent of smart devices, improve broadband coverage, and advances in nanotechnology, robotics, artificial intelligence, deep learning, big data, and autonomous vehicles to mention but a few. These technologies have found applications in all industries and don't show a sign of slowing down [3-6].

2.1.1. Key Concepts

Forecasting is at the forefront of planning and decision making. Future uncertainty is both exciting and challenging as individuals and organizations seek to minimize risk and maximize profit [27]. Many forecasting applications require different forecasting methods to meet real-world challenges, but predicting technology requires understanding about how technology evolves and matures. Understanding the dynamics of technological change is essential to making strategic decisions related to technology [28]. Historical data in many fields show that when performance attributes are tracked over time, progress follows regular patterns rather than being random and discontinuous. As products and processes have a lifecycle, so does technology [28]. According to [29], Understanding the evolution and maturation of technology holds significance for forecasters. Nevertheless, there exist overarching principles that delineate the progression of technology, and these valuable guidelines are described below. According to [30] the most predicted technology attributes are:

1. Functional capacity growth
2. Replacement rate of from old technology to new technology
3. Market penetration
4. Diffusion
5. Probability and timing of technological breakthroughs

[30] elaborated on the idea that regardless of the attributes being forecasted, it is crucial to comprehend both the technology and the series of steps involved in the formation, appearance, and dissemination that characterize its development. Functional capacity measurements may vary for seemingly similar technologies because technology growth is complex, so there **is** no single growth pattern. However, there is a general concept that describes how technology evolves: the technology lifecycle. [9] showed that technology generally follows an S-shaped growth pattern as shown in figure 1 below.

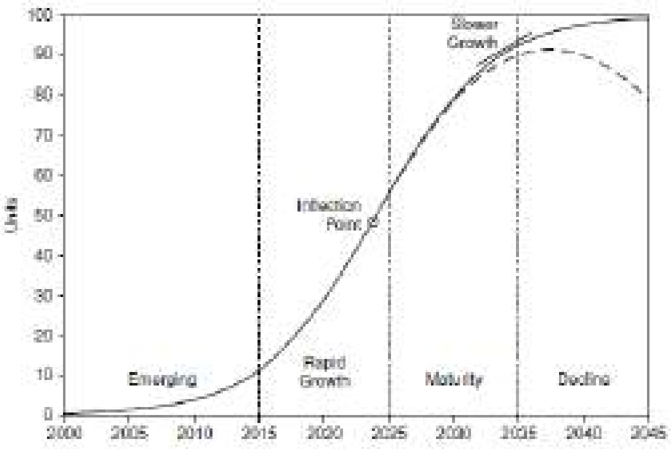

Figure 1: Growth **stages** and **S**-curve [9]

The figure shows that growth slows when a technology is on the rise, as innovators develop prototypes and try to make product configuration decisions based on the technology's capabilities. After the product is introduced, it goes through a phase of swift expansion. This is succeeded by a turning point where growth tapers, transitioning into a slower pace as the product reaches its mature stage. Ultimately, the technology becomes outdated, leading to a decline in its utilization [9]. Each phase involves different types of management. The emerging stage is dominated by research and development related to gathering and integrating market information. On the section of rapid growth is a period in which products change slowly however, companies accelerate production to dominate the industry. During the maturity stage, management decisions often focus on evolutionary improvements in function, quality, and cost. The decline phase usually involves business consolidation and downsizing. Such growth patterns can persist for long periods of time [9].

2.1.2. Classification of Technology Forecasting

According to [8] technology forecasting is commonly categorized into either exploratory or normative methodologies. The exploratory approach revolves around predicting forthcoming events based on historical data up to the present time. Conversely, the normative approach commences from a potential future state and retraces the path to the present, outlining the necessary steps and the probability of successfully reaching the desired outcome. Over the last four decades, particularly with the proliferation of information technology, scholars have formulated diverse methodologies for leveraging information resources and utilities like databases, patents, journals, and research grants, to sift through vast volumes of data and predict emerging patterns [22]. Figure 2 illustrates a chronological tree of technology forecasting based on the exploratory and normative techniques.

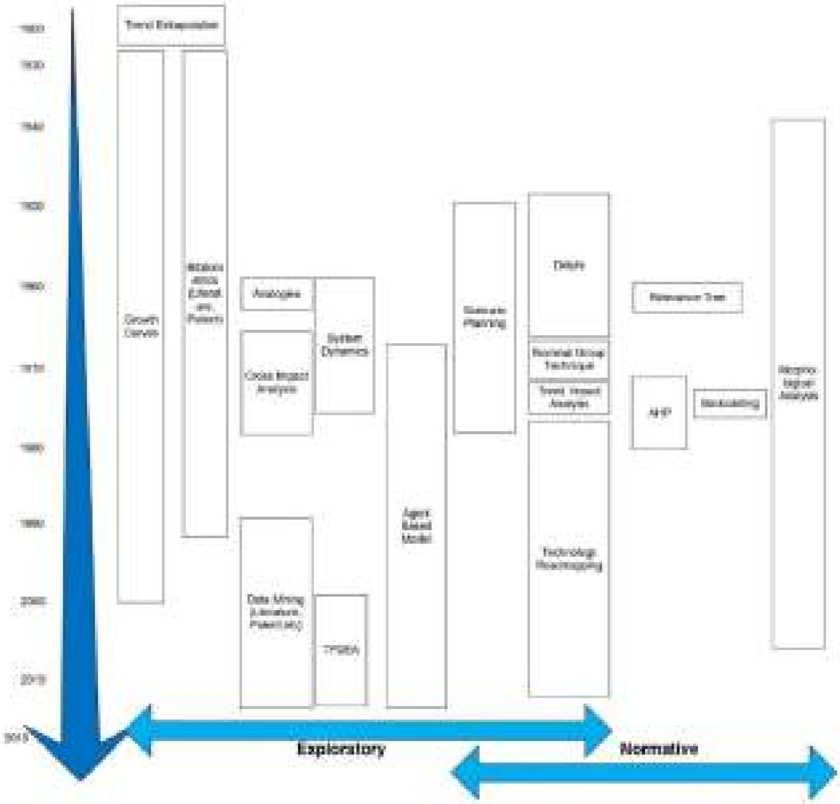

Figure 2: Timeline of technology forecasting techniques [22]

Typical characteristics leading to both exploratory and normative prediction were explored by [17] which is explained in the table 1 below.

Table 1: Classification of technology forecasting methods [17]

Term	Definition	Features

Exploratory	Efforts to anticipate the potential future technological advancements and innovations that could emerge.	• Develop following a predefined curve, such as the S-shaped curve. • Too naïve. • Project envisions potential outcomes. • Recommend alternatives to the proposed distribution.
Normative	The description of what is expected to be achievable or necessary in the future.	• Increased proactivity. • Excessively intricate from a mathematical standpoint. • The significance lies in the meaningful approach to achieving its goals. • Acknowledgment of economic possibilities. • Acknowledgment of duty to society or country. • Understanding of limitations (such as natural resources, company assets, etc.). • Acknowledgment of the utmost technological capacity. • Mitigating potential risks.
Normative/Exploratory	Applicable in two distinct methods.	

2.2. Competitive Advantage and Strategy

[31] defined competitive advantage as the position a company occupies over its competitors. It defines an organization's "uniqueness" in its relationships with its competitors. This suggests a distinct, and ideal long-term advantage over the competition. Competitive advantage is the premise of a good strategy, and a good strategy provides a competitive advantage [32]. It is more than an idea of a competitive strategy that may or may not be unique (Johnson et al, 2005). [33] asserts that gaining and sustaining competitive advantage is the defining question of strategy. [31] pointed out that competitive advantage is developed and sustained when a business performs its most important function, which is cheaper or better than its competitors. He goes on to say that sustainable competitive advantage needs efficient control over cost factors, and economies of scale, connectivity, learning, interconnection, and timing offer key opportunities to create benefits. [31] shows how companies in the industry can achieve broad profits or focus on one or several specific areas, which includes the use of cost advantage, differentiation, and focus to gain an advantage.

2.2.1. The generic building blocks of competitive advantage

[34] explained that these common blocks of competitive advantage can be customized by any company, irrespective of industry, product, or service. They are closely related and include efficiency, quality, innovation, and customer distance. Efficiency gives companies a cost-effective competitive advantage through employee productivity, as measured by productivity per employee. Quality products are products and services that you can trust in the sense that they are doing their job well. High quality has two impacts on competitive advantage, and

According to [35] this first raises the value of the product from the consumer's point of view, and second, it increases productivity and reduces the unit price. Innovations include product types, organizational structures, production process, management systems, and advances in corporate-developed strategies. Competition is seen as an innovation-driven process for providing businesses with something unique that can either charge a much higher price for a product or offer a much lower unit price than its competitors.

2.3. Futuristic Innovation & Organizational Survivability

Numerous institutions have predicted the rise of new technologies and documented their projections. Notable among these predictions are Disruptive Technologies, 10 Breakthrough Technologies, Next 5 in 5, and Top 10 Strategic Technologies [36]. Technology evolves; hence it becomes imperative for organizations to anticipate the trends and develop a good technology strategy. In the realm of technology forecasting, organizational survivability relates to a company's capacity to adjust, develop, and prosper amidst swift and transformative technological progressions and shifts within the market backdrop. In the contemporary, high-speed, and fiercely competitive business arena, technology assumes a central role in molding industries and markets [37]. Entities that can precisely anticipate technological trends, adeptly strategize for them, and seamlessly incorporate these changes into their plans are better positioned to secure their enduring viability and triumph. Technology Forecasting (TF) is a keyway to address futuristic innovation in a rapidly changing market environment and improve an organization's competitiveness in a complex and dynamic environment [37]. Due to the great and growing importance of technology, it is increasingly important to analyse and forecast trends and the future of technology. Although it is impossible to make an exact prediction, technological forecasting provides much-needed useful information [38].

2.4. Choosing a technology forecasting method

Technology forecasting is a tool for companies to formulate their technology strategy [39]. Many forecasting techniques have been developed in recent years to address the growing variety and complexity of business forecasting problems. Every forecasting method has its own specific purpose, hence careful consideration must be taken in choosing the right method for a specific application [40]. The quality of the forecast is very important for the accuracy of the results and for the future of the organization. Hence, it holds significance to choose a suitable forecasting approach, taking into account the attributes of the method and the necessary resources like expenses and time [39].

2.4.1. Framework for selecting technology forecasting methods.

A framework for choosing a technology forecasting method was developed by [41] that can help decide which methods to use in a given situation. However [29], recommends that forecasters should familiarize themselves with the strengths and weaknesses of each method and the conditions under which it is used before using it. The table below illustrates the forecasting techniques developed by [41].

Table 2: Selection of technology forecasting method considering the evolution of technology [41]

Phase in the Technology Life Cycle	Scope of data accessibility	Level of data accuracy	Ambiguity surrounding the progression of technology	Method for predicting future outcomes	Comments

Initial phase	small	Low	high	NGC	NGC is the favored choice due to the limited data accessibility. The panel of experts can deliberate potential trends that may arise.
Initial phase	small	Low or medium	medium	Delphi or Scenario	Delphi methods typically exhibit greater focus and reduced bias compared to NGC.
Intermediate phase	moderate	Low	medium	TTE	Using TTE is suitable as it offers approximate predictions of upcoming trends.
Intermediate phase	moderate	medium	medium	Growth curve	In the intermediate phase of TF, a key goal is to anticipate the upper threshold and the timing of technological advancement. This is where growth curves come into play, serving this purpose effectively.
Intermediate phase	Moderate or large	high	Medium or high	Systems dynamics	Understanding the architecture of the technology and possessing accurate and reliable data are essential.
Advanced stage	large	medium	low	ARIMA	Exponential smoothing yields less precise forecasts compared to ARIMA.
Advanced stage	Large	high	low	Regression analysis	It is possible to ascertain the collective impact of multiple factors on the development of technology.

According to [29] the first step involves identifying the main factors that exert an influence on technology forecasting. Subsequently, the significance of these elements for a specific forecasting approach is assessed. This connection between the factors affecting technology forecasting and the various forecasting methodologies aids in the selection of the most appropriate forecasting technique for a given scenario. [29] highlighted these factors as follows: Data Availability, Data Validity, Uncertainty over technological development success, The similarity between the suggested technology and the current technology, along with the multitude of factors influencing technology development.

3 RESEARCH METHODOLOGY

In carrying out the research methodology, We adhered to the five-stage methodology for Systematic Literature Reviews (SLRs) outlined by [42] . The ensuing subsections elaborate on each of these sequential steps. Some of the limitations associated with the study include the time constraints to collect new data and verify the cross-referencing. And while the major articles used were reviewed, however during the search other articles, and websites were also consulted.

3.1. Questions for the purpose of conducting a review

To present an up-to-date overview of research on technology forecasting: a futuristic innovative approach for organizational survivability, resilience & competitive advantage, we seek to address the following key questions:

- What are the various technology forecasting techniques?
- Does technology forecasting support competitive advantage?
- Are all technology predictions always correct?
- Is technology forecasting embraced by a firm’s management?
- Are all technological forecasting techniques applicable to all industries?

3.2. Identification of relevant works

A procedure for conducting a review was established, aiming to select relevant articles by following the guidelines outlined by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), as provided by [43]. The PRISMA approach stands as the widely recognized benchmark for conducting a systematic literature review. Figure 3 illustrates the sequential flowchart depicting the search strategy, followed by an elaborate account of the process employed for search and selection.

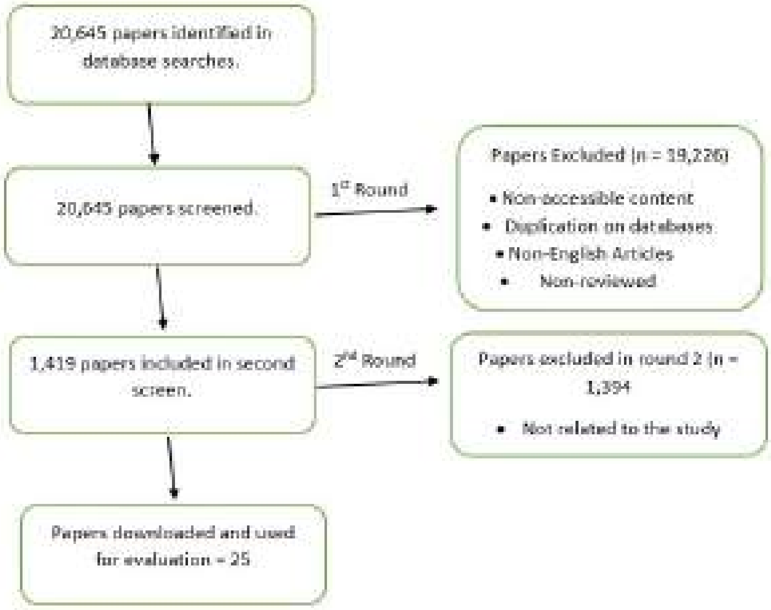

Figure 3: Flowchart depicting the process of search and selection.

The sequence of actions in the procedure is outlined below:

1. Identification

We opted to utilize Google Scholar, Science Direct & JSTOR for our publication search. Google Scholar was selected due to its broader coverage of academic publications in comparison to other online literature databases, as highlighted by [44]. Additionally, its accessibility is unrestricted. ScienceDirect serves as a comprehensive full-text repository, encompassing journal articles and book chapters sourced from over 2,500 peer-reviewed journals and 11,000 books (Harnegie, 2013). It was employed to expand the spectrum of collections and facilitate a cross-validation process. JSTOR provides access to an extensive array of primary sources within four distinct collections, bolstering research and education in the fields of humanities, social sciences, and sciences.

A catchphrase search was undertaken involving technology forecasting and how it supports organizational competitiveness and survivability as the search term to ensure the superset of papers were discovered. The reviews were conducted between April and May 2023. Three distinct queries were used, which are follows. 1. Keyword search including an overview of technology forecasting, 2. How technology forecasting supports organizational competitiveness and survivability, 3. The various technological forecasting techniques. During our search on all three databases, we established the publication date range as 1990 to 2023. This decision was made to ensure that our review remains at a manageable scope. Furthermore, we limited our search to English-language articles. The search was constrained to metadata, encompassing the abstract, keywords, and title, due to variations in filtering options based on the specific database.

Table 3: Database searches, metadata exploration, and employed search strings

Database	Searched Meta Data	Search Strings
Google Scholar	Title, keywords	(TS=(“technology forecasting” AND “competitive advantage” AND “futuristic innovation” AND “organizational survivability”))
Science Direct	Title, abstracts, keywords	(TS=(“technology forecasting” AND “competitive advantage” AND “futuristic innovation” AND “organizational survivability” AND “ strategic management of technology”))
JSTOR	Title, abstracts, keywords	(TS=(“technology forecasting” AND “competitive advantage” AND “futuristic innovation” AND “organizational survivability” AND “ strategic management of technology”))

The process of searching through literature yielded 5,055 studies. The distribution of results for each of the utilized databases is illustrated in Table 4.

Table 4: Findings from the literature exploration within each database.

Database	Google Scholar	Science Direct	JSTOR	Sum
Results	16,800	3,778	67	20,645

2. Screening

Afterward, we performed a manual assessment of the identified literature using their titles and abstracts. The aim was to narrow down the collection of articles for a comprehensive analysis of their full texts. To achieve this goal, we followed the designated criteria for including and excluding articles.

❖ Inclusion Criteria
1. Reviewed articles.
2. Articles that were published between 1990 and 2023.
3. Accessible Content

❖ Exclusion Criteria
1. The paper was composed in a language other than English.
2. Duplicate articles.
3. Not related to the study objectives.
4. Non-accessible content

The screening step's inclusion and exclusion criteria resulted in the removal of 19,226 articles. Subsequently, 1,419 articles remained eligible for further analysis. To determine which articles that meets our eligibility criteria, we examined those articles that can answer the research questions. After the additional review, 1,394 out of the remaining 1,419 articles were excluded, resulting in a final set of 25 articles that qualify for in-depth analysis. This process is illustrated in the flow chart in figure 3.

4 FINDINGS

4.1. Technology Forecasting Techniques

Technology forecasting methods encompass a variety of approaches used to predict and anticipate the future development and impact of technologies. Methods in forecasting are categorized as exploratory/extrapolative and normative, that is, those that extend current trends or work backward from a desired future to determine the necessary evolutions to achieve those goals [30]. Exploratory methods look at current trends and data to see where they can take the business, while Normative methods start with an idea or possible future and consider possible ways to get there [29].

4.1.1. Trend Extrapolation

Trend extrapolation stands as a prevalent technique in the realm of forecasting. It involves generating predictions under the premise that the future will mirror a plausible forecast derived from a given time series dataset. Older time series contains all the information needed to predict future events, and how current trends will continue into the future instead of creating another pattern, and according to [22] a good number of Economic forecasts utilizes this method. Trend extrapolation requires a forecaster to understand the factors that contributed to past changes and be confident that such factors will continue to influence similar developments in the future. A commonly used approach to extrapolating trends includes the use of growth curves. Growth curves are broadly based on the idea that technological growth can be represented in the same way as organic growth [45]. A study by [46] Looked at the trend extrapolation between electric & hydrogen vehicle technologies, with worldwide patent data from 1990 – 2010. As shown in the growth curve below.

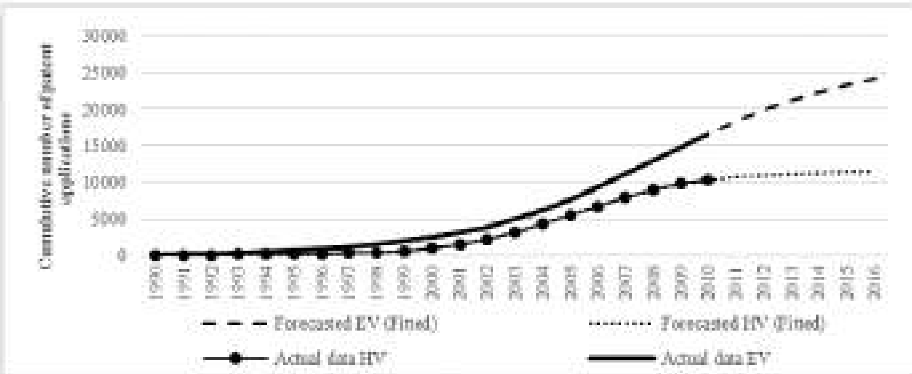

Figure 4: Trend extrapolation of the Electric Vehicle and Hydrogen Vehicle [46]

The hydrogen vehicle growth curve shows the evolution over the life of the technology, and it entered maturity and then stabilized in 2016. The graph shows saturation point for hydrogen vehicles [46]; further studies however shows that there are advancements beyond 2016 [47, 48]. Trend extrapolation is a simple and widely used forecasting method, particularly when historical data is abundant, and the underlying patterns are relatively stable. However, it is important to note that trend extrapolation assumes that the future will behave similarly to the past, which may not always hold true in dynamic or rapidly changing environments. Therefore, it is recommended to use trend extrapolation in conjunction with other forecasting methods and to consider additional factors and expert judgment when making important decisions based on the forecast.

4.1.2. Delphi

The Delphi method is a forecasting technique that involves collecting and synthesizing input from a panel of experts or stakeholders. It is designed to achieve consensus or convergence of opinions on a particular issue or question [49]. Anonymous people give numerical answers to a series of questions, such as the probability of an event occurring and the date the event will occur [50]. A summary of the responses is then compiled and sent back to the group, possibly with reasons for the responses. The individual is then given the opportunity to modify (i.e., re-prompt) the response based on the feedback received or repeat the previous response [51]. The process of iteration and controlled feedback continues until a predetermined breakpoint is reached (i.e. number of repetitions, consensus, confirmed disagreement, and stability of results) [51]. A procedure flowchart for the delphi method is shown in fig v below. The Delphi method helps in capturing diverse perspectives, reducing bias, and establishing a consensus among experts through a structured and iterative approach. It is particularly useful when dealing with complex, uncertain, or long-term technological developments where traditional forecasting methods may be inadequate [52, 53].

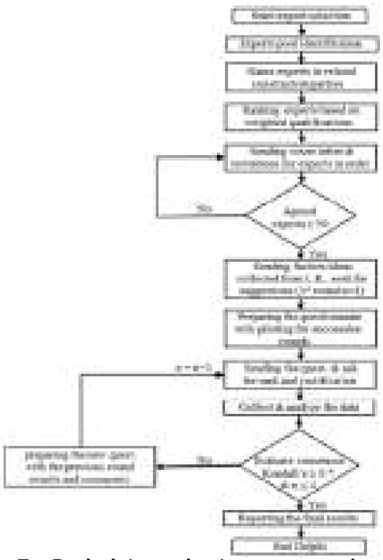

Figure 5: Delphi technique step-by-step flow chart [54]

According to the Corporate Finance Institute, the Delphi method was originally employed to predict patterns and results within the domains of science and technology. For instance, it has found application in forecasting aerospace trends, automation advancements, broadband connectivity projections, and the integration of technology in educational settings. A practical case of the application of Delphi technique was seen in a study by [55], to identify the right technological forecasting method(s) for the Iran Aviation Industries Organization. The study showed that the Delphi technique was the most suitable for the Aerospace Industry of Iran. The Delphi technique has also found application in predicting various outcomes concerning the economy, education, healthcare, and public policy. It has proven valuable in business contexts as well, displaying a remarkable 96%-97% accuracy in projecting sales in comparison to real sales figures. Consequently, the Delphi method stands as a viable technique for anticipating the success of business-related occurrences.

4.1.3. Curve Matching

The curve-matching forecasting method referred to as analog forecasting or historical analog forecasting, involves identifying and examining past patterns and trends that closely mirror present circumstances and issues. This approach operates on the assumption that comparable historical patterns are prone to reoccur in the future, underscoring the necessity of predicting forthcoming results [56]. Moreover, this method proves especially valuable in cases where there's a scarcity of data or when past data reveals evident trends that can be projected forward. Curve matching finds widespread application across diverse domains including meteorology, finance, economics, and business projection [57]. It provides a simple and intuitive approach to predicting future trends based on historical patterns. Furthermore, it offers a straightforward and instinctive method for anticipating upcoming trends by analyzing past patterns [58]. Nevertheless, it's crucial to exercise prudence when interpreting the outcomes and to account for additional factors that might impact future trends.

4.1.4. Scenario Planning

Scenario planning is a forecasting technique that involves the creation of multiple plausible and internally consistent narratives or scenarios about the future [59]. It helps organizations and decision-makers anticipate and prepare for different potential outcomes [60]. According to [60] there has been a significant rise in the utilization of scenario planning. Studies indicate a connection between the incorporation of scenario planning methods and the levels of uncertainty, unpredictability, and volatility within the broader business landscape [61]. As uncertainty increases, identifying future trends and the expected business environment is becoming more important. Therefore, the increasing complexity and uncertainty of the business environment have increased the use of scenarios. A direct correlation between scenario planning activities and innovation has also been discovered by researchers [62]. An illustration on the multiple plausible scenarios about the future is shown below.

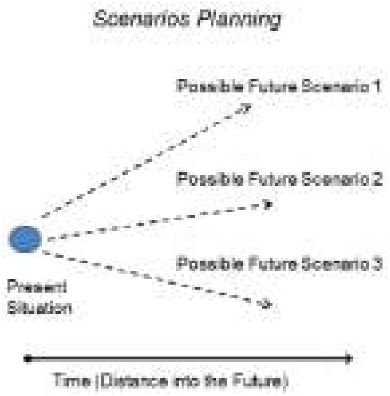

Figure 6: Scenario planning illustration [59]

Scenario planning's scope is extensive, encompassing the following aspects [63]:

- Crisis management involves employing civil defense drills where simulated future crisis scenarios are employed. These simulations serve to design and evaluate the effectiveness of systems and equipment in addressing these scenarios, while also enhancing overall preparedness for response.
- The scientific community employs scenario planning as a method for conveying the escalating intricacy of scientific models and theories in a format that is both more easily comprehensible and accessible. Illustrations of this practice encompass scenarios outlining the progression of climate change derived from environmental computer models, as well as scenarios delineating economic growth founded on econometric models.
- Public policymakers are progressively employing scenarios as platforms to engage various agencies and stakeholders in the process of making policy decisions. This approach facilitates integrated analysis and establishes a platform for collaboration to

support the implementation of policies. A notable illustration in this domain is the UK government's initiative known as the 'modernization programme for local government'.

Overall, scenario planning is a powerful tool that enables industries to navigate uncertainty and make strategic decisions that increase their resilience and competitive advantage.

4.1.5. Relevance trees

The relevance trees forecasting method is a technique used to analyze and predict outcomes by examining the relevance of various factors and their relationships within a complex system [64]. It involves constructing a hierarchical tree structure that represents the relevant factors influencing a specific outcome or event [65]. The relevance trees forecasting method helps businesses and analysts gain a holistic understanding of complex systems and make more accurate predictions by considering the interdependencies and relative importance of various factors. It provides a visual representation of the key drivers and relationships involved in the forecasting process, aiding decision-making, and strategic planning [66]. The diagram below depicts a relevance tree method used in mapping out initial ideas for a research topic.

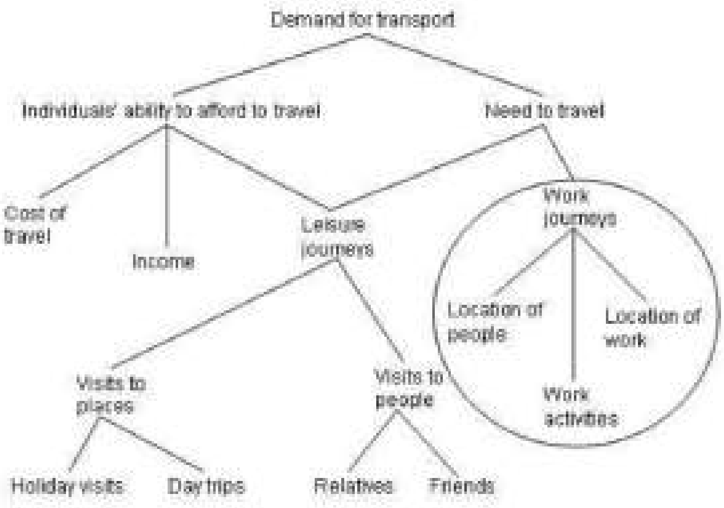

Figure 7: Relevance tree technique utilized for mapping out initial ideas for research topic [67]

4.1.6. Substitution (S-curves)

The forecasting approach known as the Substitution (S-curves) technique, or the S-curve model, serves to anticipate the future uptake and diffusion of emerging technologies or products [68]. Its foundation lies in the concept that the pace of adoption adheres to a sigmoidal S-shaped pattern over time. This is depicted in fig viii. This methodology operates on the principle that fresh technologies or innovations are progressively supplanting existing counterparts within the market [69].

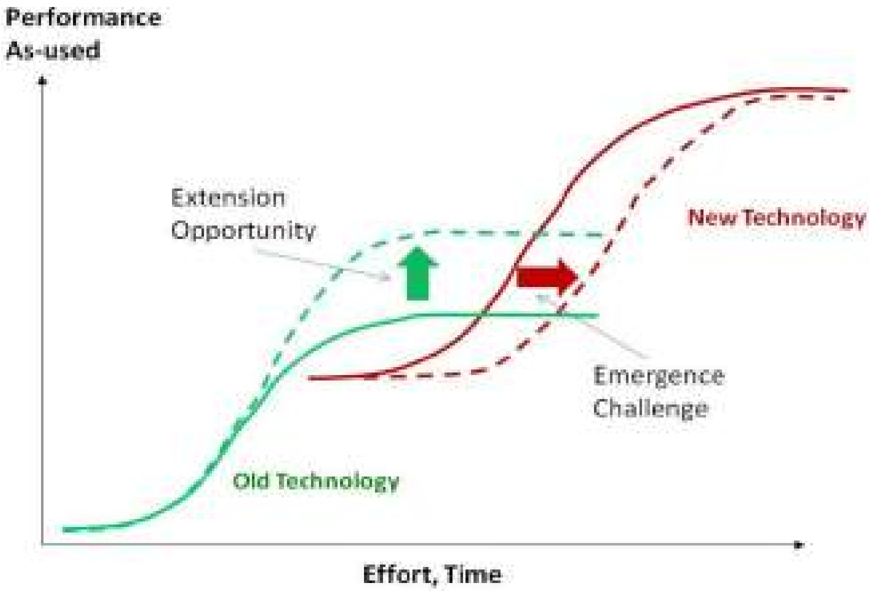

Figure 8: S-Curve forecasting technique [68]

It's crucial to underscore that the efficacy of the Substitution (S-curves) forecasting technique hinges on the accessibility and reliability of historical data, coupled with the precision of assumptions concerning market dynamics and adoption trends [70].

4.2. In answering the remaining research questions:

4.2.1. Does technology forecasting support competitive advantage?

Various studies [71-73] indicate that the practice of technology forecasting can bolster the competitive edge of businesses. By offering valuable insights, technology forecasting empowers enterprises to make knowledgeable choices, capitalize on nascent prospects, and maintain a lead over rivals. This approach aids in strategic plotting, fostering innovation, establishing market stance, and minimizing potential risks. All these elements collectively foster the attainment of a competitive advantage within the business landscape.

4.2.2. Are all technology predictions always correct?

According to [17, 74, 75] no technology predictions are guaranteed to be always correct. Although technology forecasting strives to foresee forthcoming technological progress and trends, it inherently carries uncertainty and is susceptible to diverse factors that can undermine the precision of predictions. The realm of technology forecasting entails making well-informed approximations and forecasts grounded in available data and trends, but there exist inherent ambiguities and variables that can impede the precision of predictions. The research underscores that technology predictions are vulnerable to uncertainty, intricacy, and the sway of various external influences. While technology forecasting can offer valuable insights and guide decision-making, it's vital to comprehend that it doesn't guarantee flawless precision in predicting the future.

4.2.3. Is technology forecasting embraced by a firm's management?

[76] explored the impact of technological forecasting on firm performance. Their findings argue that companies that weave technological forecasting into their strategic decision-making frameworks tend to outperform others, securing competitive edges. This underscores

management's acknowledgment and approval of the role of technology forecasting. Forward-looking enterprises' leadership readily embraces technology forecasting due to its manifold advantages and pivotal role in shaping strategic choices. Nonetheless, the degree of its implementation may fluctuate, contingent upon factors like industry, scale, corporate culture, and managerial principles. Some studies show [77-79] that a substantial number of management teams within companies are receptive to technology forecasting. This stems from its capacity to bolster innovation strategy formulation, elevate overall corporate performance, guide portfolio management determinations, and furnish strategic value. However, the level of adoption can differ across organizations, with some entities still in the process of grasping and fully embracing the benefits of technology forecasting.

4.2.4. Are all technological forecasting technique applicable to all industries?

Research conducted by [80, 81] highlights that not all technological forecasting methods can be universally applied to every industry. Distinct industries possess their own individual traits, dynamics, and technological landscapes that impact the relevance and effectiveness of particular forecasting approaches, as noted by [82]. According to (Kumar, S., & Banwet, D. K. 2008) several factors dictate the appropriateness of technological forecasting techniques for various industries. These factors encompass industry-specific trends and dynamics, the availability and quality of data, technological intricacy, industry-specific catalysts, and disruptions, as well as expertise and domain knowledge. The feasibility of applying technological forecasting techniques varies across industries due to their unique attributes, dynamics, and challenges. This research underscores that the selection and applicability of technological forecasting methods are industry-dependent. Diverse industries may have distinct requirements, contexts, and dynamics that shape the suitability of forecasting approaches. Consequently, it is imperative to consider the specific traits and demands of an industry when employing technological forecasting techniques.

5 CONCLUSION

An important aspect of technology forecasting is evaluating the impact of new technology introductions on an organization and its external environment, while ignoring its potential impacts can have dire consequences for the organization. Technology forecasting is critical in supporting business viability, resilience, and competitive advantage by enabling organizations to adapt, innovate and stay ahead of the rapidly changing technology landscape. Technology forecasting enables organizations to adapt to technological change, identify opportunities, mitigate risks, drive innovation, and maintain a competitive edge. Incorporating technology forecasting as a strategic practice can help organizations improve their survivability, resilience, and ability to thrive in a dynamic business environment.

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ENERGY PLANNING: A PERSPECTIVE ON SYSTEMS ENGINEERING AND MACHINE LEARNING INTEGRATION

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ABSTRACT

Energy planning impacts electrical energy supply, demand, and system stability. Sustainability of supply, demand and system stability show a close coupling with aspects regarding Environmental, Economic and, Security (social equity). A systematic approach to energy planning was used, leading to the use of a machine learning (ML) tool that incorporates principal component analysis (PCA) to assist decision makers shifting focus from an energy planning process to a policy perspective. The PCA tool is based on "vectorised" comparisons between top impacting criteria using open-source databases. These "vectorised" comparisons, translated to Saaty rankings, propose dimension-specific (Environment, Economic, Social and Technical) pair-wise comparisons for energy planners using multi-criteria decision making. Additionally, the SWOT analysis approach was found to aid the PCA-vectorised approach to identify proposed criterion that energy planners should consider in their modelling/ decision making process.

Keywords: energy planning, machine intelligence, systems engineering, multi-criteria decision making

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1 INTRODUCTION

An economy, business unit, or processing unit has a typical energy "catch-22", that is, what is there to gain, whether financially, environmentally, or sustainability. Therefore, the "perfect" energy policy based on an effective energy plan is challenging to attain, and Lalk [1] represented this catch-22 "dilemma" as an "Energy trilemma," shown in Figure 1. The trilemma, as presented by the World Energy Council [2] and discussed by Lalk [1], suggest that the sustainability of energy within a given economy hinges on three dimensions which are; Environmental, Economics, and Security (social equity). Business units within organisations and institutions need to understand their energy "economy" to make informed, reasonable, and intelligent decisions, especially with increasing instabilities and unreliable management within the South African energy industry.

The research could potentially assist organisations and institutions in employing effective and explicit "energy planning" within complex operational decision-making using the advancements made in artificial intelligence models supported by a systematic requirement engineering approach. The decision-making tool could alleviate the decision-making burden on organisations and institutions by enabling them to make focused decisions based on clear guidelines. With a focus on the South African energy climate, the result of the research has the potential to support decision making not only from an organisational level but from an institutional level as well. Therefore, an explicit model not limited by implicit boundary conditions is proposed to assist organisational and institutional decision-makers regarding their electrical energy initiatives needs and requirements.

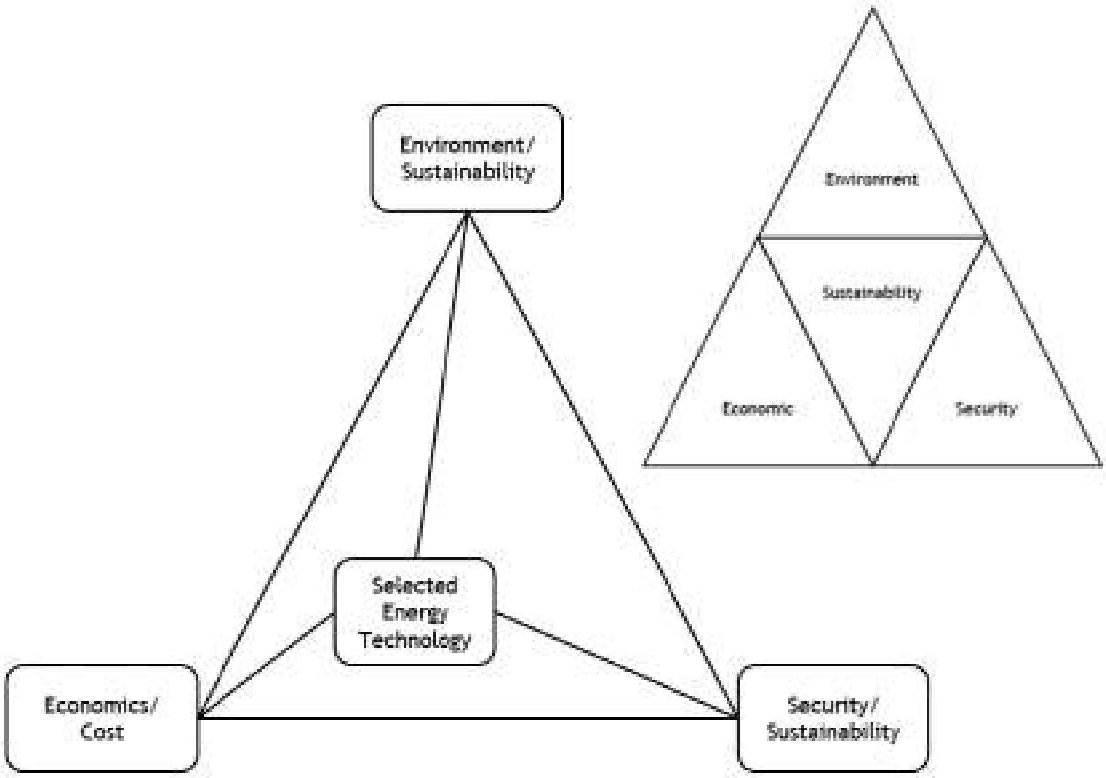

Figure 1: Suggested tri-quadrilateral sustainability effect (Adopted from [1])

From an industry perspective, energy resource planning has an implicit influence on production feasibility, process requirements, economic feasibility, and the business unit's overall costing. Furthermore, developments in the application of artificial intelligence in the engineering environment could improve process efficiency from production, process, and economic perspectives. However, explicit is better than implicit. Therefore, a direct perspective on energy planning is required. The research is concerned with integrating artificial intelligence with a system engineering approach to energy planning, which could enable a business to generate an explicit, holistic view of their process energy requirements by creating smart, intuitive systems thinking to understand their requirements.

The research questions that guided the investigation were:

1. Would machine learning algorithms for energy usage estimation complement requirements engineering principles to identify "planning deficiency" events?
2. What advantage would the systematic implementation of machine learning integration techniques, specifically dimensionality reduction, provide regarding energy planning compared to a conventional non-systematic approach such as levelised cost estimators?
3. How can a data-driven "smart energy planning tool" complement the identification of impacting criteria in decision-making and align with organisational or institutional policy making concerning energy planning?

2 LITERATURE REVIEW AND THEORETICAL FRAMEWORK

2.1 Understanding Energy Planning: Decision Making

Effective energy planning is seen as a necessity to understand short-, medium-, and long-term operational demand, supply and system stability requirements. The latter mentioned statement opens pandora's box as "requirements" are often misused and confused with what decision makers "want" versus what they "need". Energy supply and demand systems are complex and adding to the complexity is uncertainty within the energy sector resulting from socio-economic impacts and factors. Lalk [1] suggested a system thinking approach, which in its basic form, means that the "whole problem" is being looked at, not only part of it. Thus, systems thinking is more than just a technical term to address technical problems. Morgan [3] stated that systems thinking focuses "on processes, patterns and relationships" rather than a rigid, linear input/ output way of thinking. The concept of systems thinking allows a problem to have dynamic attributes, which are more behavioural than technical, objective-driven attributes.

From a modelling perspective, an interpretation of Morgan [3] explained that systems thinking is focused on learning, using experience and experiments to dynamically adapt a system to improve capacities and/ or performance. To enable stakeholders to plan energy effectively, they need to understand the relationship each subsystem has within the overall system. The latter could seem complex and difficult to grasp. Therefore, an energy system can be seen as a SoS (System of Systems); Lalk [1] quoted Haskins where an SoS can be described as ". . . a system-of-interest whose system elements are themselves systems. . . ".

Due to the complexity of regional, national and global energy spaces, which is attributed by environmental, policy, economic, socio-economical, and technical attributes, it is suggested that these complex energy spaces form part of an energy SoS (System of Systems). Energy planning requires new, fresh and effective perspectives and management of this SoS concept, by first understanding the system and then focusing decision making on system elements that impacts the efficiency of the system. Decision making specifically toward energy planning needs to be done with purpose, its implementation should be strategic (well organised and focused) and not merely an application of foreign strategies that was proven within unique socio-economic domains and policy which assisted its successes [4], [5]. Essentially, a well understood, well mapped and focused energy plan provides strategic, policy and technical driven plans based on different scenarios which provide guidance with respect to short-, medium-, and, long-term stability of an energy system [6], [7].

2.2 Energy Planning Decision Making and Quality

As a starting point, viewing energy planning from a production perspective, Weeber and Sauer [8] placed emphasis on several key points to improve not only the quality of a planned system's results but also highlight a proposed strategy to ensure economic competitiveness. These relevant points are translated explicitly [8]:

- Promote energy efficiency by justifying energy consumption.
- Promote system design flexibility.
- Promote flexibility within the production or processing environment.
- Use changing energy markets to create opportunity for profit.
- Asses the security of supply and affordability of demand

Furthermore, Weeber and Sauer [8] highlighted that energy systems in different sectors are known for being resilient to change and remain delusional in their energy planning strategies. The research done by Weeber and Sauer [8] focused on the concept of "Total Energy Planning" by addressing the question "... how can companies plan and operate the energy related infrastructure of their factories while aiming at reduced life cycle costs and environmental impact..."

2.3 Total Energy Planning and Systems Thinking

TEP (Total Energy Planning) in its core, evaluates an energy system from a demand perspective and optimises the planning strategy based on demand and minimal CO_2-footprint [8]. TEP is approached by (1), setting targets related to energy planning, (2) assessment of the measures used to quantify energy efficiency, (3) assessment of renewable energy generation within the production environment, (4) Evaluate and set the energy demand based on the operational philosophy, (5) Evaluate different technologies that can be used for supply within the operational system [8]. The concept of TEP is not limited to only factories (manufacturing environment) per say, but can be extended to energy suppliers, mining operations, processing operations etc. as the latter mentioned sectors must in some extend consider the life cycle of their operation which in most cases rely on some source of energy for sustainable and reliable operations. The key points of interest from Weeber and Sauer [8] description of total energy planning are operational targets related to energy planning, measures to quantify energy efficiency, identifying energy demand based on the operational philosophy.

The questions; "Why systems thinking?", "What benefit does it bring?" comes to mind. Pillay, Botha, and Musango [9] outlined four core scenarios to when system thinking should be applied. The "should" is removed and the scenarios are explained as a "must" together with energy system quality and reliability as presented by Weeber and Sauer [8]. The key "musts" of systems thinking in terms of energy planning are suggested to be:

- Understand that a system has several cause-and-effect variables or events.
- Implement system design flexibility.
- Understand the security of supply and affordability of demand.
- Reoccurring issues within the system that are not solved with applied solutions.
- Understand system flexibility and limitations.
- Design for energy efficiency by justifying energy consumption.
- Learn from ineffective solutions applied to systematic issues.
- Understand that energy planning requires identification of apparent and inherent complexities.
- Understand simple operational patterns that ensure energy efficiency.
- Understand the flexibility of interlocking control systems in the production or processing environment.
- Understand the interconnecting nature of changing energy markets in the production environment.
- Understand the economic energy supply patterns and identify the inherent demand controls to ensure affordability.

2.4 Traditional Energy Planning and Approaches

Traditionally, energy planning is done by considering techno-economic measures such as CAPEX (Capital Expenditures) and OPEX (Operational Expenditures) costs such as interest, taxation, labour, energy, consumables and royalties which does not provide a holistic overview [10]. Osorio-Aravena et al. [10] looked at the concept of SEP (Spatial Energy Planning) to evaluate if SEP concepts and principles could address the issues regarding energy planning further on than techno-economics. Although OsorioAravena et al. [10] investigated energy planning with respect to renewable sources, the same metrics could possibly be applied in current energy systems based on socio-economic constraints. Key understanding of the system elements can potentially result in a qualitative understanding of the energy economic environment specifically to; "Learning from ineffective solutions applied to systematic issues", "Understanding the economic energy supply patterns and identify the inherent demand controls to ensure affordability", "Understanding reoccurring issues that are not solved with applied solutions" and, "Understanding the security of supply and affordability of demand". Qualitative assessments can cause bias, from a modelling perspective. Altintas and Utlu [11] suggested a combination of the SWOT analysis and AHP to quantify the qualitative measurements as quantitative inputs.

2.5 Modelling Factors in Energy Planning

Chang et al. [12] provided a detailed review of the tools used to model the "energy transition". The study evaluated the modelling methods used to model an energy system based on the holistic usability of the energy models based on the following categories as discussed by Chang et al. [12]:

- Descriptive Overview
- Classification
- Practical Application
- Inter-comparison and suitability
- Transparency, accessibility and usability
- Policy relevance
- Model linking

For the purpose of the energy planning research, the following important factors were identified, Practical application, Transparency, accessibility and usability and policy relevance. Therefore, the overview of the tools identified by Chang et al. [12] was filtered if two of the identified factors were met. The sources with the most relevant contribution to this research are shown in Table 1.

Table 1: Sources to contribute to research efforts adopted from Chang et al. [12]

Focus topic	Technical and Spatial Identification	Contribution to Study	Source
Review of tools for evaluating energy efficiency policies	Bottom-up energy economic models	Use of policy instruments in the modelling tool development	[13]
Modelling categories and emerging challenges	National energy space	Integration of human behaviour and social risks within the model	[14]
Modelling approaches and planning support	Simulation/optimisation	Systems engineering perspective, the paper discusses two archetypes, optimal solutions approach, and analytical simulation	[15]

2.6 Modelling Tools and Multi-criteria Decision Making

In addition to the contributions identified regarding multi-criteria decision making, the following tools are suggested to be fully evaluated as part of the model development effort:

- Calliope open-source energy planning modelling tool. [16]
- TensorFlow, developed by Abadi et al. [17], is incorporated in an open-source python library, PyPSA, an energy system modelling framework. [18]
- AHP/ Analytical Network Process (ANP), tools.

The ANP, together with TOPSIS, could be a plausible candidate for developing the energy planning tool as the ANP-TOPSIS as used by Ervural et al. [19] has the potential to identify the critical existing policy indicators and prioritise them. Furthermore, these metrics can be used as inputs into a MCDM Model or ML model [17] to produce predictive energy planning metrics based on the ANP/ AHP or TOPSIS inputs. Again, the emphasis on using predictive and analytical tools such as AHP, ANP, TensorFlow and Calliope could significantly improve the rate at which decision-making occurs within institutions.

From work done by Vázquez-Canteli et al. [20], it is suggested that machine learning tools such as TensorFlow allow for an increase in learning capability within a specified system. The potential to use large sets of information and quickly digest them could assist decision-makers in identifying strategies quickly and effectively.

2.7 The AHP Method

The Analytical Hierarchal Process (AHP) is a suggested method for evaluating the impact of an indicator or criteria that is difficult to quantify by being qualitative by nature [21], [11]. Altintas and Utlu [11] applied the AHP method as an approach to quantify and make sense of the complex nature of non-technical, soft and legislative indicators and components which drives decision making within this paradigm. Therefore, its suggested that the application of the AHP within the energy planning modelling space could be valuable in quantifying "soft" issues by utilising the principles of the AHP by Saaty [21]. In principle, the AHP process is a decision-making strategy or tool that is used to "rank" alternative solutions against a specific set of criteria based on a specific goal to be achieved by the decision-making activity [21], [11]. Therefore, the AHP was interpreted in terms of energy planning as:

- Knowing the goal (identify the "soft" energy planning goals with respect to non-technical aspects)
- Understanding the evaluation criteria (what components or indicators are used to "measure" or qualitatively quantify these aspects)
- Gauging the possible alternatives or outcomes expected from the influence of these non-technical aspects.

The AHP can potentially assist the modelling effort to prioritise these difficult-to-quantify energy planning components by creating a link between the criteria that governs the "soft" component in a consistent manner to determine the expected outcome or influence the component has within the energy planning space [11]. Kluge and Malan [22] applied the AHP methodology to solve complex design issues faced in the underground mining industry within Southern Africa. The approach by Kluge and Malan [22] is very similar to that of Altintas and Utlu [11] using the principles originally developed by Saaty [21] and will be used to describe the "inner" workings of the AHP methodology, applying it to energy planning.

3 PROPOSED MODEL OR CONCEPTUAL METHOD

The conceptual model is based on the PCA-vectorised method that integrate a SWOT type analysis within the defined energy planning "space" in which the proposed model views the system's "trilemma" criteria, presented by Lalk [1], based on explained variances (for each set of criteria) that creates linkages to a SWOT type analysis similarly proposed by Solangi et al. [6]. This is shown and conceptualised in Figure 2.

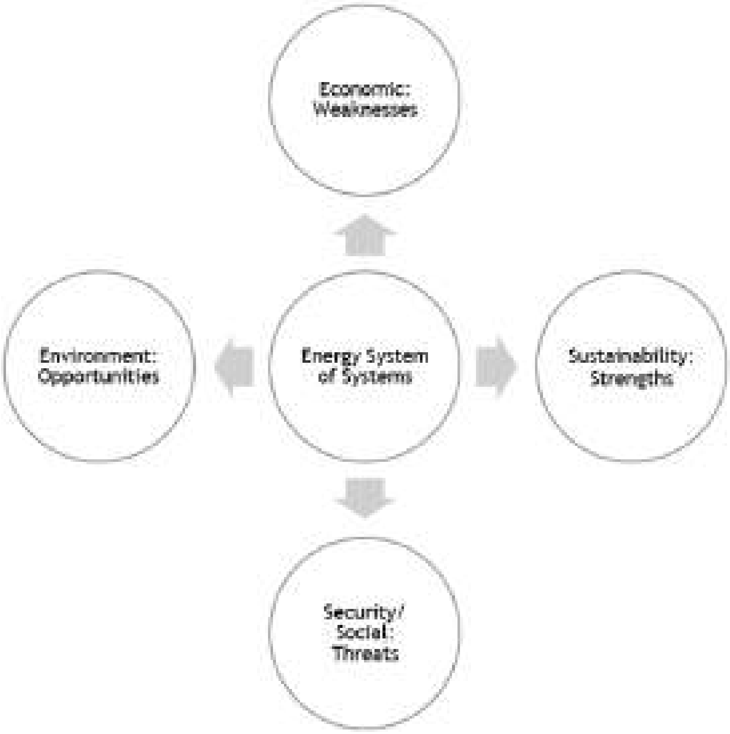

Figure 2: The proposed energy planning "space" in which the PCA-vectorised methodology was applied

The SWOT principles guided the development of the PCA-vectorised approach by defining the datasets of interest, therefore, datasets that complement the economic, environment, sustainability and security criterion. Pedregosa [23] developed a substantial library of machine learning tools, Scikit-learn Python library, and the PCA principles contained therein were used in the process.

Fundamentally, the purpose of the proposed model is to make sense of large data sets. This is done by gathering as much information as possible guided by the energy “space” of interest. Secondly PCA is a fundamental tool used to reduce the dimensionality of large data sets (i.e. importing 400 indicators in a time-series dataset can be reduced by order of magnitude, by isolating the indicators with the largest explained variances). MCDM tools has potential, however, the conceptual model disregard these tools as they are predominantly used to provide performance scores based on criteria vs alternatives Ervural et al. [19] which requires some form of “importance” weighting of each criteria considered. In this research paper the model intent was to generate these weightings based on data-inflows to reduce bias and promote data-driven decision making.

Therefore, incorporating the AHP and ANP methodologies were more aligned with the criteria vs criteria comparisons intended in this concept. Additionally, the fundamental operation (the usage of ratings developed by Saaty [21]) as part of the AHP and ANP methodology is complemented by the PCA-vectorised approach. This is conceptualised by using the scaled features/ criterion generated by the PCA process and vectorising the coefficients (known as loadings) to a cartesian mid-point. This is shown in Figure 3 (i.e. Criteria 1 is considered to be a feature in the model).

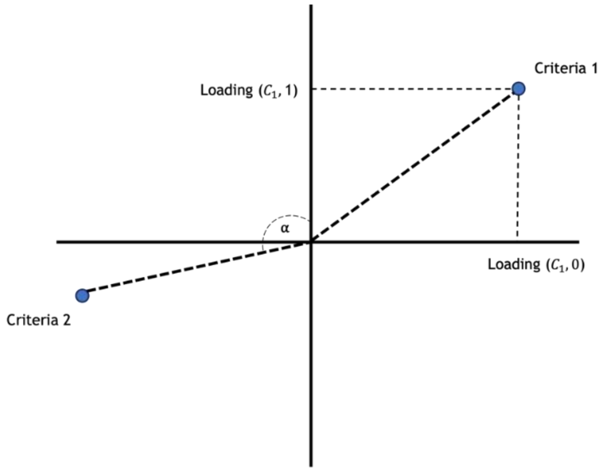

Figure 3: PCA loadings

Furthermore, the PCA-vectorised concept propose to calculate the angle $\propto$ and magnitudes between two criterion and convert those angles to Saaty [21] ratings shown in Table 2. A simplified overview of the conceptual model is shown in Figure 4.

Table 2: Quantified pairwise-comparison impact weightings methodology proposed

Weighting	Description	PCA Angle
1	Equal impact	80° - 100°
3	Moderate impact	< 80°, > 70°
5	Strong impact	> 50°, < 70°
7	Very strong impact	> 30°, < 50°
9	Extremely high impact	0° - 30°
2, 4, 6, 8	Intermediate weightings	100° - 180°

The proposed PCA-vectorised method has the potential to guide decision makers on where to focus their efforts and to assist them with defining pairwise comparisons when using hierarchical decision models. Furthermore, the significance of the criterion generated by the PCA-vectorised methodology, ought to either include or reject the criterion for use in a decision-making model. The PCA method produces a radial component comparison of vectors, shown in Figure 3, where the vector angle is described as; α=0° with direct, scaled proportionality, α=90°, zero proportionality and, α=180° with indirect, scaled proportionality.

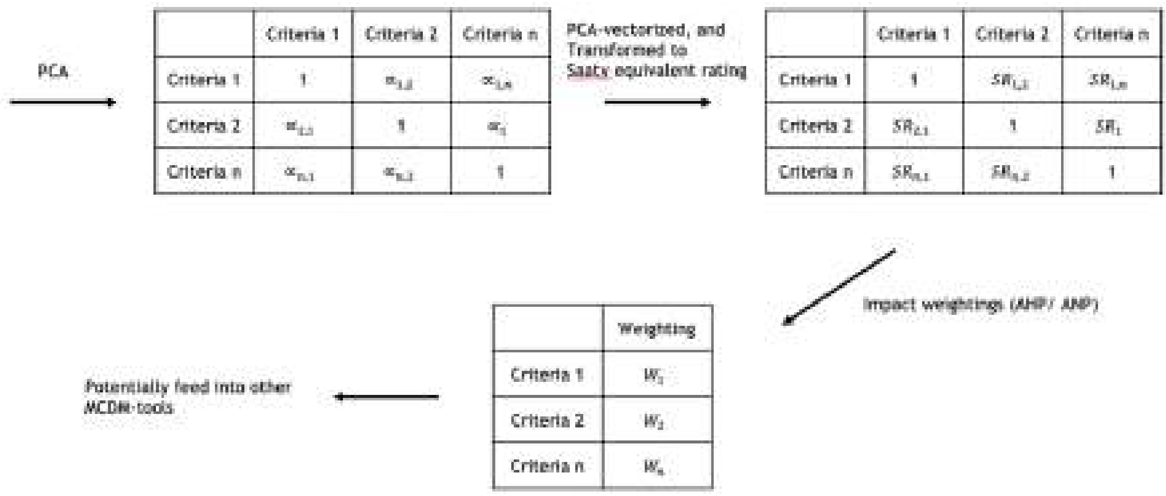

Figure 4: PCA-vectorised transformation simplified

The conceptual model attempts to explicitly address the decision-making challenges that can be faced in the energy planning systems and processes, specifically to questions such as "What criteria do we need to focus on?", "what is our current need?".

4 RESEARCH METHOD AND APPROACH

4.1 Core Research Functions

The core function of the research is primarily analytical focused on model development/ modelling methodology improvements that include (1), feature identification and extraction based on literature and system scope (2), the application of advanced mathematics and modelling (3), the use of systems thinking in the requirements engineering space and, lastly (4), the use and implementation of multiple criterion decision-making to gain managerial insights.

4.2 Core Research Focus Areas and Limitations

4.2.1 Policy

The approach regarding policy development in the research was limited and not considered as a primary driver. Although policy making is a core driver for the successful implementation of energy planning models, the research will identify possible shortcomings and make recommendations on which policies will complement energy planning. Thus, the research is not about policy development. Policy instruments will be looked at and used as model inputs if needed. However, the research is not about policy instrument development but rather a utilisation thereof.

4.2.2 Physical Modelling

The research will not use physical models but rather a mix of computational and mathematical models.

4.2.3 Theoretical Application

The research is not concerned with the theoretical application of the decision-making support but rather a means of providing a practical strategy for implementation with realistic, practical timelines.

4.2.4 Scope

The initial intended boundary constraint for the research was:

- Within the South African energy environment scoped at a national/ regional (organisational/ departmental) level which is outlined by the DST [24]
- System boundary limited to Systems of Systems (Energy Planning Effort)
- Systems (Economy, Sustainability, Security and Environmental guided by the DST [24])
- Subsystems (Not included)
- Assemblies, Components, Parts (Not included)

4.3 Data Sources and Criteria Limitations

The energy planning criteria was extracted by consulting various, open-source/ public-accessible, databases and formulating a "data-lake" which was used to define the energy planning criteria. Based on the limitation of the classic PCA methodology, future use of the PCA-vectorised method's results in decision making models such as the AHP and ANP methods and, maintaining consistency the following restrictions applied to the defined clusters where; Minimum Sub-criteria: 3 and, Maximum Sub-criteria: 10

4.4 Pre-processor Development Approach

During the research process it was identified that the initial PCA methodology required more explicit definitions and understanding thereof. A redefined approach the PCA-vectorised method was developed and is shown in Figure 4. The steps created and identified for the PCA-vectorised method is described in Section 4.4.1 to Section **Error! Reference source not found.**.

4.4.1 Step 1: Data Preparation

Similar to the SWOT linkages Solangi et al. [6] made in clustering the criteria within the energy planning "space", the same clustering was done with respect to the energy "trilemma". The data was therefore extracted from the public domain and clustered according to four main areas of interest:

- **Economic** : Datasets that relates to energy/ socio-economic drivers.
- **Environment** : Datasets that relates to environmental opportunities.
- **Sustainability** : Datasets based on sustainability.
- **Security** : Datasets based on socio economic security threats.

4.4.2 Step 2: Understand the Energy Planning Domain

The South African energy planning SoS's requirement domain is proposed and outlined in Table 3, based on the framework developed by Keating, Padilla, and Adams [25].

The criteria within the trilemma clusters will need to be carefully selected using the requirements engineering guidelines presented by Keating, Padilla, and Adams [25], as the model risks becoming overly complicated, which could result in, inconclusive results. The PCA method assists with the latter mentioned risk because of its fundamental dimensionality reduction principles.

Table 3: South African energy planning SoS's framework proposed by [24]

Performance Indicator	**Description**
System Identity	The energy planning system was identified by providing strategic, policy and technical driven plans.
System Purpose	The energy planning system need to provide guidance with respect to short-, medium and long-term stability of the energy system.
System Boundaries	The SoS boundaries were defined by the criteria within the clusters identified and parameters such as Economic-weaknesses, Environmental opportunities, Sustainability-strengths, Security-threats
Iterative System Objectives	Iterative analysis of the objectives defined by the DST [24] needs to be done to provide an indication if the purpose of the energy planning system is optimal.
Issues Regarding Context and Stakeholders	The issues, within a South African context was limited to the factors that contribute to the trilemma index that is presented by WEC [26].
Performance Index	Performance indices needs to be grouped in terms of, Cost, Environmental Impact, Social Impact, Sustainable Contribution Impact
Autonomous Measures of Sub-systems within the System	Exploiting the interconnections and "feedback" between objectives/ alternatives and the energy system criteria using the ANP methodology was suggested to ensure sub-criteria autonomy and their impact on the SoSs.
Manage Emergence	Solangi et al. [6], described the strategy as to validate the "importance" of strategies by conducting a sensitivity analysis to investigate the system responses to negative and positive changes in the criteria.

4.4.3 Step 2: Determine Principal Components and Vector Angles

Calculate the Principal Components and the angles between two features using a Python based algorithm shown in Figure 5.

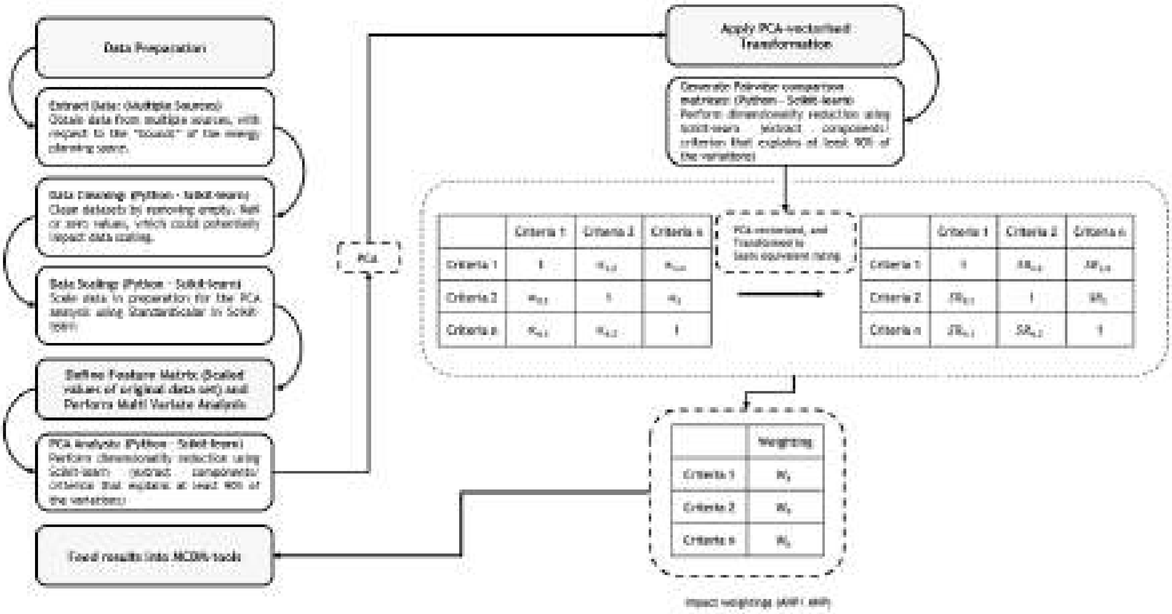

Figure 5: Sub-processing outline PCA-vectorised approach

The conceptual flow of the modelling approach presented in Figure 4 showed a simplified approach to handling the large data sets, however additional data pre-processing are required, which is shown in Figure 5.

4.4.4 Step 3: Extract Variance-co-Variance Results

The Model, extracts the variance-co-variance ("explained variances") from the defined PCA variance using the Scikit-learn package [23]. The explained variances refers to the "extent" of a feature's deviation from its mean and the correlation/ co-variance hence, how the feature responds to change given any random comparison between another [27], [28], [29].

Furthermore, the PCA aided in reducing the dimensionality of data sets by extracting the "important" features (using explained variances), for example, 35 features where reduced to 10 [27], [28], [29]. The explained variances for the analysed data sets are shown in Table 4. Here the explained variances Exp Var. were presented as the % variances that can be explained by the variance-co-variance analysis of each feature with respect to another.

5 RESULTS

5.1 Model Outputs

The datasets used in the model to generate the results are shown in

Table 4. The Sources for these datasets were gathered from [30], [2], [31].

Table 4: Datasets used to generate the results (input feeds into the model)

Dataset	Description	Criteria	ts DP	t DP
d1	Environmental/ Economic Policy Instruments	41	22	902
d2	Social - Focus on Access to Electricity	10	27	270
d3	Electricity Distribution	13	461	5993
d4	Total Energy Balance	66	31	2046
d5	Economic - Fiscal/ Sector Based	41	46	1886
d6	Environmental - Emissions	91	31	2821
d7	Social Indicators	17	47	799
d8	Utility Technical Data (Public)	30	43821	1314630
Variable: *ts DP* - Time Series Data Point *t DP* - Total Data Points				

The model outputs are shown in Table 6, which provides a summarised view of the criterion importance with respect to the % - explained variation (PCA EV). Additionally, the Weightings generated from normalised pairwise comparison matrices (performance scores - W) and their vector normalised weightings (nW) are shown. For instance, the result obtained from the PCA-vectorised methodology suggest that the criterion shown in Table 5, should be seen as "drivers" for strategy development as these variables "explain" 96.8% of the variances in all of the datasets used in the model.

However, the consistency indexes, a measure that provides insights into how effective the judgements (weightings) were determined, suggest that the pairwise comparisons are inconsistent which vary from 2% to 12% of the optimum (CI < 0.1).

Table 5 PCA-vectorised results showing criteria with largest impact

Var	Focus	Description	PCA EV
c59_d4	Energy Balance	Energy Consump. (Total)	37.482
c6_d1	Economic	Tax Revenue (in Local Currency)	20.921
c25_d4	Energy Balance	Energy Consump. (Residential - Oil Products)	9.425
c18_d7	Social Indicator	Alternative Sources (Nuclear)	8.981
c7_d2	Social	Energy Consumption (Renewable)	7.813
c23_d1	Economic	Tax Revenue (% of Total - Energy)	7.021
c64_d4	Energy Balance	Energy Consump. (Not Defined - Total)	5.208

Table 6: PCA-vectorised results (AHP/ANP – approach)

Var.	Focus	Description	PCA EV	W	nW
c59_d4	Energy Balance	Energy Consump. (Total)	37.482	0.128	0.223
c6_d1	Economic	Tax Revenue (in Local Currency)	20.921	0.167	0.291
c25_d4	Energy Balance	Energy Consump. (Residential - Oil Products)	9.425	0.103	0.179
c18_d7	Social Indicator	Alternative Sources (Nuclear)	8.981	0.136	0.236
c7_d2	Social	Energy Consumption (Renewable)	7.813	0.123	0.214
c23_d1	Economic	Tax Revenue (% of Total - Energy)	7.021	0.095	0.165
c64_d4	Energy Balance	Energy Consump. (Not Defined - Total)	5.208	0.096	0.167
c28_d1	Economic	Tax Revenue (% of Total - Mineral Resources)	5.053	0.167	0.291
c15_d5	Economic	Investment (Total)	4.829	0.140	0.245
c15_d7	Social Indicator	GDP (per Unit of Energy usage)	4.432	0.128	0.223
c62_d4	Energy Balance	Energy Consump. (Residential - Total)	3.419	0.152	0.265
c14_d4	Energy Balance	Energy Consump. (Crude - Export)	2.707	0.136	0.237
c15_d8	Tech. Utility	Renewable Energy Installed (Total)	2.524	0.095	0.166
c28_d8	Tech. Utility	Generation Unit Hours (Palmiet)	2.188	0.153	0.267
c29_d1	Economic	Tax Revenue (% of GDP)	2.184	0.095	0.165
c8_d3	Electricity Dist.	Distribution (Local - Free State)	1.907	0.121	0.211
c10_d2	Social	Renewable energy as % of output	1.666	0.089	0.155
c18_d8	Tech. Utility	Installed Electrical Capacity (Concentrated Solar Power)	1.520	0.153	0.267
c24_d8	Tech. Utility	Other Capability Loss Factor (Unavailable Energy)	1.351	0.095	0.166
c5_d2	Social	% of total population access to clean feuls	1.136	0.108	0.188
c11_d8	Tech. Utility	Renewable Energy Installed (Wind)	1.126	0.095	0.166

5.2 Model Response to PCA-vectorised Methodology

The PCA-vectorised methodology is in its early stage of development and performance improvements, to handle co-linearity, data pre-processing and, PCA-vectorised transformations in large multi-disciplinary datasets has potential to increase the reliability of the PCA-vectorised methodology with respect to the consistency of generating the importance weightings of pairwise criterion. Furthermore, the tool has potential to improve the focus of energy planning initiatives and guide energy planners that use MCDM tools by enabling energy planners to generate insights from a data-driven approach and lessen the bias introduced with “human” inputs. A summary of the model response is shown in Table 7.

Table 7: Model response to research approach

Description	Improvement
Model capability to address planning deficiencies	Data or information that contain a large amount of “missing” data points can potentially miss inform energy planners if not handles appropriately. Valuable information can therefore be included in these models by using appropriate pre-processing tools. The model attempted to incorporate this by implementing a pre-processing tool using K-nearest-neighbours imputation [23]. Therefore, the structured, systematic approach; (1), get data (2), pre-process/ clean data, (3) reduce dimensionality) to generate effective and purposeful data has potential to provide energy planners with data-driven insights .
Model capability to address large dataset complexity in energy planning	The structured approach shown in Figure 5, complements the model’s ability to minimise modelling deficiencies inferred by data that has high dimensionality. Therefore, as part of the PCA-vectorised approach, the modelling method has the ability to reduce complexity and drive focused analysis incorporating data from different data domains (environment, energy, socio-economic and, economic).
Model ability to enable energy planners to easily identify impacting criteria in decision-making	The model addresses this by incorporating the PCA dimensionality reduction technique developed by [23]. The method as part of the PCA-vectorised approach can identify the criterion that energy planners should consider in their modelling/ decision making process (% explained variances)
Model ability to support organisational and/ or institutional policy making in energy planning	The model showed potential to weight criterion of interest and identify the pairwise performance from a data driven perspective incorporating the rating and normalization methods developed by [21].

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

Machine learning algorithms, specifically the pre-processing of the data required is a crucially important aspect of ML-based modelling applications. The research identified the importance and impact of providing models with suitable data. The PCA-vectorised ranking method is a new uncommon method to weight pairwise criterion performances from a pure data-driven approach and requires further development to reduce inconsistencies in its performance results. Furthermore, the research pointed out that requirement definitions and the understanding thereof is critically important in decision making, regardless of the approach. By scoping and defining the energy planning domain using a structured approach which is supported by a system definition, allowed for obtaining purposeful results that cannot be obtained by means other than a structured/ well-defined system scoped by the policy that defines it. The research approach from a requirement engineering perspective, showed that a systematic evaluation enabled a clear definition of the energy planning domain resulting in objectively identifying explicit and implicit energy planning factors/ influences. The integration of the systematic energy domain definition, coupled with the proposed PCA-vectorised ranking approach, provided a holistic view of technical, fiscal/ economic and non-technical factors, highlighting critical systematic short-comings from an objective data driven perspective. There is, however, room for improvement, as the research suggests, with the viability/ and controversial possibility to formulate energy planning strategies using data-driven-decision making tools (such as the PCA-vectorised method) based on pure data inputs (without subjective "human-based" ranking definitions). The research presented a "proof-of-concept" of the latter by providing a conceptualised result of criterion pairwise comparison performance (using the PCA-vectorised method) which is usually formulated from "interview" type data collection.

6.2 Recommendations

The research presents several future potential studies regarding modelling, policy and, the importance of "systems thinking" specifically toward energy planning research and potentially other “energy intensive” operations that can benefit from energy planning concepts.

- Policy analysis specifically targeted at the "articulation" of policy with reference to energy and energy planning policy published by the Department of Energy [32]. Future research on how the "explicit" goals are set and how these goals complement the commitments made by the Integrated Energy Planning Report [32] carbon taxation [33] and, minerals beatification policy [34] can potentially add value to policy makers and energy planner’s efforts.
- Furthermore, additional policy-specific modelling complementing the development of technology within the renewable energy space is proposed, to determine the "likely hood" of technology implementation success based on the policy goal.
- Investigating the impact of co-linearity and “hidden” dependent variables on the PCA-vectorised transformations and developing means to address this in the modelling process.
- There is a strong drive from mining houses toward their Environmental, Social, and Governance (ESG) principles and their role in advancing sustainable practices within the mining and minerals sector specifically toward improving the energy efficiency of their operations and reducing GHG emissions. The approach defined in this research paper would therefore potentially identify organisational interdependencies and trade-offs between up and down-stream operations that have high energy requirements and highlight their impact on the overall operational efficiency. Hence, a research study that focus on optimising resources responsible for driving ESG initiatives could potentially provide mining houses with insights into what criterion/ aspects of their business are key drivers in supporting their ESG commitments.

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INTELLIGENT CONTROL FOR IRRIGATION PIVOTS

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ABSTRACT

Irrigation pivot systems are installed in different agricultural environments that vary in terms of environmental characteristics. Traditional control methods do not specifically consider variability associated with inclination, soil type, water pressure, and other variables. As a result, traditional systems operate sub-optimally with significant wastage of water and electricity. The need to function optimally during periods of power supply has identified the need to also deliver water effectively. An intelligent system was developed that considers different environmental factors with the aim of reducing cost and wastage in an environment that suffers from ongoing power supply interruptions. A set of experiments was conducted on a physical installation using this intelligent irrigation system to determine the cost saving using variable speed drives to control water pumps optimally. From the results, the cost saving warrants the additional equipment cost and ensures ongoing savings in a world that requires conservative use of scarce resources.

Keywords: irrigation, pivot, intelligent, control

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1 INTRODUCTION

Irrigation pivots are mostly located in areas either where dryland farming is not feasible or supplementary irrigation is required, and water supply from rivers, boreholes, and dams is available for agricultural purposes. As a result, water is applied to crops from main supply points using pumps, measurement, control, and reticulation systems designed to meet the specific requirements of irrigation pivots. Although a number of different physical pivot structures are being used in practice, their main functional definition and principle of operation are mostly similar, with variability in the way measurement and control is exercised.

Functionally, pressurized irrigation systems can be simplified to the following functions (F1) pumping of water obtained at the source, (F2) measuring and controlling flow along water lines, (F3) transporting water through lines, and (F4) application of water at a selected destination point. Each function has performance parameters that, when combined, produce a system that utilizes water and electricity in a particular way. Notably, water costs and irrigation efficiency have a major influence on the total cost of water application. Over the past decades, in South Africa, electricity costs increased significantly in a country that is also water-stressed. Therefore, the water-energy nexus of electrical energy and natural water resources implies that irrigation can be done efficiently using electricity sparingly in the process [1] [2].

A typical central pivot irrigation system is shown in the diagram below. Measurement and control elements are used to ensure water is applied efficaciously, predicated on a mechanical (irrigation) system that had been designed from best practices. Water pressure is typically measured at different points along the water line, most often at the source pump, pivot center, and pivot last tower (Sensors 3, 2, and 1, respectively). Most designs are to ensure maximum demand is addressed for inclined structures, which presents a problem when pivots are located on inclined fields where the pressure drops along tower structures along inclines and pressure increases along structures along declines.

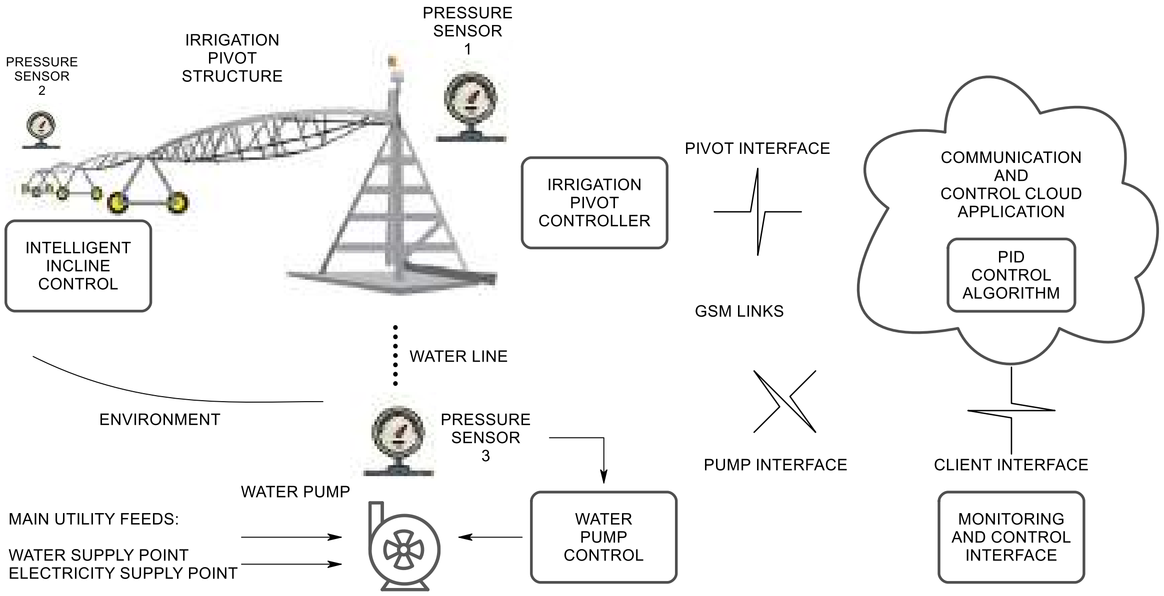

Figure 1: Operational Architecture for an IIoT Controlled Central Pivot Irrigation System.

Provided a pivot's mechanical design addresses irrigation requirements (functions F1, F3, and F4), the remaining challenge is to select an appropriate strategy to reduce power consumption and maintain irrigation effectiveness in the form of function F2: measurement and control.

Theoretical research showed that it is feasible to apply variable speed control to pumps to ensure constant pressure is achieved at the point of application. This research is discussed in the section on Prior Research (Section 2) below.

This research focused on obtaining empirical results from real-world experiments conducted on pump speed control for constant water pressure, as tested on an existing irrigation pivot structure retrofitted with industrial IoT (IIoT) measurement and control equipment. These experiments are discussed in the section on the Experimental Method (Section 3).

Finally, a life cycle economic analysis is done on empirical results to show the actual value of energy and cost saving in a South African environment. This analysis confirms simulated research results and demonstrates the value of intelligent measurement and control in a real-world setting.

2 PRIOR RESEARCH

Agricultural irrigation, as such, has developed to a point where the electro-mechanical, fluid-dynamic, and overall system designs have reached a high level of maturity in real-world applications [3]. [4]. Losses are limited when the correct technical design is implemented by considering meteorological conditions and loss factors, rarely exceeding 10% of the pumped water based on technical measurements [4]. Over the past decade, the increased focus on the efficient use of generated and natural resources, specifically energy, has resulted in research focus on pressurized irrigation systems' energy consumption and cost [1].

It is known that water is applied more effectively using pressurized irrigation systems, such as center pivot systems [5], with a focus on saving water through effective farm-level design, application of tools for irrigation system design, and actions applied to reduce energy costs. Specifically, to reduce energy consumption, benchmarking, audits, optimal use of electricity tariffs, telemetry and control, and renewable energy must be considered. Of these, this research focuses on the application of telemetry and control to reduce energy consumption and associated costs.

2.1 Energy consumption of central pivot irrigation systems

Historically, with energy being more available and less costly, systems were designed for peak demand [6], as is the case in the existing system under investigation in this research project. The topography, location of water sources, and the need for minimum pressure at the point of application are considerations when designing a central pivot irrigation system. Pumping stations are often inefficient and not designed to meet varying demands over a season [6]. A theoretical analysis was conducted and showed that different pump configurations with variable speed drives could achieve energy reduction between 27% and 35%. This was an important study as it showed that control of the average pump speed to provide the exact required pressures at the application points would lead to the greatest energy reduction.

A study conducted in 2019, the researchers modelled different scenarios of varying topographies and pivot configurations of end guns and corner sections [7]. Standard systems with tower structures of 396m span were used, and pumps were simulated to supply water from wells at varying heads. Their analysis found mean reductions in energy consumption of between 12% and 28% across 1000 different scenarios, depending on the systems' characteristics. Their economic analysis, based on the local cost of energy in Nebraska, showed that most systems with mean reductions of between 18% and 28% could achieve payback periods shorter than the lifespan of the variable frequency (speed) drives, while most systems with a mean reduction of 12% were not feasible. The factors influencing feasibility include large topographical changes, duration of corner attachment operation, hours of operation, and electricity cost. Notably, the worst reduction found was 4%, with the best reduction of 41% across all their scenarios.

The feasibility of variable speed drives in center pivot systems on variable topography fields was investigated using a simulation model to evaluate savings for a specific case in Spain [8]. The EPANET hydraulics engine was used to simulate a system with a 488 m span on a 76-ha field with a 15.3 m incline, using a 90 kW pump. The gross annual water requirement was 627 mm with an operating time of 1440 hours. A simulated energy saving of 12.2% was achieved using a variable speed drive to vary pressure according to the pivot's angular position.

Recent research on energy saving has shown, using theoretical modelling of a 70-ha field, that energy savings of up to 18% are possible [9], which resulted in high cost and energy reductions. The reported saving was possible by varying the rotational speed of a 472m span tower structure (or lateral line) to match the load requirement using a variable frequency inverter. This theoretical research project concluded with the need for practical evaluation of installations of variable topography.

In all instances, the research shows that variable topography, electricity cost, hours of operation, and capital cost of the variable speed drives will play a role in deciding whether to invest in variable speed pump control. The savings were mostly in the region between 12% - 28%. No empirical South African study was found that actually measured and controlled the energy for constant pump pressure as was done in this research project.

2.2 Center pivot automation and the Internet of Things (IoT)

The availability of the Internet of Things (IoT), cloud technology, and big data has brought exciting opportunities to improve irrigation systems' design, implementation, optimization and management [10]. The focus on a supportive water utility culture, a culture of effective infrastructure maintenance, an environment that supports data, research and improvement, and government policies that promote innovation in the irrigation sector are important drivers for improvement in the US and UK water utility industries, as is the case in South Africa [11].

In a systematic review [12], the authors indicated a number of smart technologies that will impact irrigation. Important technologies include artificial intelligence for pattern recognition, anomaly detection, and modelling; fuzzy logic for control and modelling; and IoT for data provisioning, monitoring and control. Almost exponential growth was observed in terms of research interest (publications per year) for the application of technology in smart farming. IoT, specifically, was identified as a technology that integrates different irrigation components and subsystems into larger systems.

IoT systems are known for supporting the collection of data from field devices, including pressure, voltage, current, and moisture sensors, amongst others. Data is provided at a central location for analysis purposes, and advanced processing methods are usually applied to provide actionable intelligence [12] [13]. The integrated nature of IoT thus supports irrigation systems where a number of sensors will be used for power and pressure measurements, as is the case in this research project.

In an article on IoT in agriculture [14], the authors used the three-layer definition of IoT to discuss different sensor types in the perception layer (layer 1), data transportation in the network layer (layer 2), and heterogeneity in the application layer (layer 3). Specifically, agricultural monitoring and control were identified as important areas of application with automation in mind. Wireless networks and their supporting protocols were specifically identified as cost-savers by increasing remote access and reducing manual labour and logistic costs. This was evident specifically in the open-field system, which includes cellular-type networks, personal area networks, and low-speed and low-power ad hoc networks.

A simplified smart irrigation control system was designed from research on IoT and machine learning [15]. The proposed system shows the application of sensors in the field, a cloud database implemented in MongoDB, prediction and monitoring applications also hosted in the cloud, and pump control from the cloud to the water source. Although simplified, it shows the value of using cloud applications in IoT systems for irrigation control.

Industrial IoT (IIoT) adds value to commercial IoT in that distributed industrial monitoring and control systems are used in a more structured manner than commercial IoT, with the advantage of being more reliable and focused [16]. IoT systems are not always supervised, while industrial systems perform health checks by actively monitoring the status of all system resources – hence an “always on” philosophy. In this article [16], a five-layer approach is also discussed, with a processing layer (layer 3) added above the transport layer and a business layer (layer 5) on top of the application layer.

In most publications on IoT and IIoT, sensors, networks, big data, artificial intelligence and machine learning, cloud systems, mobility, and control are recurring topics. A platform is usually present in the cloud, with edge devices that connect to the platform using different forms of communication.

In this research, the use of IIoT was investigated in a real-world setting. Pressure, voltage, and current sensors are connected to a controller that is, in turn, connected to the cloud, where monitoring, data storage, processing, and control are done to control a pump’s speed (hence, pressure) in a closed-loop control system. A publication on IIoT-based control of a center pivot system was not found in the literature.

3 EXPERIMENTAL METHOD

Two experiments were conducted on an existing center pivot irrigation system, namely (i) characterization of the “as is” open-loop system and (ii) characterization of a controlled closed-loop system.

3.1 Purpose

The aim of this set of two experiments is to determine the energy saving and associated advantages of an IIoT intelligent measurement and control system for a real-world irrigation pivot installation. It is imperative to understand that the initial design and implementation of the center pivot and its irrigation subsystem were done beforehand, and the experiments conducted are to evaluate:

1. The characteristics of an “as is” center pivot system on an inclined field;
2. A PID control function for pressure control at selected points along the line;
3. The value of IIoT measurement and control in center pivot systems;
4. The “as is” open-loop system in comparison with the controlled system.

Specific endpoints of the experiments include the following:

1. Water pressure of the “as is” system when running on a Star-Delta drive;
2. Energy consumption of the “as is” system in a full run;
3. Water pressure of the controlled system when using a variable speed drive;
4. Energy consumption of the controlled system in a full run.

3.2 Method

An Action Design Research (ADR) methodology was followed [17] in a case study conducted at a center pivot located close to Frankfort, South Africa. As a result, the research team specifically did not change the initial system configuration in line with the pragmatic research philosophy. The team wanted to add practical learnings to the technical learnings from the experiment – future experiments will consider continuous improvement and associated gains.

An existing installation was selected with which to set a reference for energy consumption and water pressures and to determine the effects of IIoT and PID pressure control:

1. Select an installation site located on a significantly inclined field;
2. Retrofit the following to the "as is" system:
    a. 3-phase voltage and current sensors for power measurement;
    b. Pressure sensors at the pump, pivot center, and end tower;
    c. IIoT-enabled center pivot control unit at the pivot main tower;
    d. A variable speed drive to control the pump at the source;
3. Characterize the "as is" open-loop system (as an uncontrolled system);
4. Add a PID control function in an IIoT-enabled system – define set points;
5. Characterize the closed-loop system (as a controlled system);
6. Identify "as is" system design shortfalls and analyze results;
7. Determine energy and cost savings provided by the closed-loop system;
8. Perform a full life cycle cost analysis - determine the return on investment.

As part of the research close-out, reflection is done to make the value of IIoT in an irrigation center pivot system visible, to understand the value and impact of closed-loop center pivot control, and to review the potential cost-benefit provided by a controlled system.

3.3 Experimental setup

3.3.1 Topography

The pivot system and field on which it is located are situated close to Frankfort, as shown in the figure below.

Figure 2: Arial Map of the Pivot Installation Close to Frankfort.

This section provides details of the topographical layout, irrigation system configuration, the physically installed system, and the control system definition.

Figure 3: Topographic View of the Center Pivot on the Inclined Field.

Shown above is a topographic view of the field on which the center pivot is located. The center pivot is located on an incline, as evident from the contour lines indicated on the view. The span of the tower structure is 470 m with an elevation difference of 35 m between the lowest (bottom 7 o'clock) and highest (top 2 o'clock) points, with true north at 12 o'clock. All diagrams that follow will be aligned with this orientation to show the effects of the landscape on the performance parameters of the center pivot system.

3.3.2 Irrigation system configuration

Function F1 (pumping) is provided using a 55 kW 3-phase main pump located at the water source (please refer to Figure 3). The pump design was done for the "as is" system and the design was not verified before the experiments were conducted – measurements from experimentation were used to characterize the installed system.

Function F2 (measurement and control) was not done in the open-loop configuration and the system was operated at full pump speed and pressure to compensate for pressure loss on the highest point of the field. In such a design, a constant pump pressure is selected for maximum demand, which results in losses for areas where lower pressure would have sufficed.

The irrigation subsystem of the "as is" installed system was verified against best practice and was found to have addressed the minimum requirements in terms of function F3 (water transportation) and F4 (water application) [18]. The center pivot is a Valley 8210 with a total length of 470.3 m and 4 m end gun. A BlueCentric control panel was used in this installation, with a BlueCentric edge device located at the pump station for measurement and control.

The Class 6 mPVC pipe with a 250 mm diameter with a total pipe length of 502 m was measured from the pump to the pivot at a topographic height difference of 14.12 m between pump and hydrant. Senninger i-Wob 15 PSI sprinklers were designed for 8.5 mm application on a 70-ha field in 24 hours, mounted 1.8 m above ground level to provide fan spray at pressures of 340 kPA (3.4 bar) at the center and 150 kPA (1.5 bar) at the end tower. The flow rate was calculated at 246 m^3/h when the maximum speed of the last tower is set at 3.7 m/min using 52:1 reduction gearbox (all towers used the same motor and gearbox drives).

A 55 kW booster pump was located at the water source, with a feeder pump located in the river. The booster pump was connected to a Delta CP2000 variable frequency/speed drive to allow the pump frequency (and pressure) to be at maximum for the open-loop test and varied between 30 and 55 Hz for the closed-loop test.

A full rotation (run) of the center pivot is completed in 16.9 hours in order to meet the net daily peak crop water requirement of 6 mm in our case study. The pivot controller on site was upgraded to the automated BlueCentric controller before the experiments were conducted to ensure accurate position control of the tower structure and equalized water application for the open-loop and closed-loop scenarios.

3.3.3 Control system definition

As the focus of this research was not on the control algorithm, a PID control algorithm was selected for its simplicity, robustness, and proven track record in closed-loop control systems. This controller can be configured using parameters that are available from similar systems, where parameters (Proportional, Integral, and Differential) have practical meaning. A control interface is made available to the system installer to optimize remotely based on the measured performance of the pivot under control.

With reference to Figure 4, a PID controller was thus implemented in the cloud using the IIoT measurement and control configuration shown below, which allowed the installers the freedom to adjust the gain parameters remotely. Note that the irrigation system's time constant is very high (refer to the pivot speed at 3.7 m/min), and the controller's response time is well below the time constant of the slow-moving pivot structure. The PID gain parameters were adjusted to meet the system's dynamics based on observation.

Two commonly used pressure measurement points were used in the measurement and control loop: the pressure at the pivot center (pressure sensor 1) and the pressure at the end tower (pressure sensor 2). The set points were selected to meet the sprinkler package's minimum pressures and were set to 3.4 bar at the center and 1.5 bar minimum at the end tower.

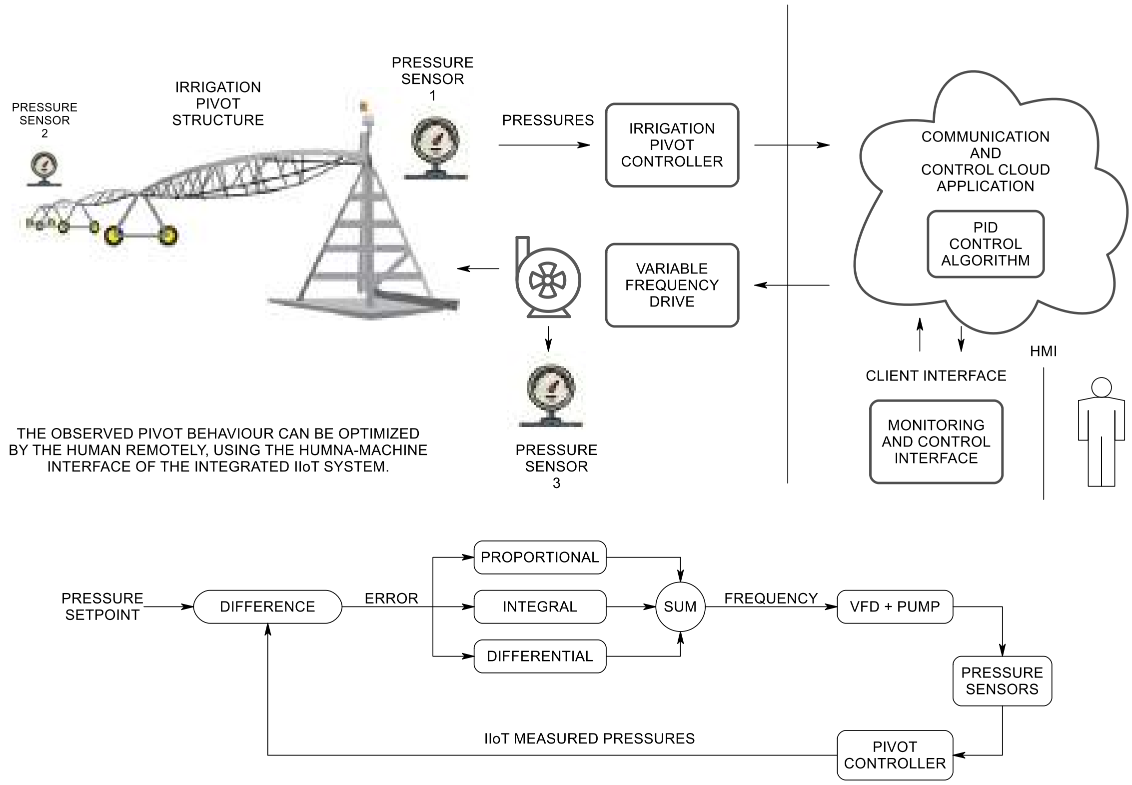

Figure 4: PID Controller Implemented in the Cloud using IIoT Principles.

The measured pressures were fed into the PID controller with a rule that requires the minimum pressure to be met at both measurement points. As a result, the pressure with the largest negative difference is used in the PID control loop.

The set points for the controller were defined to be:

- Proportional: 1.5 (a difference of 1 bar gives 1.5 Hz proportional correction)
- Integral: 0.01 (the correction will cumulatively increase with this value)
- Differential: 0.1 (the error slope is instantaneously corrected at this rate)
- Minimum control time: 1 minute
- Initial control delay: 2 minutes
- Allowed correction range: 0.05 Hz – 5 Hz
- Maximum operating frequency range: 30 Hz – 55 Hz

Observation of the pivot behaviour confirmed the configuration and the closed-loop tests were conducted using these settings.

3.3.4 Real-world installed system

The existing installation that was evaluated included a booster pump that was connected to a variable frequency/speed drive (VFD) – this is a commonly used configuration for irrigation systems that feed from rivers. The booster pump and pressure sensor 3 are shown in Figure 5 below.

A feeder pump was located at the river water level but was not controlled in this setup and also not considered in the energy and cost-saving calculations.

Figure 5: Controlled Pump and Pressure Sensor.

Pressure sensor 3 was not used in the PID control loop, although it was used in the evaluation of pump performance (and future maintenance and repair activities).

Shown in Figure 6 below are the variable frequency drive (Delta CP2000 VFD) and the IIoT edge device (BlueCentric) under construction before the experiment commenced.

Figure 6: CP2000 Variable Frequency Drive and IioT Unit Used in this Test.

3.4 Results

3.4.1 Experiment 1 – Open-loop system characteristics

For this experiment, the pump was set to the default condition, equivalent to a star-delta system designed for maximum demand. A rotational run was completed with the pump frequency at 55 Hz, and the resulting pressures were documented for analysis purposes. The radar diagram below shows the pressures at different locations with true north at the top center to align with the topographic view in Figure 3.

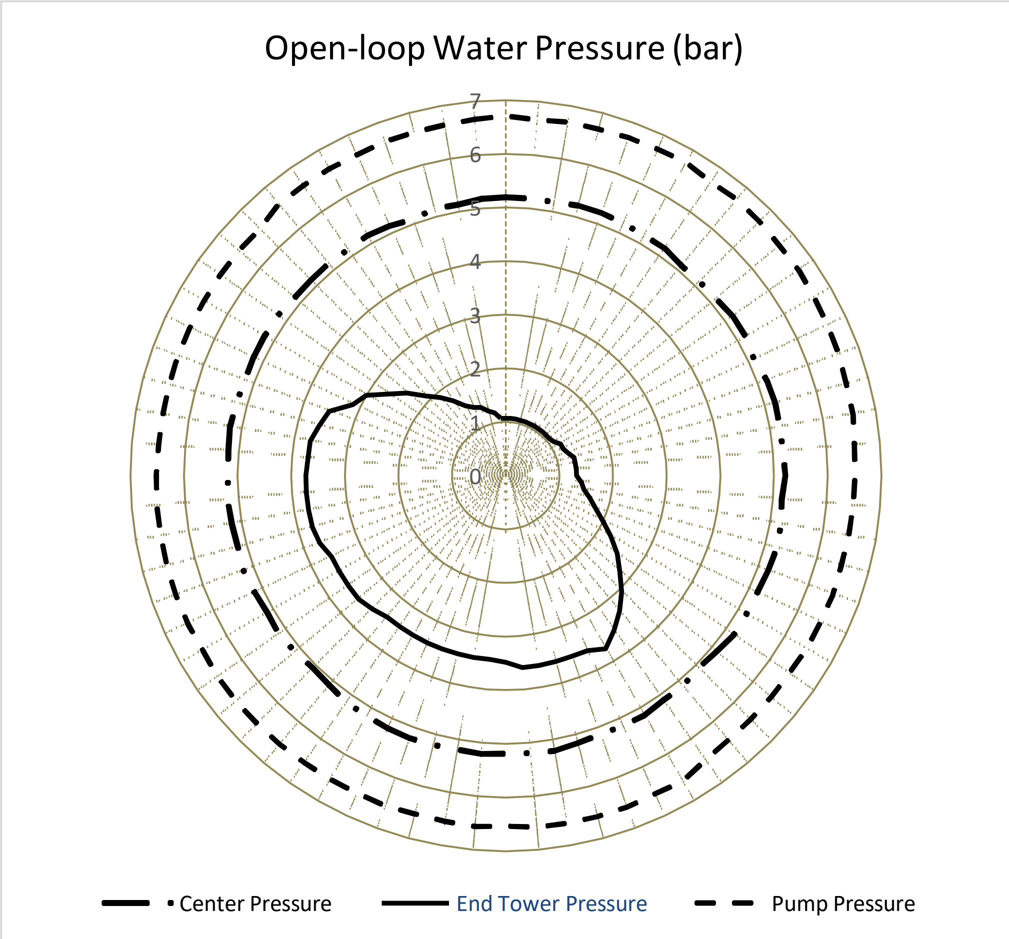

Figure 7: Open-Loop Water Pressure (Bar) at Three Measurement Points.

On the graph above, it can be seen that the pump pressure remains high (as expected) at around 6.6 bar, and the center pressure remains at around 5.2 bar due to the pump operating at a constant rate (to meet maximum demand at the top end of the field in an open-loop system).

The graph also shows that the pressure at the end tower falls below the minimum required pressure due to an underperforming booster pump (due to under-design that must be rectified). The minimum pressure at the end tower must be above 1.5 bar for the sprinkler package to function as designed, and the IIoT measurements made this shortfall visible.

Power consumption was measured to be 62.4 kW with a standard deviation of 1.7 kW and can thus be assumed fairly constant over the total run. The total energy consumption was measured to be 1044.7 kWh over a single 16.9-hour run. The energy efficiency, mainly due to the large feeder line friction losses and resulting pressure loss over the line, was calculated at 256.9 kW per megaliter. If the booster pump (the source) had been located at the center pivot, the pressure losses would have been reduced, but this is the nature of water transportation in practical installations (system function F3).

3.4.2 Experiment 2 – Closed-loop system characteristics

Measurements obtained from the closed-loop system run are shown in below in Figure 8 and Figure 9.

The PID controller controlled the closed-loop water pressure at the center and end tower to result in the pressure radar diagram in Figure 8. Note that the additional measurement at the end tower is required to ensure demand is met at the furthest point along the line through one rotation. It is clear that the minimum pressures at both the center and end towers were maintained in the lower portion of the field, while the minimum pressure at the end tower could not be maintained in the elevated section of the field. The elevated section's pump and center pressures correlate with the open-loop section, where the pump was operated at full speed (6.6 and 5.2 bar, respectively).

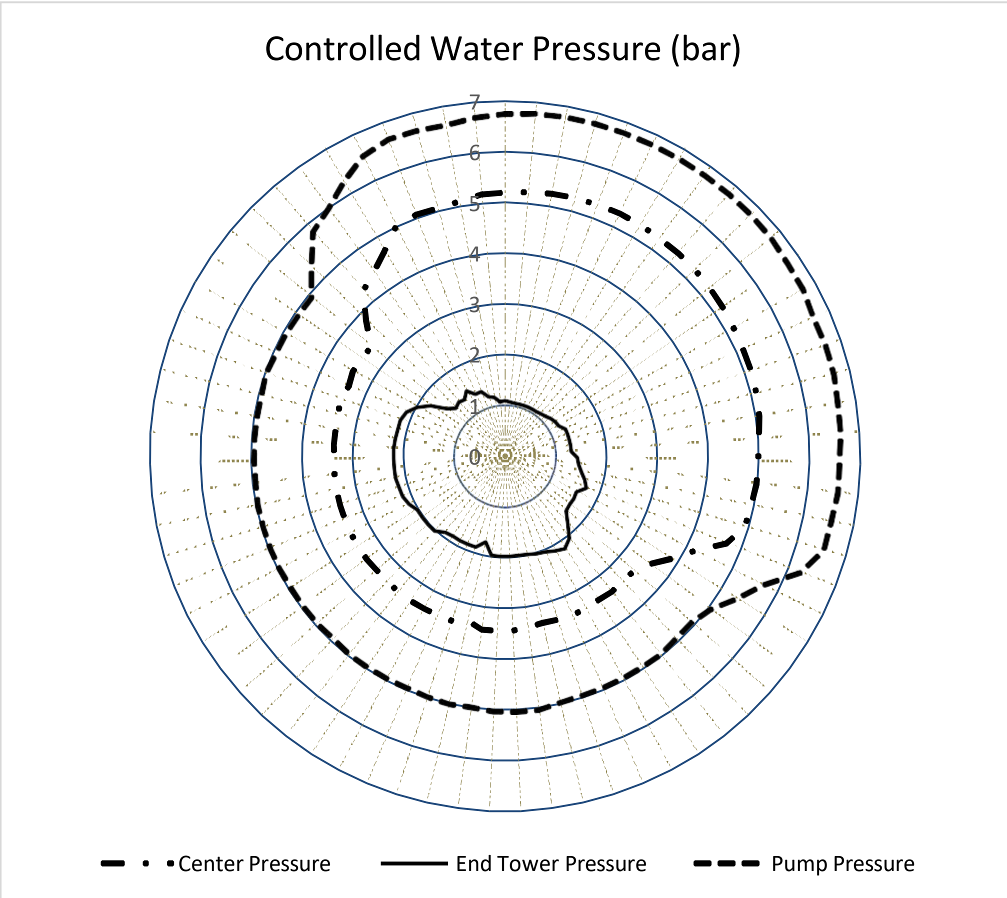

Figure 8: Closed-Loop Water Pressure (Bar) at Three Measurement Points.

There is a significant drop in pressure demand when the tower structure reaches the lower portion of the field. This is where both the center and end tower pressures are above the minimum required operating points and the pump pressure has reduced to around 5 bar from 6.8 bar at the elevated section, and the center pressure remains at a minimum of 3.4 bar, as designed. The end tower pressure increases to around 2 bar, which is above the minimum required pressure, as designed.

The graphs show that the PID control system is functional and that the pressures followed the field's topography. Having remote access to the performance data at a remote location simplified the behavioural analysis and allowed the researchers to identify areas of design improvement.

For the energy consumption, the power measurement at the pump resulted in a radar diagram, as shown in Figure 8. It is evident from the graph that the power consumption in the lower portion of the field was significantly reduced when compared to the open-loop system.

The total energy consumption for the 16.9-hour run was measured to be 857.1 kWh, and the system efficiency was calculated as 205.8 kW per megaliter.

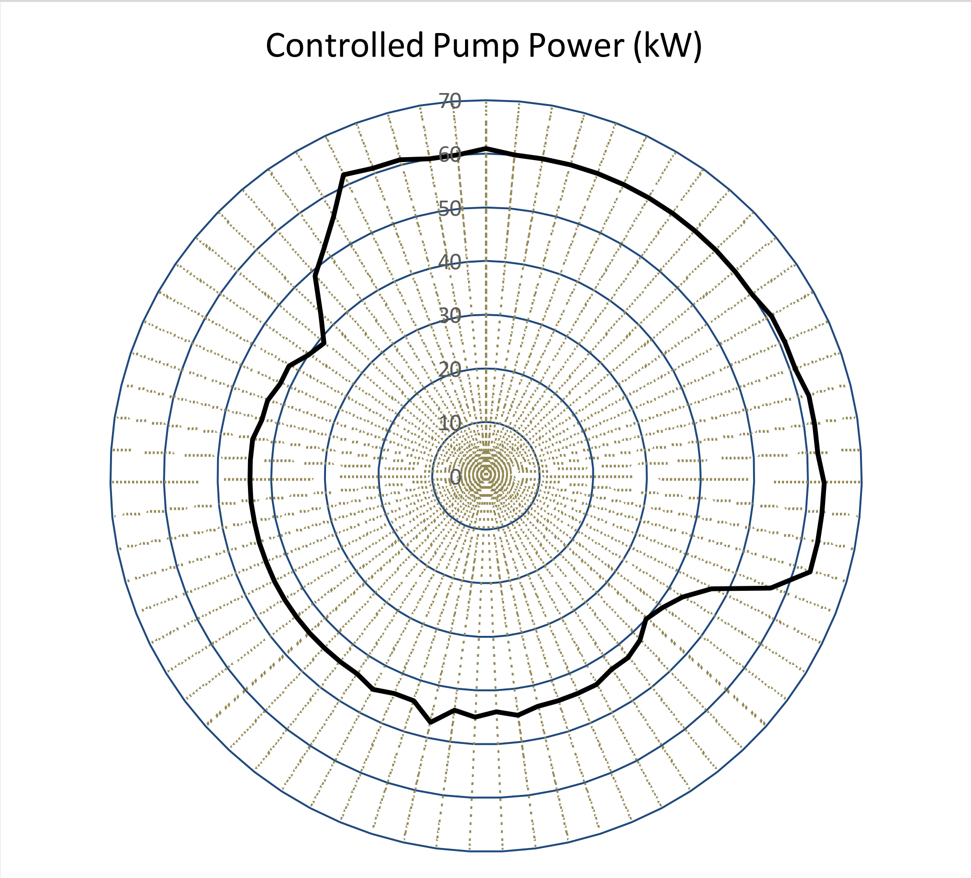

Figure 9: Closed-Loop System Pump Power Consumption (kW).

3.5 Analysis of results

The following observations were made from the two experiments:

- The performance of the open-loop system was as expected, with the exception of the uppermost section of the field, where the end tower pressure dropped below the minimum required pressure of 1.5 bar (it was measured at around 1 bar). The constant pump and center pressures resulted in constant power consumption as the system was designed for maximum demand;
- The IIoT system allowed the researchers and the farmer to visualize the effects of the topography on the system's performance. This, in turn, indicates how to effectively improve the system by selecting a pump of a higher rating. In addition, the constant application of water was controlled using a pivot controller that corrects for slopes by adjusting its speed to compensate for

inclines and declines;

- The power consumption of the open-loop system is 1044.7 kWh in comparison with the

857.1 kWh of the controlled system. This is a reduction of 20.3% in energy for a single run and is very much in line with the values found from simulations [6], [7], [8] and [9]. The improvement resulted from reduced energy consumption in the lower field region where gravitational downward pressure reduced the demand.

4 ECONOMIC ANALYSIS

A basic economic analysis was done to determine the rate of return of installing a VSD specifically for variable speed control, bearing in mind that other advantages of a VSD are indirect. For example, a VSD will protect the pump and reduce inrush currents and associated mechanical stresses at startup, which is a sufficient reason to use a VSD in all applications for improved system reliability.

Detailed economics of irrigation systems fall outside of the scope of this research, but a naïve approach is useful when using realistic water demand for different crop types, geographic locations, and rainfall (utilization) assumptions.

For this analysis, the application of water depends on the number of irrigation runs required in a year (or season) and the pivot utilization ratio (as a fraction of the total number of runs based on rainfall). These values will be different for installations elsewhere.

In order to calculate the internal rate of return (IRR) for investing in an upgraded system, including IIoT and variable speed control, it is necessary to determine the following:

- The initial capital layout of an upgraded system and its financing method;
- The utilization of the system for different crop types in different regions;
- Savings in energy and associated costs for different crops and regions;
- Minimum and maximum savings in energy cost across different crops and regions;
- IRR for the minimum and maximum savings, given the financing method.

An indication of the initial capital layout was determined to be around R 120,510.00 excl. as per quotation from an equipment supplier (the cost of equipment used in this research). This included all additional equipment installed to enable IIoT and pump control.

The values for the different runs were calculated as the minimum and maximum average runs for a variety of crops, including maize, cotton, soybeans, wheat, lucerne, sugarcane, sorghum, and groundnuts. Water requirements were obtained from actual data provided by the South African Food and Agriculture Organization (FAO) [19], [20].

The utilization of the system was thus determined from annual crop water needs for one crop per season and typical irrigation requirement with the 8.5 mm sprinkler package over a single 24-hour run. This resulted in a range of irrigation water needs expressed as the number of runs required to apply crop water at a certain rate. In this analysis, a minimum of 62 irrigation runs and a maximum of 115 runs are required on average for the different crops, which gives the worst and best cases in terms of savings.

A VSD and pump are considered to last for a minimum period of 10 years, the historical average interest rate (lending) was approximately 10% (9.75%), a loan period of 4 years was assumed, and inflation was set at 7%. A self-financed option is simply where a 0% interest rate is assumed, whereas a financed option will be at the lending rate.

From the information above, the IRR for a 10-year period was determined for each of the scenarios (on average) and was calculated to give the following indicative IRR values:

- For a financed system, the IRR was determined to be 24% at worst and 48% at best;

- For a self-financed system, the IRR was calculated to be 30% at worst and 55% at best.

In all scenarios, the IRR was found to be favourable, given the performance parameters for this specific case study. In different settings, the variability in the field's topography, the irrigation losses, different crop and irrigation needs, and differing irrigation system configurations will result in varying IRR values, making the investment option case dependent. For example, with half of the savings provided by this system, IRRs of 7% to 22% will be found for a financed option and 11% to 27% for the self-financed system. It is important to note that the utilization of a pivot is highly dependent on the crop type and geographical region – highly utilized systems will thus result in significantly increased IRR values.

In addition to direct gains, the value of having an IIoT-enabled irrigation system with variable speed on the main feeder pump and the non-tangible gains must be considered in the decision-making process. For example, the value of preventing losses by having access to risk data (failures, environmental threats, theft, and other risks) and the ability to increase pump efficacy and reduce failure losses must form part of the decision. These gains may outweigh the direct costs and gains and can be quantified in a more detailed analysis.

5 CONCLUSION AND FUTURE RESEARCH

An IIoT measurement and control system and variable speed control drive were installed on a center pivot system to allow control of end-tower pressure. This was done to determine the potential energy cost saving when using variable pump pressure on an inclined field as opposed to constantly providing pressure at maximum demand. Prior research indicated potential gains between 12% and 28% depending on the topographic and system characteristics.

From our research, real-world measurements showed a saving of 20.7% in terms of energy use. The saving is achieved by using a cloud-based PID control system that makes use of an IIoT measurement and control system to measure and control pressure to meet minimum demand. Although the system may be further optimized, the initial results are encouraging and align well with theoretical results.

From an investment perspective in this case study, a rate of return (IRR) between 24% and 54% was calculated over a period of 10 years, taking into consideration case-specific parameters. In different environments, depending on the topography and crop type, different rates of return will be achieved and must be determined on a per-case basis.

Future research should include additional sites for analyses and can consider savings obtained from utilizing IIoT and variable speed control to limit losses from failures and maintenance costs. These considerations will also influence the investment decision in the future, but the current savings indicate the gain of using performance management in irrigation systems.

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IMPLEMENTATION OF FUZZY LOGIC IN SCHEDULING A FLEXIBLE MANUFACTURING SYSTEM

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ABSTRACT

A flexible manufacturing system (FMS) has the advantage that it can easily adapt to equipment malfunctions and changes in the quantity or type of the product being processed. Proper scheduling is critical for production planning in order to meet customer demand. The case study organisation has been facing challenges in meeting due dates while concurrently minimising lead time and maximising machine utilisation. This paper presents the deployment of fuzzy logic in scheduling a flexible manufacturing system. The proposed approach identifies scheduling parameters for routing parts through system and membership functions and fuzzy rules are constructed to develop the best schedule using a toolbox on a MATLAB fuzzy logic platform. After comparison of several priority rules for job sequencing, the results demonstrated the applicability of fuzzy logic as a decision tool in the scheduling of flexible manufacturing systems.

Keywords: Scheduling, Fuzzy logic, Flexible manufacturing system

* Corresponding Author

1 INTRODUCTION

Advances in technology have aided manufacturers cut down on the time and effort taken to process a batch of products and maintain a competitive edge in their industries through ensuring customer satisfaction [1]. However, when manufacturers attempt to be flexible enough and make products as per customer orders, they face numerous scheduling challenges such as failure to proactively anticipating shop floor variability, which would induce a domino effect across many operations and resources, causing significant production delays. Such volatile operational environments prompt for the need for innovative approaches, especially for a flexible manufacturing system (FMS). An FMS is designed to adapt to fluctuations or variations in product, production volumes, new product designs with the aid of computers and machines that can automate key manufacturing processes, including loading and unloading, machining and assembly, and data processing [2]. The case study organisation has been facing challenges in meeting due dates while concurrently minimising lead time and maximising machine utilisation. This paper presents the deployment of fuzzy logic in scheduling a flexible manufacturing system. The proposed approach identifies scheduling parameters for routing parts through system and membership functions and fuzzy rules are constructed to develop the best schedule using a toolbox on a MATLAB fuzzy logic platform. Fuzzy logic has the advantage that it is flexible, conceptually easy to comprehend, tolerant of imprecise data and can be deployed tomodel non-linear functions of arbitrary complexity.

2 RELATED LITERATURE

An FMS is a group of automated processing workstations that are interlinked by a material conveyance system and a centralised computer system that would synchronise and coordinate the manufacturing activities [3]. An FMS is characterised by several possibilities of routing paths and a combination of workstations served by a material handling system that deliveres parts as well as an automatic inspection.

Fuzzy logic has demostrated some interesting potential in solving scheduling problems in flexible manufacturing systems [4-6]. Bisht et al. [7] described basics of fuzzy sets, fuzzy rule base system, fuzzy memberships and defuzzification. The study embraced some standard fuzzy logic applications, diverse traits of fuzzy manufacturing systems as well as limitations of fuzzy modeling in flexible manufacturing systems.

With a scheduling algorithm based on distributed fuzzy control system design, Swe et al. [8] developed a flexible manufacturing process for autonomous control system for modern industries. A fuzzy logic controller design was utilised for scheduling algorithm based on distributed environment, resulting in more benefits in resource management, scheduling policies, on-time processing of work and speedy delivery.

Majdzik [9] designed of a framework for the implementation of fault-tolerant control of hybrid assembly systems that linked fully automated technical systems to human operators. The main challenge in such hybrid assembly systems was interconnected to delays that emanated from objective factors such as fatigue and experience that would influence human operators' work. The designed approach was able to guarantee real-time compensation of delays that were treated as faults, while the fully automated fragment of the system was accountable for this compensation. The use of a wireless IoTplatform that enabled a reference model of human performance to be defined using fuzzy logic was proposed for predictive delays-tolerant planning.

On the other hand, using fuzzy logic and fuzzy sets, Kazerooni et al. [10] developed two decision rules for real-time dispatching of parts and tested the model in a simulated FMS. Routing flexibility was considered as a vital aspect of FMSs, and by using fuzzy sets to incorporate system status in decision making, a routing selection approach was proposed. It was also observed that a traditional dispatching rule would uncritically pursue a single objective, yet in practice, it might be crucial to concurrently consider more than one objective. Thus, in this case, real time machine loading was also taken into consideration to develop two dispatching rules using fuzzy logic.

Several researchers have addressed the diverse facets and technologies that are related to smart manufacturing systems; however, less attention has been given to establishment of new smart manufacturing systems that necessitates pre-implementation planning and assessment. By identifying apparent evaluation factors for measuring the effectiveness of a particular smart manufacturing system configuration before implementation, Grace et al. [11] formulated an evaluation framework using lead time, quality, and cost as inputs to control the output of the configuration model. Several configurations were studied based on the trained fuzzy logic model using MATLAB's Fuzzy Logic Designer tool, and the compositions were manipulated according to how the factors influenced the manufacturing cost justification in compound setups. In order to weigh the level of satisfaction derived from the evaluation framework, the results obtained from the experimental study were validated by real field engineers from the relevant manufacturing industry.

3 PROCESS DESCRIPTION

The issue of improper scheduling has been problematic for the machineshop and there was no proper allocation of jobs at the right machines at the right time. The job may be available at a machine that is busy a part while another machine was idling due to poor scheduling. As shown in Figure 1, the FMS under study is characterised by 2 similar Horizontal CNC milling machines, 2 vertical CNC milling machines, 2 drill presses and a load/unload station served by material handling system. The system can process four dissimilar part types, A, B, C and D and it takes an average of 4 minutes for loading and unloading a part.

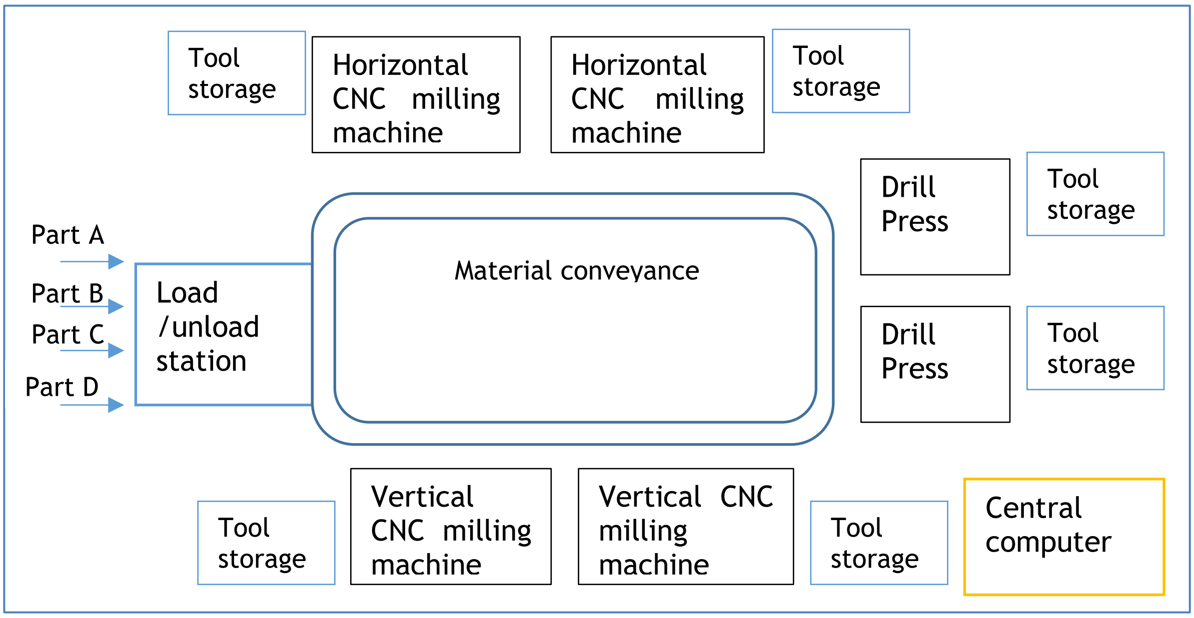

Figure 1: Schematic for FMS layout

The scheduling problem is to make a decision regarding the sequence of the jobs and alternate routes that could be chosen for individual part types. It was assumed that no machine could fabricate more than one component at an instance, every workstation has one input buffer and each machine was flexible to perform several operations. Additionally, any part type can follow numerous alternate routings and once commenced, operations cannot divided or interrupted. Set up times were considered to be independent of the job sequence and would be added to the processing times.

4 RESEARCH METHODS

Fuzzy Logic was applied in this research work to generate a fuzzy scheduling model for solving operation allocation and operation scheduling problems in FMS that can cope with several objectives of FMS scheduling. The fuzzy scheduler considered sequencing of job and routing as the two specific rules for the scheduling problem. The inputs were processing time and due dates and these were used to derive an optimal sequencing of jobs using fuzzy controllers and derive one consequent. The route for each part type loading on a machine was determined by the fuzzy system , such that if the load station or CNC machine was free, the job with the highest priority would be selected for processing. The routing problem was considered as a decisional point for selecting one route amongst several possible routes.

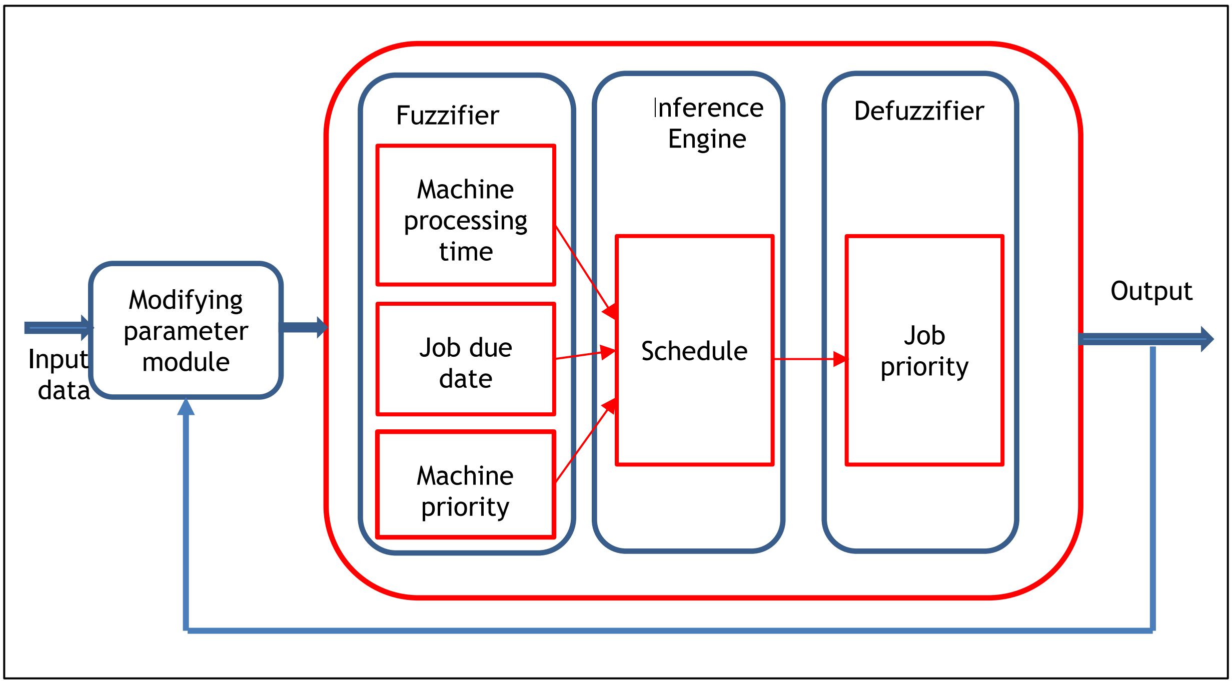

Figure 2: Steps for deployment of fuzzy logic

The first stage is fuzzification of inputs to establish the extent to which the inputs are appropriate to the applicable fuzzy sets through membership functions. The input was a crisp arithmetical value that was constrained to the universal discourse of the input variable while the output was a fuzzy degree of membership, spanning from 0 and 1.

Once the inputs have been fuzzified, the second step is applying the fuzzy operator since the extent to which each component of the antecedent has been fulfilled for each rule. The fuzzy operator was deployed to attain a numerical value that represented the yield of the antecedent for a specified rule if the antecedent of the specified rule had more than one component.

The third step was to apply the implication method whereby every rule was given a weight, that is a number between 0 and 1 before applying the method. Based on the antecedent, the implication method was defined as the shaping of the consequent fuzzy set. A single number given by the antecedent is the input for the implication process while the output is a fuzzy set. Implication occurs for each rule. The min (minimum) function which truncates the output fuzzy set is a built-in method that was used as the implication method.

The fourth step was to aggregate all outputs whereby the outputs of each rule were unified by joining the parallel threads. Aggregation would occur once for each output variable whereby all the fuzzy sets that represented the output of each rule were combined into a single fuzzy set. A list of truncated output functions returned by the implication process for each rule was input to the aggregation process while the output of the aggregation process is a single fuzzy set for each output variable.

The fifth and final step for fuzzy logic process was defuzzification process whereby the aggregate output fuzzy set was input and the output is a single crisp number. The centroid calculation was deployed as the defuzzification method.

5 RESULTS AND DISCUSSION

The study proposed to categorise dissimilar scheduling parameters and in this case, the job procesing time and routing and construct the membership functions and fuzzy rules. Using MATLAB fuzzy logic toolbox, the membership functions and fuzzy rules were used to develop a fuzzy interference system to select the best route. Figure 3 shows a sample fuzzy input variables for membership functions. Triangular membership function was assigned to all the variables, split into three zones viz small, medium and high. Job priority, varying from 0 to 1 was coded as the output of the processing time and due date variables. The priority variable was divided into nine portions and was also assigned with triangular membership functions as shown in Table 1.

Table 1: Categories for the priority variable

Maximum (MX)	Positive Average (PA)	Low (LO)
Positive High (PH)	Average (AV)	Negative Low (NL)
High (HI)	Negative Average (NA)	Minimum (MN)

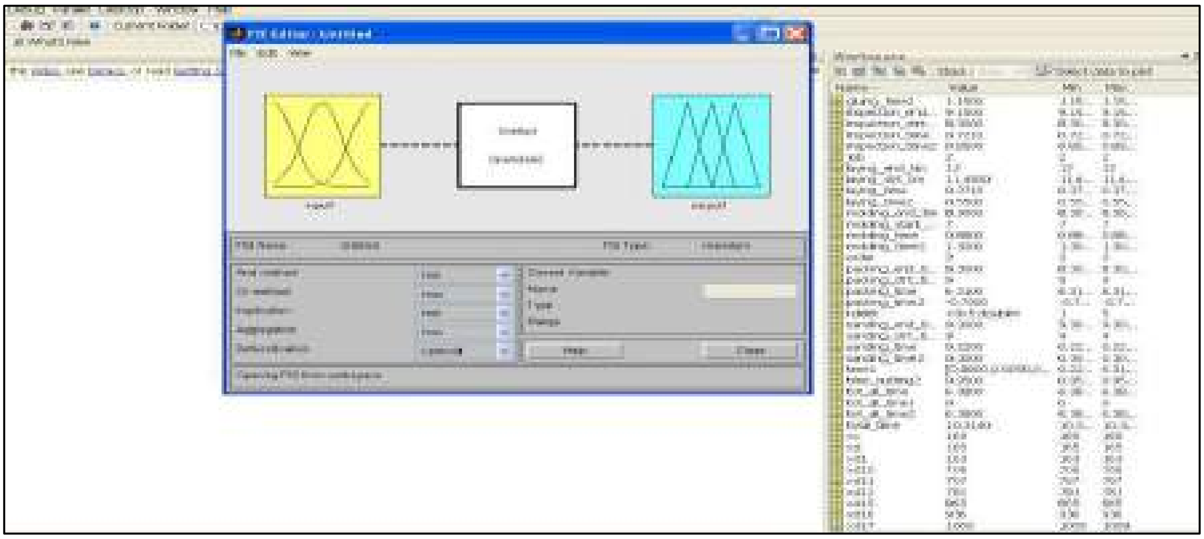

Figure 3: Sample fuzzy input variables for membership functions

Similar to job sequencing, concerning route selection, from the processing time variables, one had to establish the optimal state of variable route priority from a possible ordered 27 pairs. If l, m, n denote the number of categories defined for time of arrival, size of burst, priority respectively then the fuzzy rule base will have (lmn××) rules. Therefore, for the inference rules for route selection from using two inputs and one output, the decision is for instance, shown below:

1. If (Processing Time is High) then (Route Priority is Minimum)
2. If (Processing Time is High) then (Route Priority is Negative Low)

…
26. If (Processing Time is Small) then (Route Priority is Positive High)
27. If (Processing Time is Small) then (Route Priority is Maximum)

Table 2 shows a sample experimenental results for routing from using fuzzy model with 1 denoting the horizontal CNC milling machine, 2 denoting the vertical CNC milling machine, and 3 denoting the drill press.

Table 2: Sample experimental results for routing from using fuzzy model

		Machine centre allocated to process part			Total processing time (Hours)
Part type or job	A	1	3	2	8.5
	D	2	1	3	9.2
	C	3	1	2	8.7
	D	1	2	3	8.5
	C	1	3	2	9.1
	B	3	1	2	8.2
	C	2	1	3	9.6
	D	1	3	2	8.8
	A	2	3	1	9.3
	B	3	1	2	9.4
	A	1	2	3	8.9

The results demonstrate that, for instance, that if job B with the smallest total processing time is scheduled first, considering due date constraints, it should first be processed on the drill press, followed by the horizontal CNC milling machine,and lastly on the vertical CNC milling machine.

6 CONCLUSION

The study provided insight into investigating the applicability of fuzzy logic as an aid to decision making for organisations has been facing challenges in meeting due dates while concurrently minimising lead time and maximising machine utilisation in their flexible manufacturing systems. The proposed approach identified scheduling parameters for routing parts through system and membership functions and fuzzy rules are constructed to develop the best schedule using a toolbox on a MATLAB fuzzy logic platform. After comparison of several priority rules for job sequencing, the results demonstrated the applicability of fuzzy logic as a decision tool in the scheduling of flexible manufacturing systems. Further investigations would embrace the robustness of the scheduling approaches in accommodating trends in Industry 4.0 and artificial intellegence.

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MIXED MODEL LINE BALANCING FOR MANUAL ASSEMBLY SYSTEM

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ABSTRACT

It is imperative for organisations in the automotive industry to adopt a culture of continuous improvement due to a highly competitive market environment. An automotive manufacturer had adopted a takt time of 60 minutes but has been facing challenges in meeting the daily target of vehicles produced per day. The challenges were attributed to the imbalance of the assembly line and waste generated from non-value adding activities. The focus of this work is to improve a manual automotive assembly system. Time studies were conducted, a list of tools and shovel-ware components was compiled, and work stations were allocated to all the operations. After line balancing, the bus trailer was moved from the sub-assembly bay to the production line leading to more productivity. Additionally, the centralisation of bus trailer allowed for the optimal use of the tools, and the savings that were derived amounted to R350 000 per year.

Keywords: Line balancing, Manual assembly system, Mixed model

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1 INTRODUCTION

The global landscape is characterised by an inflationary environment where wages have failed kept pace with the increased cost of living. It has become increasingly vital for firms to adopt a culture of continuous improvement, especially in a market as competitive as the automotive industry [1]. In South Africa, the automotive industry's localisation ambitions are retarded and it is difficult to create sustainable jobs or attract investment opportunities to grow the South African economy due to loadshedding which is the prevailing biggest inhibitor [2]. The case study organisation is a leading manufacturer of medium, heavy and extra-heavy trucks, as well as buses and coaches, based in South Africa. The assembly plant is basically made up of 15 workstations; which are divided into 3 zones and at the end of the assembly line, there is a quality inspection bay where all vehicles produced on the line are inspected for faults. The scope of the study was improve the manual assembly efficiency through the deployment of mixed model assembly line analysis with focus on the DBC bus train chassis assembly and XLA truck. The XLA was the most difficult vehicle to assembly due to the nature of its design. The studied manual automotive component assembly system was characterised by a bus chassis that was built on the bus assembly line, while the chassis extension or trailer is built separately on a pre-assembly station next to the assembly line. The preliminary study of the manual assembly line demostrated inherent waste in terms of ineffective space and manpower utilisation. The study focused on improving process effectiveness by integrating the two chassis and assembling them on the assembly line while concurrently keeping the daily target the same.

2 RELATED LITERATURE

Lean philosophy fundamentally targets identifying and eliminating waste from production processes, fousing on maintaining the product value wihile using less work [3, 4]. A manual assembly line consists of a sequence of consecutive workstations where assembly tasks are performed by human workers as the product moves along the line, with the workers performing a subset of assigned assembly tasks within a specified time range [5]. The factors that favour the use of manual assembly lines include identical or similar products, high or medium demand for product, total work content that can be divided into work elements, and when it is economically infeasible or technologically impossible to automate the assembly operations [6].

Arising from the complexity of necessary tasks that must be accomplished manually, manual assembly line may be characterised by inefficient processes that are inherently wasteful. Waste from assembly processes is basically caused by inefficient processes, unnecessary delays, costs and human errors [7]. The fundamental seven forms of waste that characterise manual assembly systems include transportation, overproduction, processing, motion, inventory, waiting and defects. Yerasi [8], in improving the overall performance of a production line, re-configured an assembly system from two manual assembly line configurations and the results demonstrated that the operator productivity was improved when the existing assembly method was changing over to a single-stage assembly line configuration.

Correia et al. [9] posited that despite the notion that manual assembly lines are generally studied heavily before implementation, numerious challenges emanate if the product needs some modifications. The product design modifications sometimes create huge problems for the already installed manual assembly line, creating line imbalances and other forms of waste. In such circumstances, visual management techniques and value stream mapping can be deployed to fully comprehend the different tasks and operations. Lean line balancing can be used to reduce the line bottlenecks by balancing the workstation task times to reduce delays, and even out worker taskloads resulting in better line efficiency and production rate [9].

To cope with the excessive information flow, Aljinović et al. [10] developed a procedure to aid decision-makers in selecting the most applicable Industry 4.0 technology to integrate into a prevailing assembly line to enable the transformation of production towards smart production. The proposed production paradigm was aligned with the expected organisation's strategic goals since the procedure took into consideration the current production plans, scheduling, throughput, value from the end-user perspective and other related production metrics. The results were validated through a real assembly line providing a decision support system that enabled the decision-makers to express preferences through criteria weights and preference functions [10].

Scheduling decisions in assembly lines can be multi-objective, using seven different products, Ostermeier [11], while modelling human learning and deterioration effects explicitly, simulated a real unpaced mixed-model assembly line to analyse the effect of different sequence types on the desired objectives. The results demonstrated that sizeable trade-offs existed as different sequence types were preferred for several scheduling objectives.

3 RESEARCH METHODS

3.1 Background

Figure 1 shows a schematic for the research methods that were deployed to reduce waste and improve the manual automotive component assembly system.

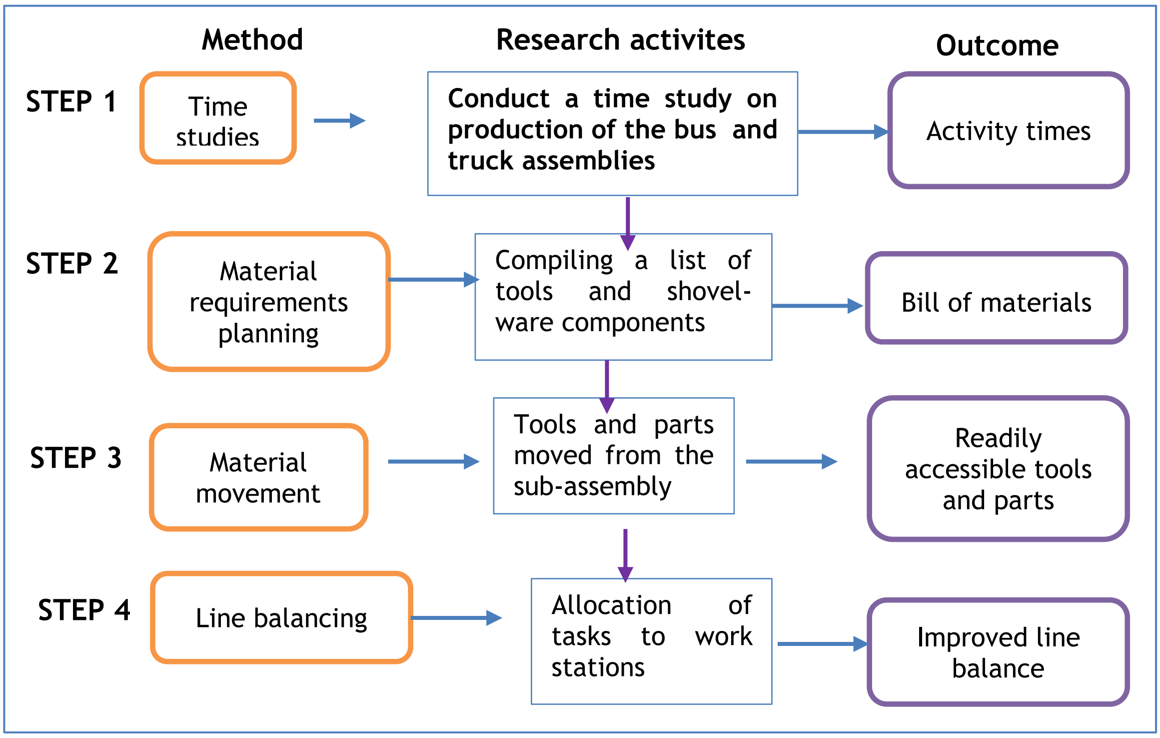

Figure 1: Schematic for research methods

Figure 2 shows a schematic for process flow manual automotive component assembly system, characterised by 15 workstations and a quality inspection bay.

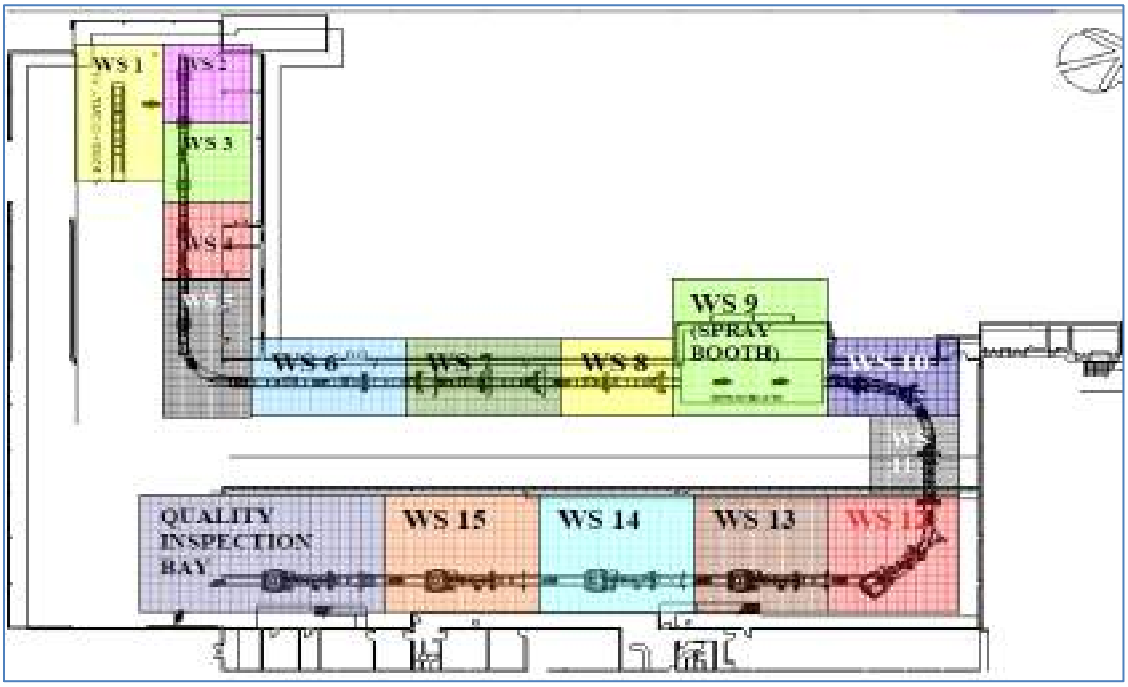

Figure 2: Process flow manual automotive component assembly system

The bus train shown in Figure 3 (the bus with a chassis extension is one of the vehicles built on the line (bus assembly line). Currently the actual chassis was built on the assembly line while the chassis extension (hereafter referred to as the trailer) is built separately on a pre-assembly station next to the assembly line, the assembly line only makes bus chassis without a body.

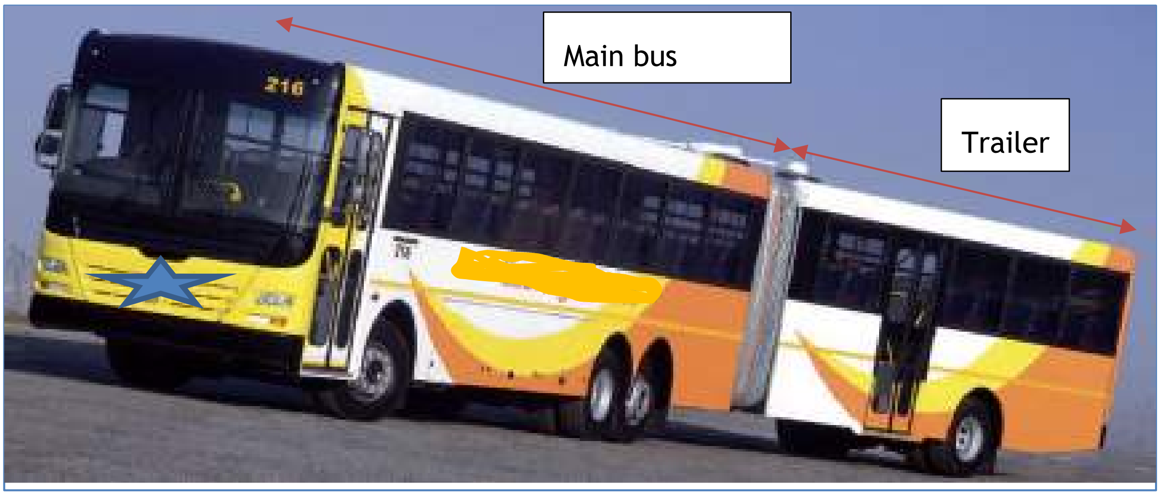

Figure 3: A completed bus train

3.2 Time and work study

Table 1 shows the time study results for DBC main bus chassis assembly as well as for the sub-assembly. A time study was conducted for production of the trailer on the sub-assembly work station to get the total assembly time required to produce a complete trailer and it was found that the trailer chassis took 6 hours and 6 minutes to make. The data showing all the operations required to assemble the trailer was also collected. The next step was to compile a list of all the tools and shovel-ware components that are required to assemble the trailer. It was crucial to ensure that all the tools and parts are available on the assembly line before commencing the bus trailer integration project so that the activities would be executed smoothly without stoppages. All the tools were moved from the sub-assembly work station to the main assembly line and placed at the work stations for easy access by the operator.

Table 1: Time study results for DBC bus chassis main an sub-assembly

Work element	Description	DBC bus chassis		XLA truck
		Duration (mins) main assembly	Duration (mins) for sub-assembly	
1	Chassis ladder assembly	30	28	68
2	Peripheral mounting and chassis coupling	25	25	30
3	Brake valves sub assembly mounting	52	50	45
4	Chassis electric system connection and air brake pipe mounting	60	58	60
5	Axle sub assembly	53	50	46
6	Axle mounting	60	58	56
7	Chassis turning	30	25	28
8	Preparation for chassis painting by masking of paint sensitive parts	20	20	25
9	Chassis painting	15	15	20
10	Wheel mounting and exit the assembly line	50	50	45

3.3 Allocation of operations to work stations for mixed model assembly line

Using the time and work study data for the vehicles produced on the line and functions performed every day, the next step was to allocate work stations to all the operations. The Kilbridge & Wester rule, where assignment of work elements to stations is grounded on the time that is required each work element, was used as a line balancing algorithm.

With regards to determining the number of workers, ***w***, for a mixed model assembly line:

$$w = \frac{WL}{AT} \qquad (1)$$

and

$$WL = \sum_{j=1}^{P} R_{pj} T_{wcj} \qquad (2)$$

where ***WL*** is workload to be accomplished over a scheduled period of time, and ***AT*** is the available time per worker in the period. ***P*** is number of models to be produced and ***j*** is denoting the model.

The objective of mixed model assembly line balancing was to distribute the total work content on the assembly line as uniformly as possible among the operators.

The objective function was expressed as:

$$Minimise(wAT - WL)\ or\ Minimise\ \sum_{i=1}^{w}(AT - TT_{si}) \quad (3)$$

where w is number of workers assuming that *Mi =1*, so that *n* = *w*. The available time (AT) during the period of interest in minutes, and TT_{si} was total service time at station *i* to perform its assigned portion of the workload in minutes.

$$WL = \sum_{j=1}^{P} R_{pj} T_{wcj} \quad (4)$$

Total time per element, TT_k is:

$$TT_k = \sum_{j=1}^{P} R_{pj} T_{ejk} \quad (5)$$

Total service time at each station is computed as:

$$TT_{si} = \sum_{k\varepsilon i}^{P} TT_k \quad (6)$$

where TT_{si} is total service time at station *i*

Balance efficiency, E_b is computed as

$$E_b = \frac{WL}{w(Max\{TT_{si}\})} \quad (7)$$

where $Max\{TT_{si}\}$ is the maximum value of total service time among all stations.

4 RESULTS AND DISCUSSION

4.1 Allocation of bus trailer sub-assembly functions to main assembly line

The study focused on improving process effectiveness by integrating the two chassis and built both of them on the assembly line. The bus trailer was initially assembled on its own small bay; with all the tools and shovel ware components required to build a trailer available on that small bay and the dates on which the DBC bus trailer was completely assembled was different from the date on which the trailer was produced because of the fact that they are built on “different” production lines. Due to poor planning of shovel-ware, in some cases, it took just over two shifts to produce the DBC bus chassis on the assembly line and just over 6 hours to produce a trailer, so this means that a completed trailer chassis have to wait for over 1 shift to be coupled with its DBC bus. The aim was therefore to keep the daily target (the daily number of vehicles expected to be produce every day) the same (8 vehicles per shift), so that meant the bus trailer was not going to be counted as a unit. An operator was assigned to assemble the bus trailer with the help of the operators on the line in some instances. This operator would follow the chassis around the production line until it goes into the spray booth (work station 9) for chassis painting. To move this small trailer around the line it was crucial to couple it to the DBC bus train which is part of the goofy using a specially designed coupling. The main reason for coupling this trailer to another vehicle was to avoid counting it as a complete unit, and eliminate unnecessary pre-assembly station and centralise production.

4.2 Mixed mode assembly line balancing

After the allocation of bus trailer sub-assembly functions to main assembly line, it was imperative to ensure that the line was well balanced. The automotive manufacturer had adopted a takt time of 60 minutes but has been facing challenges in meeting the daily target of vehicles produced per day. The two models, the DBC bus train chassis assembly and XLA truck were to be assembled on a mixed model manual assembly line, taking into consideration, their work elements, element times, and precedence constraints. Given the target of 60-minute takt time, that would cascade to one DBC bus train chassis assembly per 2 hours and one XLA truck chassis per 2 hours. The bus trailer elemental times were integrated into main bus chassis so that a bus chassis and trailer chaiss would be counted as one unit, hence the mixed model analysis considered the the DBC bus train chassis assembly and XLA truck. Assuming an ideal efficiency of 100%, repositioning efficiency of 100%, and average manning level of 2 workers per station, the ideal minimum number of workstations that were required to realise the required production rate was computed and thereafter the Kilbridge & Wester method was deployed to solve the line balancing problem.

Table 3 shows the totals for the product of elemental times and production rates (R_p) that were used to derive the minimum number of workstations that were required to achieve production rates the DBC bus train chassis assembly and the XLA truck chassis.

Table 2: Workloads for production rates the DBC bus train and the XLA truck chassis

Work element	Description	R_p x DBC bus chassis duration	R_p x XLA truck chassis duration	Sum
1	Chassis ladder assembly	30	34	64
2	Peripheral mounting and chassis coupling	13	15	28
3	Brake valves sub assembly mounting	26	23	49
4	Chassis electric system connection and air brake pipe mounting	30	28	58
5	Axle sub assembly	27	23	50
6	Axle mounting	30	24	54
7	Chassis turning	15	14	29
8	Preparation for chassis painting by masking of paint sensitive parts	10	13	23
9	Chassis painting	8	10	18
10	Wheel mounting and exit the assembly line	25	23	48
Total				418 mins

Given the available takt time of 60 min, total service time at each station was 60 min and the minimum number of work stations required was found to be 7 stations.

Table 3 shows the line balancing results by using the Kilbridge & Wester method.

Table 3: Allocation of elements to workstations

List of elements by column			Allocation of elements to workstations			
Element	TT_k (mins)	Column	Station	Element	TT_k (mins)	TT_{si}
1	64	I	1	1	64	64 min
2	28	II	2	2	28	28 min

3	49	III
4	58	IV
5	50	V
6	54	VI
7	29	VII
8	23	VIII
9	18	IX
10	48	X
	418min	

3	3	49	49 min
4	4	58	58 min
5	5	50	50 min
6	6	54	54 min
7	7	29	
	8	23	52 min
8	9	18	18 min
9	10	48	50 min
			418 min

Given that maximum {TTsi} = 60 min, balance efficiency,

$$E_b = \frac{WL}{w(Max\{TT_{si}\})} = \frac{418.0}{9(60)} = 0.774 = \mathbf{77.4}\%$$

It is worth noting that the XLA is one of the trucks produced on the assembly line, the XLA is the most difficult vehicle to assembly because of its design; hence the need to introduce a sub-assembly concept for XLA truck on station 1 (TT_{si} = 64 minutes).

5 CONCLUSION

Without compromising efficiency, assembly lines nowdays must be as flexible as possible. The engineers of today need to embrace diverse physical tools such as flexible workstations, flow racks, pick-to-light systems and visual work instructions in complementing the deployment of lean tools on mixed-model assembly lines. Mixed model assembly line balancing ensured the distribution of the total work content on the manual assembly line as uniformly as possible among the operators. The automotive manufacturer was able to meet the daily target of vehicles produced per day from the adopted takt time of 60 minutes. After implementing the mixed model line balancing solution for manual assembly system, extra space was created at the trailer static bay and this could be used for sub-assembling other models. The centralisation of bus trailer enabled effective manpower and time utilisation as well as the optimal use of the tools since the same tools and jigs used for all the other vehicles were used for the trailer.

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FMEA/FMECA APPLICATION FOR THE SAFER INDUSTRY - SYSTEMATIC LITERATURE REVIEW

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ABSTRACT

Despite astronomical investments in plant safety, poor plant uptime and accidents continue to prevail. The objective of this study was to explore the application of FMEA/FMECA cases in the literature. FMEA/FMECA articles (52) were identified from 2010-2022 studies. This was done by applying a general systematic literature review research methodology and the Thematic Analysis Framework. Risk Priority Number determination was found to be based on subjective data (Severity, Occurrence, and Detectability), this had a negative effect on the apparatus results and ultimately on plant maintenance strategy. A computerised maintenance management system was identified as the most common source of data. The integration of mathematical tools and data analytics into the tool framework offered promise in improving risk assessment by providing objective estimations and reducing subjectivity. Practitioners were provided with a list detailing the limitations of this tool and areas that need further improvement. Research output in this sector had positive growth in the application of this tool.

Keywords: FMEA, FMECA, RPN, Safety, Maintenance.

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1 INTRODUCTION

The American military issued a directive to suppliers called MIL-STD 1629 in 1949, which served as the impetus for the concept of *risk management planning*. For the benefit of the aerospace industry, this directive was updated and reissued as ARP 926 [1]. This directive was Failure Mode and Effects Analysis/ Failure Mode, Effects, and Critical Analysis (FMEA/FMECA).

The purpose of FMEA/FMECA is to identify all possible risk elements and assess their causes as well as their subsequent effects on the function of the system's *risk* and *reliability* under consideration. The goal of this tool is to engage in prevention management rather than finding a solution after system failure has taken place. When does the maintenance strategy designer apply FMEA and FMECA? Nardo, *et al*. [2] argue that the criticality analysis results turn FMEA into FMECA - in this process, failures are prioritised based on the likelihood of the item failure mode and the severity of its impacts.

In aviation and power plant industries, FMECA is used during the design and development stages of an aircraft or plant, as well as during its operation and maintenance. It is typically applied to critical systems such as flight control, and pneumatic systems, while in the power plant, this is applied in turbine lubricating oil systems, and ash handling plants amongst others [3]. During the FMEA/FMECA process, potential failure modes are identified for each component, and their associated effects and criticality are analysed. The criticality is based on factors such as the likelihood of occurrence, the severity of the consequences, and the ability to detect or prevent the failure. The outcome of such exercises helps to identify and mitigate potential risks before they become actual failures [4]. It is also used to inform maintenance procedures, as the results of FMECA can help determine the frequency and type of maintenance strategy (see Figure 1 below) required for different components and systems.

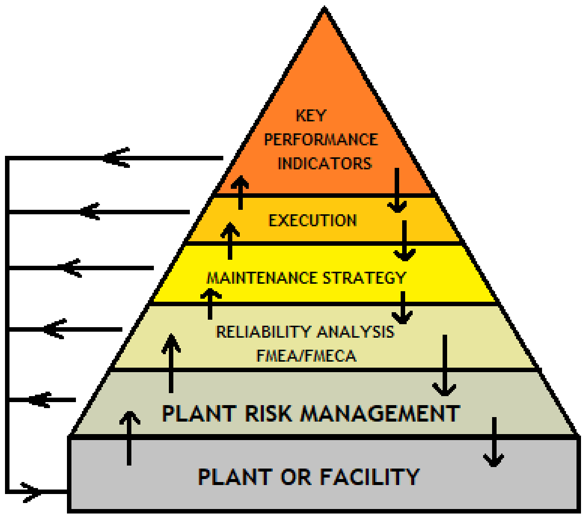

Figure 1:FMEA/FMECA tool relationship with plant health or safety.

The application of FMEA/FMECA in the aviation and power industry is supported by various studies as listed in the reference section. Additionally, the International Civil Aviation Organization (ICAO) recognizes FMEA/FMECA as a proactive risk assessment tool in aviation safety management in its Safety Management Manual (SMM). Major energy research institutes also support the FMEA/FMECA.

The goal is to explore the significance of FMEA/FMECA in improving safety, and plant performance, minimizing risks, and fostering continuous improvement in the general industry through a systematic literature review. Also, in learning how the Risk Priority Number (RPN) is determined through systematic literature review. Most of the studies under Appendix A have shown that RPN is established through the views and experiences of the experts and not an objective assessment.

RPN = SEVERITY X OCCURENCE X DETECTABILITY

According to [5], [6], [7], this method is having high duplication rates and is often subjective perceptions, which significantly affect the accuracy of the analysis results. Zhang, et al. [8] caution the FMEA/FMECA tool users to be aware of the psychological behaviours of FMEA members during the risk evaluation process. Saffaei, *et al*. [9] posit that: "*The first shortcoming is that the RPN elements are not equally weighted concerning one another in terms of risk. As a result, some (S, O, D) scenarios produce RPNs that are lower than other combinations, but potentially dangerous. For example, the scenario (exceedingly high severity, low rate of occurrence, very high detection) with RPN 9X3X2=54 is lower than the scenario (Moderate severity, Moderate rate of occurrence, low detection) with RPN 4X5X6 =120 even though it should have a higher priority for corrective action. The second shortcoming is that the RPN scale itself has some non-intuitive statistical properties. The initial and correct assumption observation that the scale starts at 1 and ends at 1000, often leads to incorrect assumptions about the middle of the scale. Fig. 2 shows the 1000 RPN numbers generated from all possible combinations. Notice that nearly every RPN value is non-unique, some being recycled as many as 24 times*". Figure 2 shows the histogram of RPN numbers.

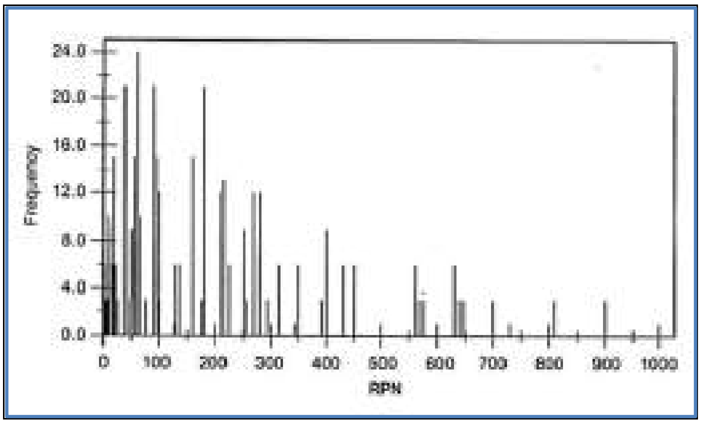

Figure 2: Histogram of RPN numbers, Source: [9].

According to [10], "In traditional FMEA/FMECA, once the causes of critical failures have been identified, they are analysed individually and statically, i.e., without seeing how they evolve. Furthermore, in doing so, the interdependencies between the different failure modes are not considered."

2 RESEARCH OBJECTIVE

The researchers were tasked to explore the benefits of the FMEA/FMECA tool in the industry to make South African industries to be safer and plant performance increase. Hence a need was identified to conduct joint research. This study is based on the articles (52) that were published from 2010 to 2022. Therefore, the main objectives include the following:

- To identify and analyse the range of industries in which FMEA/FMECA methodologies have been applied.
- To examine the specific applications of FMEA/FMECA within different industries and explore their benefits, limitations, and challenges as reported in the literature.

- To assess the trends and evolution of FMEA/FMECA methodologies in the industry over the past two decades, including any notable changes in their application, techniques used, or areas of focus.
- To identify research gaps and areas for future exploration within the field of FMEA/FMECA in industry, based on the findings of the systematic literature review.
- To present a summary of the implications of the systematic literature review findings for industry practitioners, researchers, and policymakers, offering insights into the potential benefits and challenges associated with the application of FMEA/FMECA.

By addressing these research objectives, the systematic literature review can contribute to a deeper understanding of the application of FMEA/FMECA in various industries over the specified timeframe, inform future research directions, and provide practical insights for industry professionals seeking to implement or optimize FMEA/FMECA methodologies.

3 RESEARCH QUESTIONS

Based on the above-mentioned background, a systematic literature review had been espoused to explore FMEA/FMECA research to date. This study strives to provide an answer to the following question:

How is FMEA/FMECA applied in the general industry to contribute to safe and improved plant health?

This will be pursued through the characterisation of the studies (52) by paying attention to the following themes: *RPN research instrument, Industries that applied FMEA/FMECA, Maintenance strategy, Technology applied in determining RPN, Number of experts in the FMEA/FMECA team, Experts experience level, Sources of data to determine RPN, Type of publications and Publication trends* in the studies under review. The outcome of this study shall assist industry practitioners in developing effective maintenance strategies in the future based on the learnings obtained through this systematic literature review.

4 RESEARCH METHODOLOGY

A systematic literature review method was adopted, and google scholar was indexed on the 29th of April 2023 to extract relevant journals, conference papers, theses, and books that applied to the general industry. Then, data were coded and extracted from the manual and included studies to synthesize and appraise the results, describe how the FMEA/FMECA was applied in practice, and highlight any gaps or discrepancies. A total of about 52 FMEA/FMECA articles were mapped in this study. The investigation process made use of an explicit and replicable search strategy, studies were excluded or included, based on the inclusion criteria.

The advantages and disadvantages of this methodology were known; hence research controls were put in place to eliminate bias. This study could explore several FMEA/FMECA cases from various socio-cultural contexts and present a holistic view as its main strength. There were several restrictions to be aware of in addition to its strength, researchers provided country-specific cases that were subject to their interpretation and may be somewhat subjective [11].

5 SEARCH STRATEGY AND SELECTION PROCEDURE

Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) systematic review principles [12]. have been used for assessing and reporting the FMEA/FMECA research data to identify levers that can be used to make South African industries safer and enhance plant performance. The research methodology that was followed is represented in Figure 3 below. The authors made use of the modified PRISMA 2020 for abstracts checklist and in cases where the abstract was not comprehensive, the authors had to review the entire article so that value could be extracted from the selected papers. The search engine made use of the following search string: *FMEA/FMECA case study*. Owing to the lack of structured research in the FMEA/FMECA studies it was rather cumbersome to select the appropriate search words, a total of 52 articles were identified for the systematic review, to select the final articles to be included in this review, a practical screening was conducted, this was based on the setting of inclusion criteria and flow diagram in figure 3.

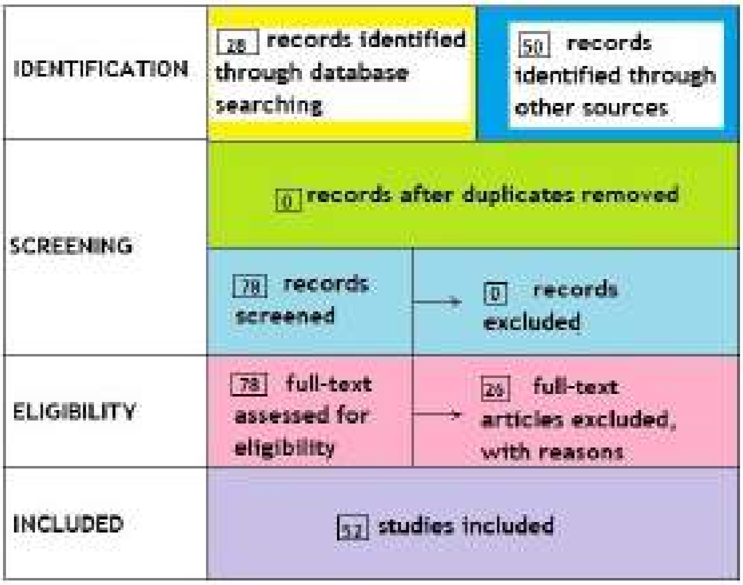

Figure 3:Systematic review flow diagram. Source: Adapted from [12].

6 INCLUSION CRITERIA

The 78 records from the original search were loaded into the Mendeley program. The remaining 52 abstracts and titles were then assessed using the inclusion/exclusion criteria (Table 1 below) after 26 papers were eliminated with reasons (figure 4). Studies were included if they appeared between 2010 and 2022 (Appendix A). The 52 books, theses, journal articles, conference papers, and technical reports were included. This procedure was followed to help the peer reviewers quickly determine whether this study could be easily replicated to boost trust in the research findings.

Table 1: Inclusion criteria

Item	Description
Database searched	Google Scholar and manual search
Date of search	28 April 2023
Person searching	Sello David Koloane and Makhabane Lawson Molapo
Database settings	Open to all areas that had researched FMEA/FMECA case studies in the general industry
Language	English
Timespan	2010-2022
No. of records obtained	52
Search string	"FMEA/FMECA case studies”
Questions	**Review focus**
Population – who?	FMEA/FMECA case studies locally and internationally.

Item	Description
Intervention – what?	FMEA/FMECA case studies that had been duly developed and tested so that the learning could be transferred to the South African industries.
Comparator/s – compared to?	Best FMEA/FMECA case studies with emphasis on achieving safer and higher performing systems.
Outcomes – expected result	Identification of the FMEA/FMECA levers that can be explored and transferred to the industry in general
Time – when?	2010-2022
Setting – where?	In the general industry setup

7 STUDIES SELECTION

The articles for this study underwent a double filtration process, which involved removing the 31 articles that did not match the requirements for inclusion. Using qualitative data analysis, all papers that matched the requirements were examined and coded [13]. Thematic analysis, according to [14], "is a method for identifying, analysing, and reporting patterns (themes) with data." This followed six (6) steps process as outlined in Figure 4 below.

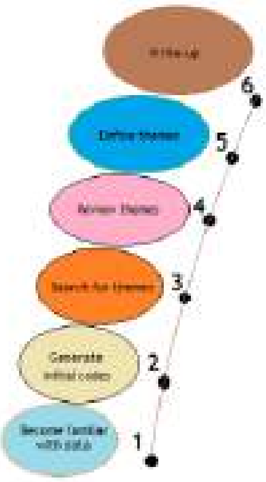

Figure 4:Framework for doing thematic analysis [14]-[15].

Appendix A contains detailed thematic analysis results. This was mainly divided into: *RPN research instrument, Industries that applied FMEA/FMECA, Maintenance strategy, Technology applied in determining RPN, Number of experts in the FMEA/FMECA team, Expert's experience level, Sources of data to determine RPN, Type of publications and Publication trends in the studies under review*. The studies were found to be poorly structured during the application of the systematic literature review and thematic analysis technique, and for this and other reasons, a meta-analysis could not be used because the studies were heterogeneous and did not adhere to PRISMA standards.

8 STUDY CHARACTERISTICS

8.1 The research instrument used to quantify SEVERITY, OCCURRENCE, AND DETECTABILITY – RISK PRIORITY NUMBER (RPN)

RPN is an index that is used to establish the risk of a component or system in FMEA/FMECA studies. The determination of this index is based on several research instruments and the focus of the study under this theme was to establish which tools are commonly applied by the industry.

RPN = SEVERITY X OCCURENCE X DETECTABILITY

A wide variety of instruments were employed in the studies (Appendix A). Analysis results indicate that 59% of the reviews utilized a team of experts and this suggests the importance of expert judgment and knowledge in assessing and quantifying risk factors. Expert input can provide valuable insights and enhance the accuracy of the RPN calculations. It is worth noting that 11% of the articles did not specify any research instrument, lack of this data could result in disputes and future practitioners will be faced with a replication crisis.

The percentages of articles that employed combinations of research instruments are also notable. For example, 2% utilized a team of experts in conjunction with questionnaires, while 2% employed brainstorming and questionnaires. These combinations likely aimed to capture different perspectives and gather a broader range of data to support the risk assessment process. The utilization of other research instruments such as the Delphi technique, experimental data, interviews, observations, and reliability modelling demonstrates the diverse approaches adopted by researchers in quantifying risk factors. These methods provide additional avenues for gathering information and enhancing the accuracy of risk assessments.

A study by [15], titled "Reliability and Validity of Research Instruments" emphasizes the significance of the usage of research instruments in research.

Overall, the distribution of research approaches indicates the flexibility and adaptability of researchers in employing various instruments to quantify severity, occurrence, and detectability. It also highlights the importance of considering multiple sources of data and expert input to ensure comprehensive risk analysis. Figure 5 below depicts the thematic analysis results based on the 52 studies under review.

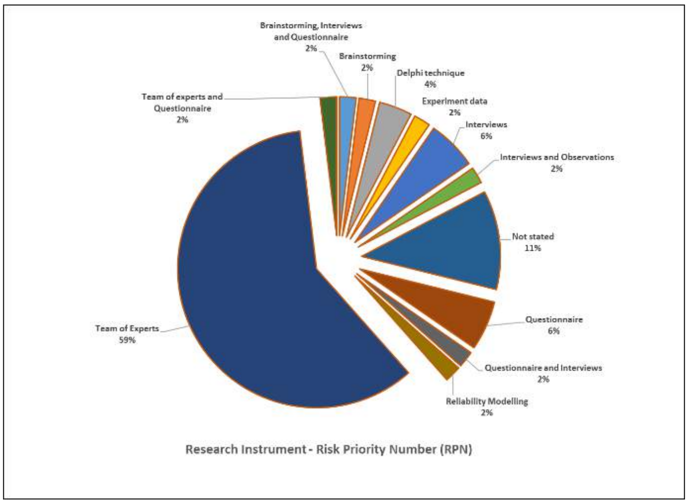

Figure 5: Research Instruments used to quantify RPN.

8.2 Experience level of the experts in the team that scored the Severity (S), Occurrence (O), and Detectability (D).

FMEA/FMECA methodology demands that the experts appointed to the team must have adequate experience to decide on the risk profile of a plant or equipment. A study by [16], titled "Expert System Supporting Failure Mode and Effect Analysis" emphasizes the significance of expertise in FMEA/FMECA, stating that experts' experience can enhance the quality of failure mode identification and evaluation.

Most of the papers (56%) that were systematically reviewed did not indicate the experience level of the panel of experts. This was found to be in contradiction with the safety standards and goals of having a plant with high uptime. On the other hand, 21% of the reviewed papers did provide some information about the experience of the experts. While this is a smaller percentage, it is still beneficial to have some insight into the expertise of the team members. It allows researchers to gauge the qualifications and background of the experts involved, which can help in assessing the validity of their findings. Moreover, the findings suggest that a minority of the reviewed papers (23%) went into detail about the experience of the panelists. This additional level of information is valuable as it provides a more comprehensive understanding of the expertise brought to the analysis. It enables researchers to evaluate the competency and specialization of the panelists, which can enhance the trustworthiness of the study. Overall, it is worth noting that a significant proportion of the reviewed articles did not provide explicit information about the experience levels of the experts in the FMEA/FMECA team. This lack of transparency may be a concern for those seeking to understand the robustness of the analyses conducted. It underscores the importance of clearly documenting and reporting the qualifications and experience of the experts involved to ensure the reliability of FMEA/FMECA studies. Figure 6 displays the experience level of the experts in the reviewed papers.

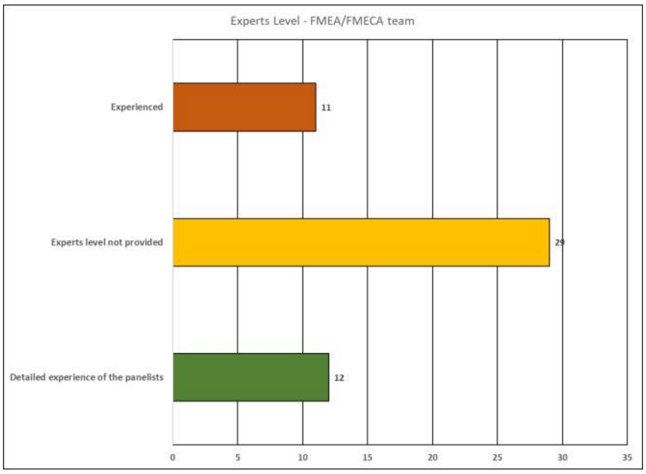

Figure 6: Experience level of the experts in the FMEA/FMECA studies.

8.3 Several experts are involved in quantifying RPN.

The analysis of the number of experts involved in quantifying the Risk Priority Number (RPN) based on the reviewed articles presents an interesting distribution. According to the data, a significant portion of the articles (57%) did not indicate the number of experts involved in the process. This lack of information can be seen as a limitation, as it hampers the understanding of the robustness and reliability of the RPN calculations. Among the articles that did provide information, the distribution of the number of experts varied. The percentages indicate that 7% of the papers reviewed mentioned the involvement of two experts, suggesting a collaborative approach to RPN assessment. Similarly, 6% of the articles indicated the participation of three, four, or five experts, which further supports the notion of a multidisciplinary team contributing to the RPN evaluation. This diversity of expertise helps capture a broader understanding of risks and can lead to more accurate and robust RPN calculations. A study by [17], titled “Evaluation of risk priority number (RPN) in design failure modes and effects analysis (DFMEA) using factor analysis” emphasizes the importance of involving multiple experts to leverage their diverse perspectives and knowledge in quantifying RPN.

Interestingly, a small percentage of the reviewed papers reported many experts involved, such as 2% with twenty-four (24) experts and 2% with thirteen (13) experts. While the reasons behind these large expert panels are not explicitly stated, it could indicate a highly specialized and diverse group brought together to tackle complex or critical systems. Furthermore, the presence of 2% of the papers indicating the involvement of one (1) expert - lack reliability and validity – this was found to be in contradiction with the foundation of the principle of FMEA/FMECA. RPN quantification typically benefits from collaboration and multiple perspectives, so relying on a single expert may introduce bias or limited viewpoints into the analysis.

Overall, the distribution of the number of experts involved in quantifying the RPN, as presented in the reviewed articles, showcases a wide range of scenarios. It highlights the need for transparency in reporting the number of experts involved, as well as the justification for the chosen team size. This information is crucial for researchers to evaluate the reliability and credibility of the RPN calculations performed in FMEA/FMECA studies. Figure 7 below indicates several experts stated by the articles in the study.

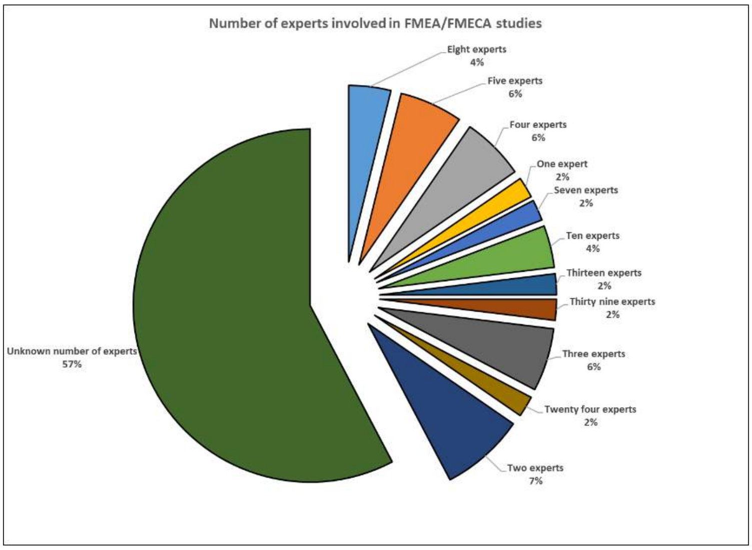

Figure 7: Number of experts involved in the FMEA/FMECA studies under review.

8.4 Maintenance statistics – data source

A popular source (65%) of maintenance data was the plant or equipment database, the chart indicates that a significant proportion of the maintenance data used in the reviewed articles for FMEA and FMECA analysis was sourced from plant or equipment databases. The use of plant or equipment databases can also enhance the accuracy and reliability of the maintenance statistics. Since these databases are often maintained by dedicated maintenance personnel or management systems, the data recorded within are typically standardized, validated, and regularly updated.

Twenty-three (23%) of the reviewed articles did not provide the source of their maintenance data, the absence of source reference for maintenance data within the reviewed articles raises concerns about the credibility of the finding. It becomes difficult for other researchers to verify the accuracy of the data, replicate the analysis, or draw conclusions based on the results. Six (6%) of the reviewed articles obtained their data through experiments, this suggests that a small percentage of the reviewed articles used experimental data as their source of maintenance statistics for FMEA/FMECA. Experimental data can help establish a cause-and-effect relationship between maintenance actions and their effects on system performance.

Two (2%) obtained their data through interviews, observation, and inspection. This indicates that this portion of the research relied on qualitative data obtained through direct interactions observations, and visual inspections. Using interviews, observations, and inspection reports can provide valuable insights into the maintenance practices and their impact on system performance. Two (2%) also suggest that an exceedingly small percentage of the reviewed articles relied on personnel and transportation experiences as a source of maintenance statistics. A computerised FMECA tool called AUTAS has been designed for the aerospace industry [18]. This software is tied to the component's maintenance data library.

Maintenance statistics serve as a crucial data source for organizations in various industries. They provide valuable insights into equipment performance, maintenance activities, and failure patterns, enabling informed decision-making and the optimization of maintenance practices. A research paper by [19], titled "Big data analytics for predictive maintenance in maintenance management". Emphasizes the role of maintenance statistics in continuous improvement and performance monitoring, also in addition a study by [20], titled "Challenges in predictive maintenance – A review". Highlights the importance of maintenance statistics in optimizing maintenance practices and improving operational efficiency. Figure 8 illustrates the distribution of maintenance data sources.

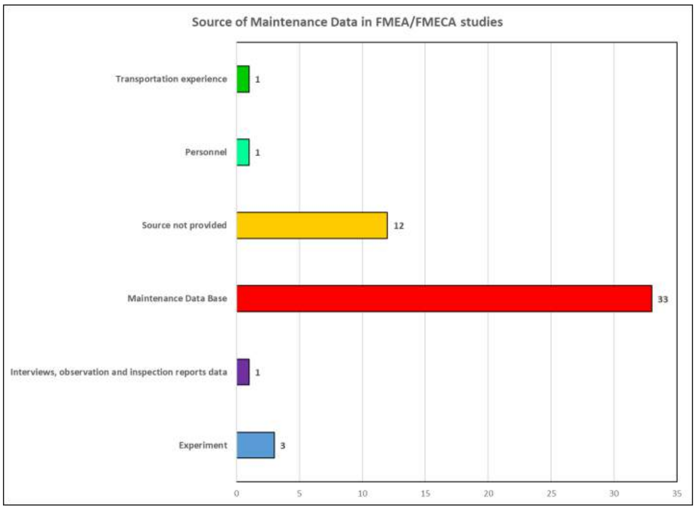

Figure 8: Data sources for the FMEA/FMECA studies under review.

8.5 Type of Maintenance Strategy adopted in the studies.

The chart below provides information on the types of maintenance strategies adopted in the study, along with their respective percentages of usage. The high percentage of preventive maintenance (59%) indicates its wide adoption as a primary maintenance strategy in the study. Preventive maintenance involves regularly scheduled inspections, maintenance tasks, and replacements to prevent failures and maintain equipment or systems in optimal condition. The presence of corrective and preventive maintenance (10%) highlights the recognition of the need for both reactive and proactive maintenance approaches. Corrective maintenance focuses on repairing or restoring failed equipment, while preventive maintenance aims to prevent failures through scheduled maintenance actions. The inclusion of corrective, preventive, and predictive maintenance (11%) indicates a comprehensive maintenance approach that combines reactive, proactive, and predictive techniques.

Predictive maintenance utilizes condition monitoring, data analysis, and predictive models to identify potential failures and schedule maintenance activities accordingly. The utilization of reliability-cantered maintenance (6%) suggests the application of a systematic approach to optimize maintenance strategies based on reliability analysis. This approach prioritizes critical components or failure modes to allocate maintenance resources effectively.

The presence of zero manufacturing defects (8%) suggests a focus on improving production processes and quality control to minimize the occurrence of defects and failures in the first place. This approach emphasizes a proactive and preventive mindset to reduce the need for maintenance. The smaller percentages for cost-efficiency operation (2%), predictive maintenance (2%), and preventative risk in transportation of hazardous substances (2%) indicate a relatively lower presence of these specific maintenance strategies in the study.

In FMEA/FMECA, several types of maintenance strategies can be adopted based on the identified risks and criticality of failure modes. These maintenance strategies aim to prevent or mitigate failures and ensure the reliability and availability of the systems. A study by [21]. titled "Preventive Maintenance (PM) Planning a Review", highlights the importance of the application of maintenance strategies in FMEA/FMECA to manage risks effectively. Figure 9 shows the distribution of maintenance strategies applied in the research.

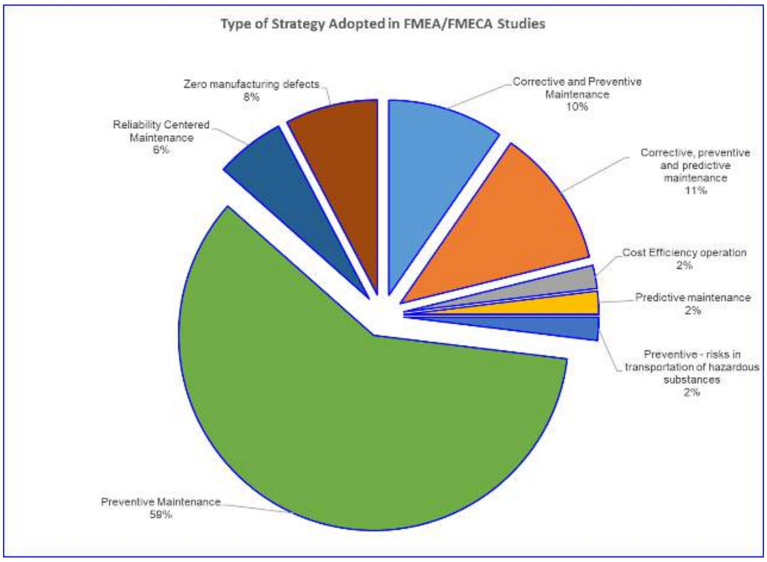

Figure 9: Maintenance Strategies applied in the FMEA/FMECA studies under review.

8.6 Type of scientific techniques used to determine RPN in the studies.

The selection of appropriate techniques for FMEA/FMECA is crucial to ensure accurate and effective risk assessment. Different techniques can be used to support the identification, analysis, and prioritization of failure modes.

The chart provides information on the several types of techniques used for FMEA/FMECA analysis, along with their respective percentages of usage within the study. Manual FMEA/FMECA (56%), Fuzzy FMEA/FMECA (22%) Other FMEA/FMECA methods (2%). The high percentage of manual FMEA/FMECA (56%) indicates that the traditional approach, where experts analyse failure modes and their potential effects manually, is widely employed in the studies. This method involves experts' knowledge and expertise to identify and assess failure modes, their severity, and potential mitigations. The shortfall and benefits of this technique have been covered in the introduction section above [5], [6], [7], [8], and [22].

The significant presence of fuzzy FMEA/FMECA (22%) suggests the utilization of fuzzy logic-based approaches to handle *uncertainty* and *vagueness* in the analysis. Fuzzy FMEA/FMECA incorporates fuzzy sets and fuzzy reasoning to assess the severity of failure modes and the effectiveness of mitigation measures in a more nuanced manner. According to Filz, *et al*. [23], by using historical and operational data as a source of knowledge, data analytics tools are used to predict component-specific failure probabilities [24]. This has been corroborated by Lennard [25], titled "Maintenance Strategy Selection Based on FMEA/FMECA Approach Using Time-Dependent Failure Probability" which highlights the importance of maintenance strategy selection using time-dependent failure probabilities.

The remaining 2% represents the usage of various other FMEA/FMECA methods, including multiple criteria decision-making (MCDM) techniques such as TOPSIS, AHP, VIKOR, and EDAS. These methods provide systematic approaches for decision-making based on multiple criteria.

Additionally, other approaches like the entropy method [26]. Shaeffer evidence theory, rough set theory, system dynamics, and data-driven techniques like Z-Number and grey theory were also employed in the studies (Appendix A).

The inclusion of these diverse methods indicates a recognition of the need for specialized techniques to address specific challenges or incorporate different perspectives in FMEA/FMECA analyses. These methods contribute to enhanced decision-making and provide additional insights into risk assessment and mitigation strategies. It is important to note that the distribution of techniques may vary depending on the specific objectives, industry domains, and the nature of the analysed systems. Researchers may select the appropriate method based on their research goals, available data, and the complexity of the analysed system. In summary, the study demonstrates the use of manual FMEA/FMECA as the predominant technique, with a notable presence of fuzzy FMEA/FMECA and various other specialized methods. This diversity highlights the continuous development and application of different approaches to cater to the specific needs and challenges of FMEA/FMECA analysis. Figure 10 illustrates the type of techniques used by the literature articles.

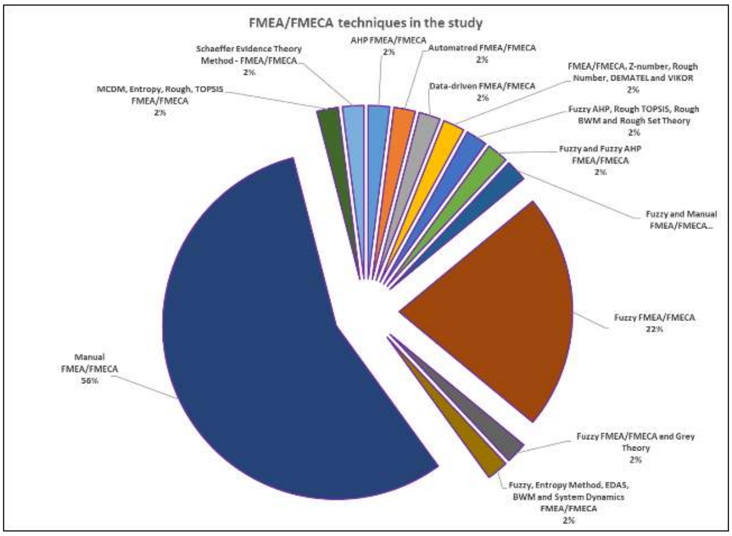

Figure 10: Types of scientific techniques applied to determine RPN.

8.7 Industries that FMEA/FMECA techniques were applied in this study.

The distribution of FMEA/FMECA techniques across different industries reflects the diversity of applications and the relevance of these techniques in addressing failure modes and improving system reliability in various sectors. The high percentage of applications in the aviation industry (36%) and aerospace industry (11%) is not surprising. These industries prioritize safety and have stringent requirements for risk management, making FMEA/FMECA crucial tools for identifying potential failure modes and mitigating their effects. The research paper by [27], titled "An Application of Failure Mode, and Criticality Analysis (FMECA) for Composite Structures of Airplanes' Wings" explores the application of FMECA in assessing risks and developing effective maintenance strategies for composite structures in airplane wings, highlighting the relevance of FMEA/FMECA in the aviation industry.

The presence of manufacturing (11%) and energy (10%) industries also aligns with their focus on operational efficiency and reliability. By applying FMEA/FMECA techniques, these sectors can identify critical failure modes, prioritize maintenance activities, and optimize production processes. The general category (8%) suggests that FMEA/FMECA techniques were applied in a broad range of industries, highlighting their versatility and applicability beyond specific sectors. This further emphasizes the importance of these techniques in various domains. The study by [28], titled "Risk and Reliability Improvement Analysis of Boiler System Using FMECA

Method. Case Study: PLTU Nii Tanasa Kendari" discusses the application of FMEA/FMECA in risk assessment for plant boilers systems, underscoring the importance of FMEA/FMECA in the power generation industry.

The lower percentages for the railway industry (2%), military (2%), information technology (2%), hazardous transportation (2%), health industry (2%), and chemical industry (2%) indicate a relatively smaller presence in the study. Nonetheless, the application of FMEA/FMECA in these sectors underscores the potential benefits of risk systems and reliability analysis in their specific context. The presence of the defense industry, food industry, and automotive industry at 4% each indicates a moderate level of application in these sectors. Figure 11 shows the type of industries where FMEA/FMECA is being applied.

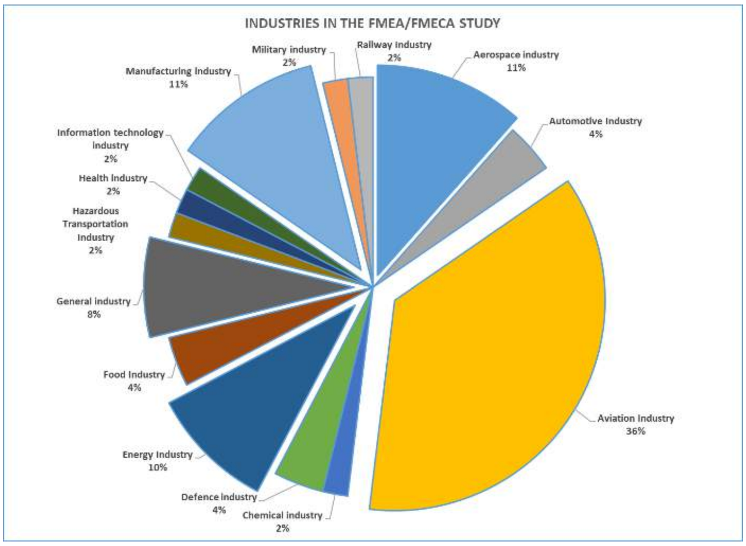

Figure 11:Type of industries that applied FMEA/FMECA in studies.

8.8 Type of publication of the FMEA/FMECA studies.

The high percentage of journal publications (65%) of that FMEA/FMECA research is predominantly disseminated through peer-reviewed journals in this study. Journal publications are often considered a reliable and rigorous form of academic communication. The significant presence of conference papers (23%) indicates that FMEA\FMECA research is also commonly presented and shared at conferences. The inclusion of theses (10%) highlights the contribution of academic research conducted at the graduate level. These often delve into more extensive and in-depth investigations, offering valuable insights and advancing knowledge in the field of FMEA\FMECA. In summary, journal publications dominate the dissemination of FMEA/FMECA research, indicating the emphasis on rigorous peer-reviewed dissemination. Figure 12 indicates the type of publications used for the literature review.

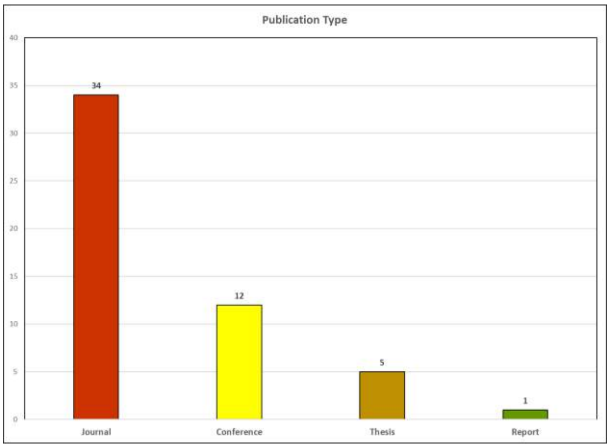

Figure 12:Publication types in the studies under review.

8.9 Several FMEA/FMECA publications per year in the study.

The chart presents the number of FMEA/FMECA publications per year in the study, indicating the publication trends over the specified period. From 2008 to 2011, there was a relatively low number of publications, with only one publication per year. This suggests a limited focus on FMEA/FMECA research during that period. In the subsequent years, from 2012 to 2017, there was a gradual increase in the number of publications per year, with a consistent growth pattern. The number of publications ranged from two to four during this period, indicating a growing interest in FMEA/FMECA research.

In 2018, the number of publications increased to five, further demonstrating the expanding presence of FMEA\FMECA studies in the field. This trend continued in 2019, with seven publications, indicating a significant increase in research activity. In 2020, the number of publications decreased to three, suggesting a possible fluctuation in research output during that year. However, the subsequent year, 2021, saw another peak with seven publications, reflecting a resurgence of research interest.

In 2022, six publications were indicating a sustained level of research activity in the field. Finally, in 2023, there were two publications, which might suggest a relatively lower research output in the early part of that year, although it is important to note that this data point reflects the current year. Overall, the data indicates a growing interest and research activity in the field of FMEA\FMECA from 2008 to 2023, with some fluctuations in publication numbers across different years. This trend suggests an increasing recognition of the importance of FMEA\FMECA in various domains and highlights the ongoing efforts to enhance system reliability and risk management through these techniques [29]. Figure 13 states the number of FMEA\FMECA publications, published per year from 2008 to 2023.

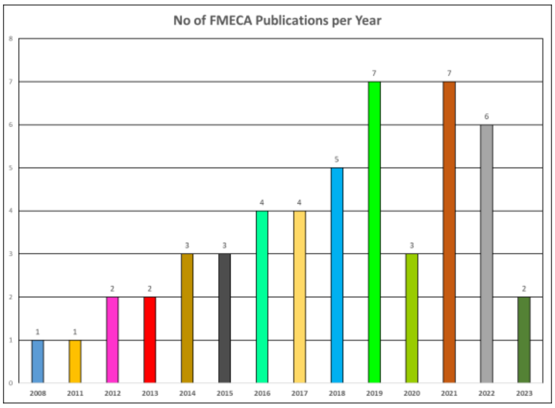

Figure 13: Number of publications in the FMEA\FMECA studies under review.

9 DISCUSSION OF THE REVIEW FINDINGS

Table 2 below provides a summary of the systematic literature review and learnings that are important for the FMEA/FMECA industry practitioners.

Item	**Study findings**	Notes for FMEA/FMECA practitioners to counter FMEA/FMECA replicability crisis and enhance safety and plant uptime.
Research instruments used to establish RPN	System literature review findings indicated that 59% of the studies made use of a team of experts, 6% interviews, 2% reliability modelling, 6% questionnaires, 4% Delphi technique, 2% team experts with a questionnaire, 2% used brainstorming with questionnaires, 2% brainstorming interviews and questionnaires, 2% interviews and observations, 2% experimental data and while the remainder did not mention the instruments used (11 %).	Based on the findings it is evident that practitioners made use of several types of instruments. These instruments have advantages and disadvantages that are covered very well by qualitative research specialists. Practitioners must design their research instruments carefully and ensure that the weaknesses of their chosen instrument are mitigated to produce reliable and valid FMEA/FMECA results. Zhang, et al. [8] cautioned the FMEA/FMECA tool users to be aware of the psychological behaviours of the members during the risk evaluation process. The presence of senior managers could suppress the junior personnel from participating objectively. There is a need to develop a standard for the type of instrument used to establish RPN. The instrument selected should eliminate subjectivity so that the outcome is replicable.
Experience level of the experts in the team that scored the Severity (S), Occurrence (O), and Detectability (D)	FMEA/FMECA methodology used in the industry to appoint the panel of experts under section 8.2 was generally subjective as it did not have scientific criteria to determine the level of experience required. Most of the articles (57%) reviewed through the study did not indicate the experience level of the panelists.	FMEA/FMECA studies must state the experience of the experts if the safety performance and uptime must increase. The lack of this important item compromises the integrity of the study and brings this into disrepute. Panelists must be experienced in the plant under review to qualify to participate in the study and realise enhanced plant safety and uptime in the industry. There is a need to develop and implement standardised criteria for the selection and appointment of a panel of experts so that bias can be minimised.
Number of experts involved in quantifying RPN	Based on the findings (8.3) from the literature review it was observed that the industry did not have a standardised number of experts required to form a panel.	There is a need to establish criteria for the number of experts required in conducting the FMEA/FMECA study. This will aid in enhancing the plant performance and make it easier for FMEA/FMECA industry practitioners to benchmark and transfer learnings.
Maintenance statistics – data source	The outcome of the literature review (8.4) has indicated that most of the FMEA/FMECA studies made use of data that was tapped from the computerised maintenance management system (CMMS). A minority of the studies (23%) did not cite their data sources while 2% obtained through qualitative methods.	There is a need for FMEA/FMECA practitioners in the industry to institute a maintenance data source standard so that the FMEA/FMECA study outcome could be replicable. The use of the CMMS database is the most preferred as it has been based on actual plant maintenance versus other sources. Master data governance controls must be in place for the CMMS to prevent intruders from compromising the data integrity. Data management in the 21st century is crucial as Industry 4.0's success hinges on this foundation. The industry must develop and implement data warehouse standards so that the FMEA/FMECA study is based on data that has integrity to produce replicable results and improve the safety and uptime of the plant.
Type of Maintenance Strategy adopted in the studies	The maintenance strategy foundation was based on the outcome (8.5) of the FMEA/FMECA study and this was found to cover a wide spectrum of the plant strategies. The most strategy that FMEA/FMECA used, was the preventive maintenance strategy. The results obtained	Di Nardo, *et al*. [82] identified this gap and made system dynamics theory to cater for the dynamic relationship between strategy and FMEA/FMECA. There is also a need for the industry to develop plant maintenance strategies that are based on current data so that the FMEA/FMECA study

Item	Study findings	Notes for FMEA/FMECA practitioners to counter FMEA/FMECA replicability crisis and enhance safety and plant uptime.
	through the FMEA/FMECA studies were based on static data, this had shortfalls as the plant risk was continuously changing. Figure 1 indicates that the relationship between FMEA/FMECA study and maintenance strategy must be dynamic.	outcome is also current for the decision-makers to steer the plant in the right direction for a safer and higher uptime.
Type of scientific techniques used to determine RPN in the studies	The majority (56%) of the industry FMEA/FMECA studies made use of manual methodology to determine RPN under section 8.6. This technique is prone to errors as it requires accuracy, speed, multitasking, and high storage capacity. The fuzzy technique (22%) was used as the scientific method for decision-making, this technique can handle uncertainty and vagueness. S, O, and D weights were assumed to be equally distributed and this was incorrect thus affecting the FMECA/FMEA study negatively.	There is a need to increase the adoption of scientific methods so that the FMEA/FMECA studies can produce results that are reliable and valid. Espousal of the Fuzzy FMEA/FMECA technique or equivalent can assist the practitioner to cover a wider scope at a faster pace with high accuracy. The study highlighted that only 2% of the studies had made use of Multiple Criteria Decision-Making (MCDM) techniques hence a need to increase its use if the industry performance must improve. The entropy method was developed by Shannon [26] to distribute the weighting of the S, O, and D scientifically when determining RPN or any similar project. The work of Safaei, *et al*. [9] has demonstrated dangers associated with RPN that the FMEA/FMECA practitioners must avoid when applying this tool. This can be applied by the FMEA/FMECA practitioners in the industry to increase the integrity level of RPN, better safety, and uptime performance of the plant.
In industries, the FMEA/FMECA tool was applied	Most of the studies (47%) were based on the aviation and aerospace industry under section 8.7. This was informed by the research design and the nature of these industries as they have stringent safety requirements. The remainder of the studies covered other industry sectors at smaller percentages such as health, military, chemical, etc.	Application of FMEA/FMECA is to be applied in all industries so that the safety and uptime indicators in the general industry can be enhanced.
Type of publication if the FMEA/FMECA studies	Most of the FMEA/FMECA studies (65%) were published through the Journals as stated in section 8.9. This platform was advantageous as the peer-review mechanism forced the practitioners to apply rigorous scientific methods.	There is a need to subject the FMEA/FMECA studies to a meticulous review to isolate the blind spots that have been identified in this study so that industry safety and uptime targets can be exceeded.
Several FMEA/FMECA publications per year in the study	FMEA/FMECA publications have been increasing since 2008 but during 2022 and 2023 the studies conducted in this field of FMEA/FMECA decreased (8.10). This could be attributed to the research design and sample that lacks the characteristics of the parent.	The systematic literature review design aims at a representative sample and the application of FMEA/FMECA to be intensified and updated regularly so that industry performance can be enhanced.

10 LIMITATIONS

This research was based on the publications between 2010 and 2022. It was conducted with English-speaking lenses and entered the google database. The google database provided the 52 studies, but it might have missed any other significant research that was published elsewhere or in languages other than English. Examples of studies that were overlooked due to the nature of the inclusion criteria include those that were conducted in Sotho, Tswana, Oshiwambo, Damara, Japanese, Chinese, and German among other languages. Future research should therefore be aware of English-based and one-index searches and aim to incorporate studies from regions previously thought to be underrepresented. This could involve looking for FMEA/FMECA literature using alternative techniques and using translation software for non-English studies **[11]**. The abstracts for some of the research were not comprehensive. The writers had to thoroughly evaluate such articles to locate themes of interest because several of the research abstracts were insufficient because they omitted important findings. Due to the possibility of author bias, this study flaw could contribute to the replication issue **[30]**.

11 CONCLUSION

While FMEA/FMECA is a valuable tool for identifying and assessing potential risks in a system, it has certain limitations and disadvantages. The traditional RPN approach used in FMEA/FMECA suffers from shortcomings such as equal weighting of elements, subjective perceptions from analysts, and the inability to accurately quantify risk factors. One major drawback is the reliance on the RPN, which is determined by the product of Severity (S), Occurrence (O), and Detectability (D). The use of RPNs to evaluate risk factors has been criticized due to the equal weighting of elements, high duplication rate, and lack of consideration for subjective perceptions. This can lead to inaccuracies in the analysis results. Furthermore, this method often does not encompass the entire range of causal risk elements, and the measurement of severity (S), occurrence (O), and detectability (D) lacks holistic characterisation and can be subjective.

The reliance on qualitative risk assessment methods introduces subjectivity and uncertainty, which can vary depending on the perceptions of the individuals conducting the analysis. To overcome these limitations, researchers have proposed various risk priority models and techniques that aim to manage uncertainty, imprecision, and subjective perceptions more effectively. Qualitative risk assessment methods, although useful, may not yield consistent results and are dependent on the perceptions of the evaluators. The integration of mathematical tools and data analytics into the FMEA framework has shown promise in improving risk assessment by providing objective estimations and reducing subjectivity. Additionally, the advent of Industry 4.0 and the use of data analytics tools offer opportunities to enhance this technique by utilizing historical and operational data for predicting failure probabilities and making risk assessments less subjective. In conclusion, while FMEA/FMECA is a widely used and valuable technique for risk management, it is important to recognize its limitations (see Table 2 above) and consider alternative approaches to improve its effectiveness so that plant safety and uptime can be enhanced. Future research and advancements in the field can lead to more robust and accurate methods for identifying and mitigating risks in various industries.

12 COMPETING INTERESTS

The authors declare that they did not have competing interests.

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14 APPENDIX A – FMEA/FMECA STUDIES THEMES OF INTEREST

ID	Author(s)	Industry sector	Research instrument in RPN	Experts Level	Number of experts	Source of data	Maintenance Strategy	Technology applied in FMECA	Type of publication
A1	Fateme Dinmohammadi, Babakalli Alkali, Mahmood Shafiee, Christophe Be´renguer, and Ashraf Labib (2015)	Railway Industry	Delphi technique	academics, maintenance engineers with 15 years of experience, 1 OEM designer, and 1 consultant	8	Equinox and DATASYS BUGLE software. TRUST database	Preventive Maintenance	Manual	Journal Urban Rail Transit
A2	Gajanand Gupta, Hamed Ghasemian and Ayub Ahmed Janvekar (2017)	General Industry	Team of experts	None	10	None	Preventive Maintenance	FMECA model based on fuzzy logic and Dempster-Shafer theory (D-S theory)	Journal of Engineering Failure Analysis
A3	Marsetio, A., Octavian, A., Ahmadi, Siswo Hadi Sumantri , Rajab Ritonga and Yusnaldi (2017)	Military industry	FMECA Questionnaire Result Data Calculation	HOD electronic workshop. TECHNICAL DIRECTOR.	2	None	Preventive Maintenance	Application of Fuzzy and TOPSIS method of FMEA. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS).	International Journal of Future Generation Communication and Networking
A4	A Adel, R Ahmad, A M Badiea and S A Mustafa (2023).	General Industry	Team of experts	None	None	Plant maintenance records.	Preventive Maintenance	Manual and MATLAB fuzzy logic toolbox	AIP Conference Proceedings 2544, 040039 (2023)
A5	Shanfeng Zhang, Mengwei Li , Haiyan Zheng and Ruili Zhang (2015)	Aviation Industry	Team of experts	Professional and technical experts	4	2009-2011	Preventive Maintenance	Fuzzy logic in FMEA AND FMECA	International Conference on Information Sciences, Machinery, Materials, and Energy
A6	Qiang Wang, Ruicong Xia, Qiuhan Liu and Qiuping Hu (2020)	Aviation Industry	An experiment was done using the Drop hammer impact test machine in the laboratory.	None	None	Experiment to confirm the criticality of impact failure both low and high energy impact.	Preventive Maintenance	Manual	IOP Conference Series: Materials Science and Engineering
A7	Nurul Ain Ahmad, Shaza Sheran, Rosmaini Ahmad and Noorhafiza Muhammad (2014)	Automotive Industry	Interviews of management	None	None	2012 to 2013 in a factory manufacturing seals.	Zero manufacturing defects	Manual	8th MUCET conference
A8	Ranintia Adhi Citra Pramesti; Bambang Purwanggono and Arfan Bakhtiar (2016)	Manufacturing industry	Interviews	None	None	Interviews, observation, and inspection reports data	Cost Efficiency operation	The analytic Hierarchy Process (AHP) technique was applied. The analytic Hierarchy Process (AHP) method is a basic approach in the decision-making process whose goal is to determine the optimum alternative to certain criteria.	Ind. Eng. Online J

ID	Author(s)	Industry sector	Research instrument in RPN	Experts Level	Number of experts	Source of data	Maintenance Strategy	Technology applied in FMECA	Type of publication
A9	Iing Pamungkas and Isdaryanto Iskandar (2022)	Manufacturing industry	Interviews, observations	None	None	Primary data and secondary data. July 2021 to March 2022	Zero manufacturing defects	Manual and fishbone techniques	International Journal of Innovative Science and Research Technology
A10	Yoong-Tae Byeon, Dong-Jin Kim, Jin-O Kim (2008)	Electrical Industry	Delphi technique	Doctor, Master, and Bachelor	10	None	Preventive Maintenance	Fuzzy expert system	AIP Conference Proceedings 1052
A11	S.Nabdi and B.Herrou (2016)	General Industry	Team of experts	Decision makers in maintenance (managers)	None	None	Preventive Maintenance	Manual	International Journal of Advanced Information Science and Technology
A12	El-Arkam Mechhoud, Riad Bendib and Youcef Zennir (2020)	Energy Industry	None	None	None	History of the plant	Preventive Maintenance	Matlab was used to develop the program - Automated technique for FMECA.	ALGERIAN JOURNAL OF SIGNALS AND SYSTEMS
A13	Mukadder Nur Tanyeri (2019)	Aviation Industry	Team of experts	Structured PFMEA team - Brainstorming method and experience-based knowledge. Moderator, Facilitator, Specialists, and Suppliers.	None but it is more than 1	Past data, Experiences, customer feedback, and reports.	Preventive Maintenance	Manual	MSc Eng Thesis
A14	Huai-Wei Lo , James J. H. Liou , Jen-Jen Yang, Chun-Nen Huang and Yu-Hsuan Lu (2021)	Energy Industry	A questionnaire, interviews,	Professors, Nuclear engineers, analysts, and government regulators. Each analyst had a minimum of 10 years of experience.	24	None	Preventive Maintenance	Multiple-criteria decision-making (MCDM). Entropy-based rough FMEA technique. TOPSIS technique.	Hindawi Complexity Journal
A15	Yahya El Osman El Dandach (2017)	Aviation Industry	Questionnaire for AHP	Ph.D. (1), M.Eng (8), B.Eng (21), and Diploma (5)	39	History of the aircraft	Preventive Maintenance	Fuzzy FMEA. Technique for Order of Preference by Similarity to Ideal Solution -TOPSIS	M.Eng Thesis
A16	Hengjie Zhang , Yucheng Dong , Ivan Palomares-Carrascosa and Haiwei Zhou (2018)	Aviation Industry	Interview	Team of experts. *Real-world FMEA problems involve not only mathematical aspects but also the psychological behaviors of FMEA members. We argue that it will be interesting to investigate the psychological behaviors of FMEA members in the process of reaching a consensus on FMEA problems.*	3	None	Preventive Maintenance	An interactive model for reaching consensus is developed to generate consensual FM risk classes. This study uses the possibilistic of a hesitant fuzzy linguistic approach to address linguistic assessment information from FMEA team members.	IEEE Transactions on Reliability Journal
A17	Jiri Hlinkaa, Rostislav Kostiala, Michaela Horpatzkaa (2021)	Aviation Industry	None	None	None	None	Preventive Maintenance	Fuzzy logic in FMEA AND FMECA	Eksploatacja I Niezawodnosc - Maintenance and Reliability Journal

ID	Author(s)	Industry sector	Research instrument in RPN	Experts Level	Number of experts	Source of data	Maintenance Strategy	Technology applied in FMECA	Type of publication
A18	J. A. L. Anjalee, V. Rutter, and N. R. Samaranayake (2021)	Health industry	Brainstorming. Interviews. Questionnaire	Pharmacists (teams A and B). Facilitator. Graduate pharmacist, Senior (10 years exp.), Junior.	13	Data was collected from August to October 2018. Outpatients were the candidates.	Zero medication dispensing defects	MANUAL	BMC Public Health Journal
A19	M. Dudek-Burlikowska (2011)	Manufacturing industry	Brainstorming.	Chief Technologist, Production Manager, Main Mechanics, Quality Manager	8	Company records	Zero manufacturing defects	MANUAL	Journal of Achievements in Materials and Manufacturing Engineering
A20	Justin Francis C. Victoria, Yogi Tri Prasetyo, Thanatorn Chuenyindee, Satria Fadil Persada and Reny Nadlifatin (2023)	Aviation Industry	Team of experts	None	None	Maintenance records. MIREPS. PIREPS. CAMP.	Preventive Maintenance	MANUAL	The 8th International Conference on Industrial and Business Engineering (ICIBE 2022)
A21	Marc-André Filz, Jonas Ernst Bernhard Langner, Christoph Herrmann, and Sebastian Thiede (2021)	Aviation Industry	Team of experts	None	None	Historical and operational data. Severity (S) and Detective (D) factors are obtained through a team of experts for RPN.	Predictive maintenance	Deep learning models on historical and operational data. Data-driven FMEA methodology. Occurrence is the only factor in the RPN that is data driven.	Computers in Industry Journal
A22	Hamed Ghasemian and Qasim Zeeshan (2017)	Aviation Industry	Team of experts	None	None	Maintenance history data AND experience of workers	Corrective, preventive, and predictive maintenance	Fuzzy Risk Priority Ranking (FRPR)	International Journal of Soft Computing and Engineering (IJSCE)
A23	Hamed Ghasemian (2017)	Energy Industry	Team of experts	None	3	Maintenance history data AND experience of workers	Corrective, preventive, and predictive maintenance	Manual and fuzzy technique. Matlab software. Simulink for fuzzy RPN model.	MSc Eng Thesis
A24	Heshmat Mohammad Khanlo and Ali Mohammad Mahmodi Kohan (2022)	Aviation Industry	Team of experts. Questionnaire.	Two master's degrees and one diploma and one bachelor's degree	Four (4). Evidence theory is used as a tool to analyze uncertainty in inaccurate probability theory	Maintenance history data AND experience of workers	Preventive maintenance	Scheffer Evidence Theory Method. Dempster-Schaefer's theory of evidence attempts to reduce uncertainty as much as possible, through which qualitative and quantitative information on a particular subject is controlled and model outputs can be evaluated and controlled.	IJRRS journal
A25	Mohamed Haykal Ammar, Mounir Benaissa AND Habib Chabchoub (2014)	Hazardous Transportation Industry	Team of experts	Lead manager, Deputy general manager, Central manager, and Two safety officers.	5	Transportation experience.	Prevention of criticalities in transport	Manual	International Conference on Advanced Logistics and Transport

ID	Author(s)	Industry sector	Research instrument in RPN	Experts Level	Number of experts	Source of data	Maintenance Strategy	Technology applied in FMECA	Type of publication
A26	M. Bevilacqua, F. E. Ciarapica; L. Postacchini and G. Mazzuto (2013)	Energy Industry	Team of experts	None	None	Maintenance history data AND experience of workers	Corrective, preventive, and predictive maintenance	Grey relation analysis and Manual	Proceedings of the 19th ISSAT International Conference on Reliability and Quality in Design
A27	K. R. Aswin, V. R. Renjith, and K. R. Akshay (2022)	Chemical industry	Team of experts	None	None	None	Corrective, preventive, and predictive maintenance	Fuzzy-FMECA (Matlab) and grey theory	International Journal of System Assurance Engineering and Management,
A28	Castellano Luca (2019)	Food Industry	Team of experts	None	None	Personnel	Corrective, preventive, and predictive maintenance	Manual	PhD thesis, ING - Scuola di Ingegneria Industriale e dell'Informazione
A29	Ahmed Tijjani Dahiru (2014)	Manufacturing industry	None	None	None	None	Corrective, preventive, and predictive maintenance	ELECTRACE - computerised software FMECA	IJCRR Journal
A30	Huai-Wei Lo, James J.H. Liou, Chun-Nen Huang, and Yen-Ching Chuang (2019)	Manufacturing industry	Team of experts	Production management, Production technology, Research and development, Business, and Quality with more than 20 years of experience.	7	None	Corrective and preventive	Hybrid FMEA (Fuzzy AHP) multi-criteria group decision-making (MCGDM), Rough-TOPSIS, Rough-BWM, and rough set theory.	Reliability Engineering and System Safety Journal
A31	Sahand Daneshvar,Mohammad Yazdi, Kehinde A. Adesina (2019)	Aviation	Team of Experts	Safety engineers with Meng and 15 years, Academic staff with Ph.D. and 10 years experience, and Engineers with 20 years experience with BSc degree.	3	DEA (Data Envelopment Analysis)	Preventative Maintenance	Fuzzy FMECA, Fuzzy Analytic Hierarchy Process (FAHP) for experts' evaluation.	Quality Reliability Engineering International Journal
A32	Li Jun and Xu Huibin (2012)	Aviation	Reliability Modelling	None	None	Maintenance database GJB/Z299-91	Preventative Maintenance	Manual FMECA	2012 International Conference on Solid-State Devices and Materials Science
A33	Han-Ning, Wu Guoqing, Xia-Mingfei, and Wang Xiaocong (2015)	Aviation	Team of Experts	None	None	SOD Database	Preventative Maintenance	Fuzzy FMECA	5th International Conference on Information Engineering for Mechanics and Materials (ICIMM 2015)
A34	Ceren ÜnlükaL and Mustafa Yücel (2021)	Aviation	Team of Experts	Quality Engineers, Experienced	2	Maintenance Data Base	Corrective and Preventative Maintenance	Intuitionistic Fuzzy Topsis Logic Approach FMECA	Dumlupinar University Journal of Social Sciences
A35	James Joseph, Sriram. K. V, Asish Oommen Mathew, and Arjun Kanoor (2019)	Aerospace	Team of Experts	Trained Engineers	2	Plant Maintenance History	Preventative Maintenance	Process Failure Mode and Effects Analysis (PFMEA)	International Journal of Mechanical and Production Engineering
A36	Vitor Anes, Teresa Morgado, António Abreu, João Calado, and Luis Reis (2022)	Aviation	Team of Experts	Trained Engineers	None	Plant Maintenance History	Preventative Maintenance	Qualitative Model Coupled with FMECA	Journal Applied Science

ID	Author(s)	Industry sector	Research instrument in RPN	Experts Level	Number of experts	Source of data	Maintenance Strategy	Technology applied in FMECA	Type of publication
A37	Zhen Wang, Rongxi Wang, Wei Deng, and Yong Zhao (2021)	Manufacturing	Team of Experts	Experienced	4	Plant Maintenance History	Preventative Maintenance	Integrated Approach-Based FMECA, Z-number, rough number, DEMATEL Method and VIKOR	Journal Energies
A38	Mahendra Prasad (2012)	Defence	Questionnaire	None	None	System Fault Analysis Register	Corrective, Preventative, and Condition-based Maintenance	Manual FMECA	IDSA Report
A39	Cheng-Min Feng and Chi-Chun Chung (2013)	Aviation	Team of Experts	One Airline Practitioner, OneFlyer, and Three Government Officials.	5	International Civil Aviation Organization (ICAO) aviation accidents	Preventative Maintenance	Fuzzy FMECA	Mathematical Problems in Engineering Journal
A40	Federica Bonfante, Matteo D. L. Dalla Vedova, and Paolo Maggiore (2018)	Aviation	None	None	None	None	Preventative Maintenance	FMECA and FTA	MATEC Web of Conferences 233, 00002 (2018)
A41	A. D. I. Bandono, O. S. Suharyo, and Riono (2019)	Military	Team of Experts	None	None	Plant Maintenance History	Preventative Maintenance	Fuzzy FMECA	Journal of Theoretical and Applied Information Technology
A42	Enrico Petritoli, Fabio Leccese,and Lorenzo Ciani (2018)	Aviation	None	None	None	Experiment	Preventive Maintenance	Reliability and Maintenance	Sensors Journal
A43	Wang Kun (2018)	Aerospace & Defence	None	None	None	Plant Maintenance History	Preventive and Corrective Maintenance	Manual FMECA	International Conference on Advanced Engineering and Technology (4th ICAET)
A44	Petru-Eduart Dodu (2014)	Military Aviation	Team of Experts	None	None	Plant Maintenance History	Preventive and Corrective Maintenance	Manual FMECA	UPB Scientific Bulletin
A45	Marc Banghart, Kari Babski-Reeves, Linkan Bian, and Lesley Strawderman (2018)	Aeronautics and Aerospace	Team of Experts	Experienced	None	Plant Maintenance History	Reliability Centered Maintenance	Manual FMECA	International Journal of Aviation, Aeronautics, and Aerospace
A46	Darli Rodrigues Vieira, Mohamed-Larbi Rebaiaia, and Milena Chang Chain (2016)	Aerospace	Team of Experts	None	None	None	Reliability Centered Maintenance	Manual FMECA	American Journal of Industrial and Business Management
A47	Hengameh Fakhravar (2020)	Aerospace	Team of Experts	None	None	Plant Maintenance History	Preventative Maintenance	Manual FMECA	Thesis
A48	Wirnkar Basil Nsanyuy, Chu Donatus Iweh, Nde Donatus Nguti, Felix Nkellefack Tapang and Emmanuel Tanyi (2022)	Information technology	Team of Experts	None	None	Plant Maintenance History	Prentative Maintenance	Manual FMECA	International Journal of Engineering Trends and Technology
A49	Rim Bakhat, Chaimaa Bentaher, and Soumaya Aharouay (2021)	Aerospace Engineering	Team of Experts	Highly Experienced Experts with many years of experience in the aerospace industry	5	Experiment	Preventive maintenance	Manual FMECA	Journal of Integrated Studies in Economics, Law, Technical Sciences & Communication
A50	Tamer M. El-Dogdog, Ahmed M. El-Assal, Islam H. Abdel-Aziz, and Ahmed A. El-Betar (2016)	General Industry	Team of Experts	None	None	Plant Maintenance History	Preventive Maintenance and Reliability-centered Maintenance	FMECA and Fishbone Technique	International Journal of Innovative Research in Science, Engineering, and Technology

ID	Author(s)	Industry sector	Research instrument in RPN	Experts Level	Number of experts	Source of data	Maintenance Strategy	Technology applied in FMECA	Type of publication
A51	Mario Di Nardo, Teresa Murino, Gianluca Osteria, and Liberatina Carmela Santillo (2022)	Agricultural Industry	Team of Experts	Experienced	None	Plant Maintenance History	Preventative Maintenance	Fuzzy FMECA, Entropy (Weights), EDAS (Ranking method used to rank critical issues), BWM (Best Worst Method), and System Dynamics (Criticality Analysis)	Applied System Innovation Journal
A52	I. BenBrahim, Sid-AliAddouche, A.ElMhamedi, and Y.Boujelbene (2019)	Automotive	Team of Experts	None	1	None	Preventative Maintenance	Manual FMECA	International Federation of Automatic Control Journal

A META MODEL FOR ENTERPRISE SYSTEMS DYNAMICS: REDUCING MODEL AMBIGUITY

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ABSTRACT

Three complementary knowledge areas developed concurrently during the last two decades. Performance measurement (PM) focuses on systems control. Systems dynamics (SD) addresses time delays, cause-and-effect behaviour and structural interventions, whereas Enterprise engineering (EE) acknowledges both the functional and structural aspects of enterprises to guide the re-design of structural design domains in a coherent way, focusing less on PM. A popular SD-associated conceptual model, i.e. the causal-loop diagram (CLD) is useful to represent PM and EE concepts together on one diagram, to better understand an observed phenomenon. However, a critical analysis of CLD instances indicates inconsistent use of concepts that impairs diagram interpretation and conversion of the CLD into a stock-and-flow diagram (SFD). We use an ontology specification language to provide more precise definitions for concepts that are used for a combined CLD and SFD, called a causal loop stock flow diagram, also relating some concepts to equivalents in EE.

Keywords: systems dynamics, general ontology specification language, causal loop diagram, stock and flow diagram

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1 INTRODUCTION AND PROBLEM DEFINITION

Performance measurement (PM) systems developed into an important strategic management tool to control processes in an enterprise [1]. Although PM systems evolved to include both financial and non-financial measures, little empirical evidence exists to indicate that these advancements have led to measurable improvements in organizational performance [2]. One of the possible reasons for the lack of success in implementing PM systems is that enterprises have increased in complexity that require complex problem solving [3] and that PM systems fail to capture system complexity, such as time delays, and cause-and-effect behaviours, needed for dynamic performance management [4].

Systems dynamics (SD) is an approach to understand the nonlinear behaviour of complex systems over time, using concepts such as stocks, flows, internal feedback loops and time delays [5, 6]. Since SD modelling helps to *understand* both functions and behaviour [7], the models assist in understanding counterintuitive behaviours of a complex system, identifying leverage points to intervene in a system [8].

The discipline of *enterprise engineering* (EE), multi-disciplinary in nature [9], was founded in 2013 as a means to create scientific rigor in developing and testing theories within enterprise engineering, contributing towards a sound body of knowledge in EE [10]. Whereas PM focuses on measures that are useful to management to assess enterprise performance [1], EE identifies alternative ways and initiatives to improve existing performance, often changing the design of multiple design domains [11]. One of the knowledge areas within EE, called *enterprise architecture* (EA), provides "a coherent and consistent set of principles that guide enterprise design" [12, p. 314]. Although the principles assist in creating a coherent enterprise design, enterprises pose high conditions of uncertainty that require additional mechanisms to know "what to do" to improve existing performance [12].

SD has the potential to provide a systematic understanding of system behaviour to direct attention on "what to do" in (re)designing the enterprise. Researchers are already exploring the possibility of using SD in combination with EE [13, 14], using SD's simulation capabilities to support decision-making. Used in combination, SD and EE can become the missing piece of the enterprise solution puzzle.

When different disciplines, e.g. PM, EE (including EA) and SD, each with their own set of concepts, need to be integrated, additional techniques for model abstraction may be required, as demonstrated by Guizzardi et al. [15]. Danesh et al. [16] suggest a meta-model to unite concepts that are required to design enterprise capabilities and services, indicating that concepts-in-use need to support the entire enterprise design cycle.

A popular SD-associated conceptual model, i.e. the causal-loop diagram (CLD) may be useful to include EE concepts to better understand an observed phenomenon. However, since concepts within the different disciplines developed within different research communities, concepts may not be well-aligned in terms of their meaning. CLDs are also ambiguous, lack detail and are difficult to conceptualize [17-20].

Since CLDs are converted to stock-and-flow diagrams (SFDs) where facets in SLDs need to be quantifiable to enable quantitative simulation and prediction, informing enterprise interventions [21], conceptual clarification will improve the quality of the CLDs, the derived SFDs and therefore also the credibility of the simulation results. Binder *et al*. [18] suggest that a *structured CLD*, that we label *causal loop stock and flow diagram* (CLSFD), should already reflect the more specialised concepts of SFDs. We support this view in our article, since an early identification of stocks also removes some of the ambiguity inherent in CLDs.

One example of ambiguity evident in the CLD, is the use of polarity. Sterman [22] indicates that a causal link with *negative* polarity on a CLD can be interpreted in two ways: 1) All else equal, if X increases, then Y *decreases* above what it would have been; 2) In the case of decumulations X *subtracts from* Y. Accumulations and decumulations indicate the existence of *stock* facets on a stock flow diagram. Conceptually, when a different *type of entity* has been identified, we believe that the symbolism on a diagram should already reflect the different *type* of entity. When stock and flow concepts are *not* distinguished during SD analyses, especially where the physical flow of products exist, a representation of *conservation of material* in the stock and flow chain is lost [22].

Based on the premise that EE may be informed by SD to support better decision-making on where to focus actions, interventions and re-design efforts, we suggest that the use of the *general ontology specification language* (GOSL), can provide additional clarity on the concepts that are used in SD. The SD-associated diagram, the CLD already includes concepts that feature within the EE discipline, but EE offers further specialisation on some of the concepts. Our research question is therefor as follows:

What meta model for enterprise systems dynamics can be developed, also relating SD concepts to EE concepts, using the general ontology specification language (GOSL)?

Answering the research question, this article is structured as follows. Section 2 provides background about conceptual modelling (CM), phenomena addressed by CM, and the use of CM within enterprise engineering. Section 3 introduces related work on translating concepts between modelling languages, and the possibility of using the general ontology specification language (GOSL) to unite SD with EE. Section 4 presents both the *method* that we used in developing a *meta model for enterprise systems dynamics* (MMESD), as well as the MMESD itself, expressed in GOSL, whereas section 5 validates the MMESD by generating an instantiation of a MMESD to produce a *causal loop stock and flow diagram* (CLSFD). Finally, section 6 presents conclusions and ideas for future research.

2 CONCEPTUAL MODELLING

Conceptual modelling (CM) is primarily associated with information system development as a means of communication to capture user requirements and facts about an application domain [23, 24]. CM research is about the study of finding more suitable forms of abstraction to aid with effective software construction [25]. Some of the prominent themes that underlies CM, is theories of *concepts and ontologies* and techniques for transforming conceptual models into effective implementations [26]. Ontology is a cross-cutting knowledge area that involves multi-disciplinary teams to express the fundamental nature of being [26, 27], using appropriate concepts [28].

2.1 Phenomena addressed by conceptual modelling

Although CM is used primarily during software development during database design and software requirements modelling [29], conceptual models are also used to communicate concepts when human beings need to express the design or re-design of enterprise design domains via enterprise models [30, 31]. Verdonck and Gailly [32] identified three broad perspectives to structure phenomena that are addressed by CM, summarized in Table 1.

Table 1: Three perspectives to structure phenomena addressed by CM

Perspective	Description
Static perspective	The focus is on describing the structure of a system, using constructs named entity, thing or object where an entity is uniquely identified and entities are connected through a variety of relationships.
Dynamic perspective	Due to goals and intentions, the focus is on describing phenomena that represent change and time, e.g. describing events and processes, where a process is a trace of events during

Perspective	Description
	the existence of an entity. Models that represent the *dynamics* of a domain, use concepts, such as events, activities and gateways [33, 34].
Behaviour and function perspective (*Agent-goal perspective*)	This perspective includes social phenomena where actors have goals. Actors collaborate in transforming an existing state into a future state or set of phenomena. In this article, we will refer to the *agent-goal perspective*, focusing specifically on human agent behaviour and function concepts, such as goals/desires/objectives, as well as values and intentions, communicated via performance areas [35, 36].

Although the discipline of systems dynamics (SD) acknowledges the *dynamic behaviours* of systems, represented by diagrams, such as causal-loop diagrams and stock-and-flow diagrams, SD conceptual models emerged from a systems engineering community, rather than the conceptual modelling community. Although the German conceptual modelling community is active in conceptual modelling that relates to information systems, modelling the dynamics of more generic systems, are not prominent within the active German conceptual modelling community [37].

2.2 Conceptual modelling in enterprise engineering

Several examples exist of using conceptual modelling within different domains, including the *enterprise engineering* (EE) domain, where the use of the ontology-driven conceptual modelling language, OntoUML, is growing [32, 38]. Acknowledging the emergence of multiple modelling languages the Unified Enterprise Modelling Language (UEML) connects *enterprise modelling* and *information systems modelling* constructs by providing a common ontology to interrelate construct descriptions at the semantic level, defining a core language for enterprise and information system (IS) modelling [39]. The UEML focuses on describing *“the semantics of modelling constructs*” [39, p. 102] and the meta-meta model includes classes such as “language” and “diagram type”. Hence the ontology already includes entities that are *specific* to concepts that are related to *model* constructs.

Within *enterprise engineering* (EE), modelling languages are still emerging, notably the mature language called DEMOSL (Design and Engineering Methodology for Organization Specification Language) [30, 40] that relate to the *dynamic perspective* and *static perspective* of Table 1. DEMOSL is useful to represent the essence of enterprise operation to include both the process model regarding the dynamic perspective, i.e. the ontological model of the state space and transition space of its *coordination world*, and the fact model regarding the static perspective of its *production world* [41]. EE concepts that relate to the *agent-goal perspective*, as evident in the Teleology, Affordance, Ontology (TAO) theory, also emerge within the EE body of knowledge [12, 42].

SD models do not represent the detailed construction of enterprise operation, but rather aim at simulating the dynamic behaviour of a system over time, including the *agent-goal perspective*, where human agents drive goals/desires, related to performance areas, often called *key* performance areas. Focusing on only key performance areas, human agents may induce counter-intuitive behaviours within the enterprise system, reducing the effectiveness of well-intended enterprise change initiatives [9].

3 RELATED WORK ON TRANSLATING CONCEPTS BETWEEN MODELLING LANGUAGES

Some researchers already identified the need to translate concepts from enterprise architecture (EA) languages into SD concepts. For instance, Roychoudhury *et al.’s* [43] metamodel of SD is based on the assumption that EA concepts, extracted from ArchiMate-based concepts are comprehensive, classifying EA concepts in accordance with the business layer metamodel of ArchiMate [44], as active structure concepts (i.e. the *agent-goal* *perspective* in Table 1), behavioural concepts (i.e. the *dynamic perspective* in Table 1) and passive structure concepts (i.e. the *static perspective* Table 1). Although [43] presented a metamodel of systems dynamics, using Archimate concepts within a UML class diagram, the model excludes essential SD concepts, such as *link polarity*.

We reason that SD concepts should only be related or linked to EE concepts, *once SD concepts are well-defined*, using a more abstract language, that has the ability of expressing concepts that exist within a wide range of knowledge domains. Section 3.1 introduces *ontology specification languages* in general, followed by one instance of an ontology specification language, called the *general ontology specification language* (GOSL).

3.1 Ontology specification languages

Guarino [27, p. 9] indicates that an "*ontology is just a set of such axioms, i.e., a logical theory designed in order to capture the intended models corresponding to a certain conceptualization and to exclude the unintended ones*". Thus, an approximate specification of a conceptualisation will help to capture *intended models* and exclude *non-intended* models [27]. An ontology specification language is thus a *general* specification language to express conceptual schemas, whereas each conceptual schema will be used to capture only intended models, i.e. a particular perspective as an approximation of the real world. Ontological specification languages differ in their expressiveness, where informal approaches, such as ordinary glossaries are less expressive than formal approaches that reduce ambiguity, such as logical languages [45].

UntoUML is an emerging language, used to express conceptual schemas, that complies with Guizzardi's Unified Foundational Ontology (UFO) [15], where users of the previous Bunge Wand Weber (BWW) ontology, have switched to UFO since 2005 [32]. Other examples of languages that are also used to express conceptual schemas, include entity relationship (ER) modelling [46], and the unified modelling language (UML) [47], but according to [15] ER and UML, treat all types of entities as *entity types*, semantically overloading the single *entity type* construct and hence fail to represent different types of ontological categories.

A fairly new ontology specification language, the General Ontology Specification Language (GOSL) presented by Dietz & Mulder [30], has been applied primarily within the EE discipline. One of the main differences between GOSL and some of the other languages, is that GOSL omits labels that are used to assign people to things when people communicate about things, whereas ER an UML specifically refer to proper names for constituents of the real world [30]. Dietz & Mulder [30] reason that a name of a *thing* is not an attribute, since the *thing* will not change if its name changes.

3.2 The general ontology specification language (GOSL)

Dietz & Mulder [30] developed the *general ontology specification language* (GOSL) as a successor of the World Ontology Specification Language (WOSL), as a first-order logic language for specifying the *state space and transition space* of a world. Peano Russel Notation (PRN) and some form of structured English is used, of which the syntax is defined in Extended Backus-Naur Form (EBNF). Figure 2 provides a graphical representation of GOSL as a *meta meta model of state space and transition space* (MMMST) of describing a world in general, i.e. a language to represent the top level of abstraction indicated in Figure 1. Dietz & Mulder [30, p.40] state that they adopt both the world ontology (*statics*) and system ontology (*dynamics*) as fundamentals in conceptualizing about the enterprise.

Although Dietz & Mulder [30] did not claim that GOSL provides a generic ontology to represent SD, the community co-developed multiple theories that acknowledge the *statics* of a world, the *dynamics* of a system, and the *agent-goal* perspective that exists within systems that include the human being.

The Design and Engineering Methodology for Organizations Specification Language (DEMOSL) incorporates *static* and *dynamic* components of a system. Dietz and Mulder [30, p. 78-79] indicate how the operating logic of an enterprise can be expressed either using DEMOSL or GOSL, highlighting their semantic equivalence. However, GOSL has not been used to express *goal-related* concepts, associated with the Teleology, Affordance, Ontology (TAO) theory, and also evident in SD causal loop diagrams (CLDs), where the word "desire" is used.

4 DEVELOPMENT OF A META MODEL FOR ENTERPRISE SYSTEMS DYNAMICS

In section 4.1, we present the method for developing the meta model for enterprise systems dynamics (MMESD), whereas section 4.2 validates the MMESD.

4.1 Research methodology

The design science research methodology (DSRM), guided by Peffers et al. [48, 49] is an appropriate methodology when a novel artefact is developed to address an existing problem. Using the ontology of artefacts, presented by Weigand et al. [50], the MMESD, as an artefact, falls within the category of "*analysis model used for artifact design*", further explained, elaborating on the first four design cycle phases of [49] in Table 2.

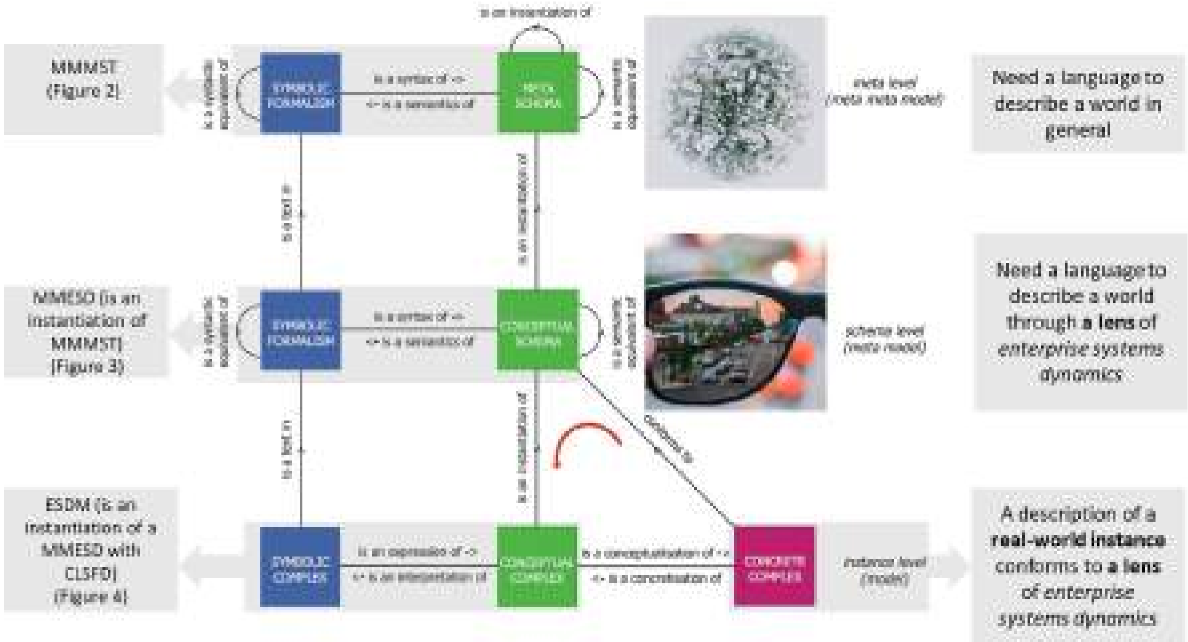

Figure 1: The General Conceptual Modelling Framework of Dietz and Mulder [30], a need for a meta model for enterprise systems dynamics (MMESD)

Table 2: Design cycle phases for developing the MMESD

Identify a problem: The main problems were introduced in section 1: (1) CLDs are ambiguous, lack detail and are difficult to conceptualize; (2) Currently, disciplines, such as performance measurement, enterprise engineering (including enterprise architecture) and systems dynamics, share the same concepts, but each discipline developed their own symbolic formalisms to represent and analyse phenomena related to enterprise design and behaviour.
Define objectives of the artefact: The main objective is to develop an artefact, the MMESD to provide additional clarity on the concepts that are used in SD. The SD-associated diagram, the CLD already includes concepts that feature within the EE discipline, but EE offers further specialisation on some of the concepts, also with the potential of reducing ambiguity of CLD concepts.
Design and development: Figure 1 is based on the General Conceptual Modelling Framework of Dietz and Mulder [30] to explain different levels of abstraction in conceptual modelling. We use Figure 1 to indicate where our main contribution, the MMESD is positioned. Indicated in the top-most level of Figure 1, the *meta meta model of state space and transition space* (MMMST), can be instantiated to provide a specific view or lens on the word. Our article focuses primarily on the middle level, when we present a *meta model for enterprise systems dynamics* (MMESD), presented in section 4.2, to describe the world through a lens of enterprise systems dynamics, using the *general ontology specification language* (GOSL) to specialize some of the concepts with EE concepts, also providing additional clarity on the use of the concepts. We agree with the approach, indicated in [18], [51], [52] and [22], to start with an early identification of stocks and flows, already including stock flow concepts during cause-and-effect analysis, where the combination of stock flow concepts and causal loop concepts are included in a causal loop stock flow diagram (CLSFD). We agree with [53] that some facets on a CLD may not be easily quantised, a pre-condition for running simulations. Rather than following the reductionist view of incorrectly quantising all facets, we are in favour of using a CLSFD, retaining facets, to facilitate the initial collaborative stakeholder analysis of a system.
Demonstration: We use the third level of Figure 1 as a means to validate the MMESD, i.e. when the MMESD is instantiated, an *enterprise systems dynamics model* (ESDM), represented using a CLSFD, is used to provide a description of a real-world instance that conforms to a lens of enterprise systems dynamics. We use an extended case presented by Sterman [5] to present an adapted version of Sterman's CLSFD in section 5.

The top level, indicated in Figure 1 relates to the MMMST, with a detailed representation of the MMMST in Figure 2. The symbolic formalism used for the MMMST is called GOSL.

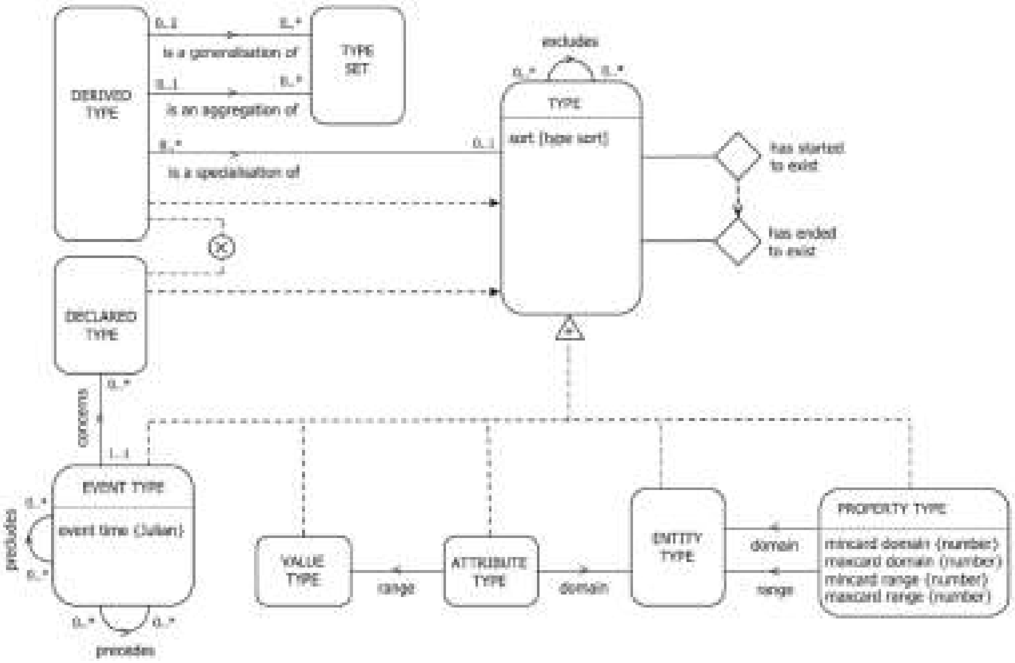

Figure 2: The meta meta model of state space and transition space (MMMST)

More details about the meaning of concepts included in the MMMST, such as *type*, *derived type* and *declared type*, is given in [30]. Not all of the MMMST concepts in Figure 2 were instantiated in the MMESD in Figure 3. Since the SD model does not represent deterministic events of an operating system, the EVENT TYPE in Figure 2, is not instantiated in the MMESD in Figure 3.

4.2 Meta model of enterprise systems dynamics (MMESD)

We use the same symbolic formalism, associated with GOSL, to instantiate a meta model for enterprise systems (MMESD) as an instantiation of the MMMST. Using graphical formalism of GOSL, Figure 3 indicates the main types currently in use within the SD knowledge base, also using specialisation from existing EE-related concepts.

Figure 3 indicates that the FACET type has subtypes QUANTITY, INTERVENTION, REALITY ASPECT and PERFORMANCE AREA (PA) ASPECT. Some types may *not* be quantifiable, such as INTERVENTION, and therefore INTERVENTION cannot be a specialisation of the quantifiable QUANTITY. Furthermore, any FACET may be connected to LINK instances. A STOCK may *also* be connected to FLOW instances. A FEEDBACK LOOP includes a set of LINK instances as well as a set of FLOW instances. When one or more FLOW instances are connected to an unrestricted ENVIRONMENT (AS SINK or SOURCE), an OPEN SYSTEM exists. Some types, in Figure 3, are shaded, indicating that these concept form part of the MMESD, but will not appear graphically on a CLSFD.

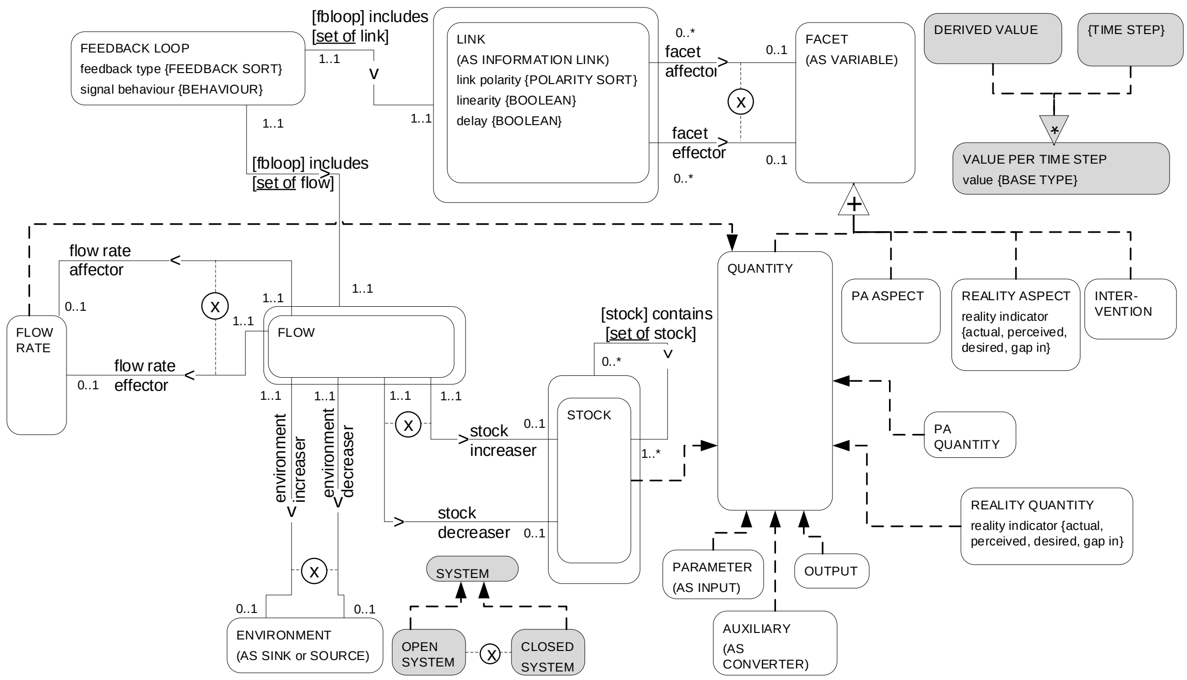

Figure 3: The meta model of enterprise systems dynamics (MMESD) expressed in GOSL

5 VALIDATION OF A META MODEL FOR SYSTEMS DYNAMICS

In Table 4 (in the Appendix), we present all of the MMESD entity types in the *first column*, corroborating concepts from multiple sources, i.e. [18], [54], [51], [52] and [55] where concepts are also graphically depicted in Figure 3 using GOSL's graphical formalism. For each concept in Table 4, the *second column* provides additional *explanation*, additional *existence and exclusion laws* specified in *Peano Russell Notation (PRN)*, as well as *modelling guidance* to the systems engineering practitioner when the types should be used to construct an ESDM, using a CLSFD. The modelling software, Vensim, allowed us to visually distinguish between some types, further explained in Table 4. The step-by-step method on creating a SFD from a

CLD by [51] also informed the guidance provided in Table 4. Furthermore, we present concepts in Table 4 in a *systematic way* rather than sorting types alphabetically.

Validating the MMESD, we extended an existing CLSFD for a very specific car industry case, presented by John Sterman [5]. The case was used to inform General Motor's decision-making in their North American Operations. We extended the diagram with quality improvement behaviour from [56], to further validate the first version of the MMESD, constructing a CLSFD, presented in Figure 4. Table 3 provides a summary of the MMESD concepts that were instantiated in Figure 4. The grey-shaded types in Figure 3, included in Table 3, are not explicitly shown in Figure 4, even though the types are required to enable simulation within an SD software package, where additional input values are provided via a user-interface. We use "<not shown explicitly>" when a concept is not shown visually as instantiations in a CLSFD and hence not in Figure 4.

We already applied appropriate phrasing of instantiations, using dotted-underline to indicate changes to the original phrasing used by [5]. Figure 4 only includes delay indicators (shown as double-bar) for balancing loop B7 to distinguish a *delay* from a *no-delay* effect, whereas *no-delay* lines are shown as a thick-arrowed lines, i.e. l8 and l9.

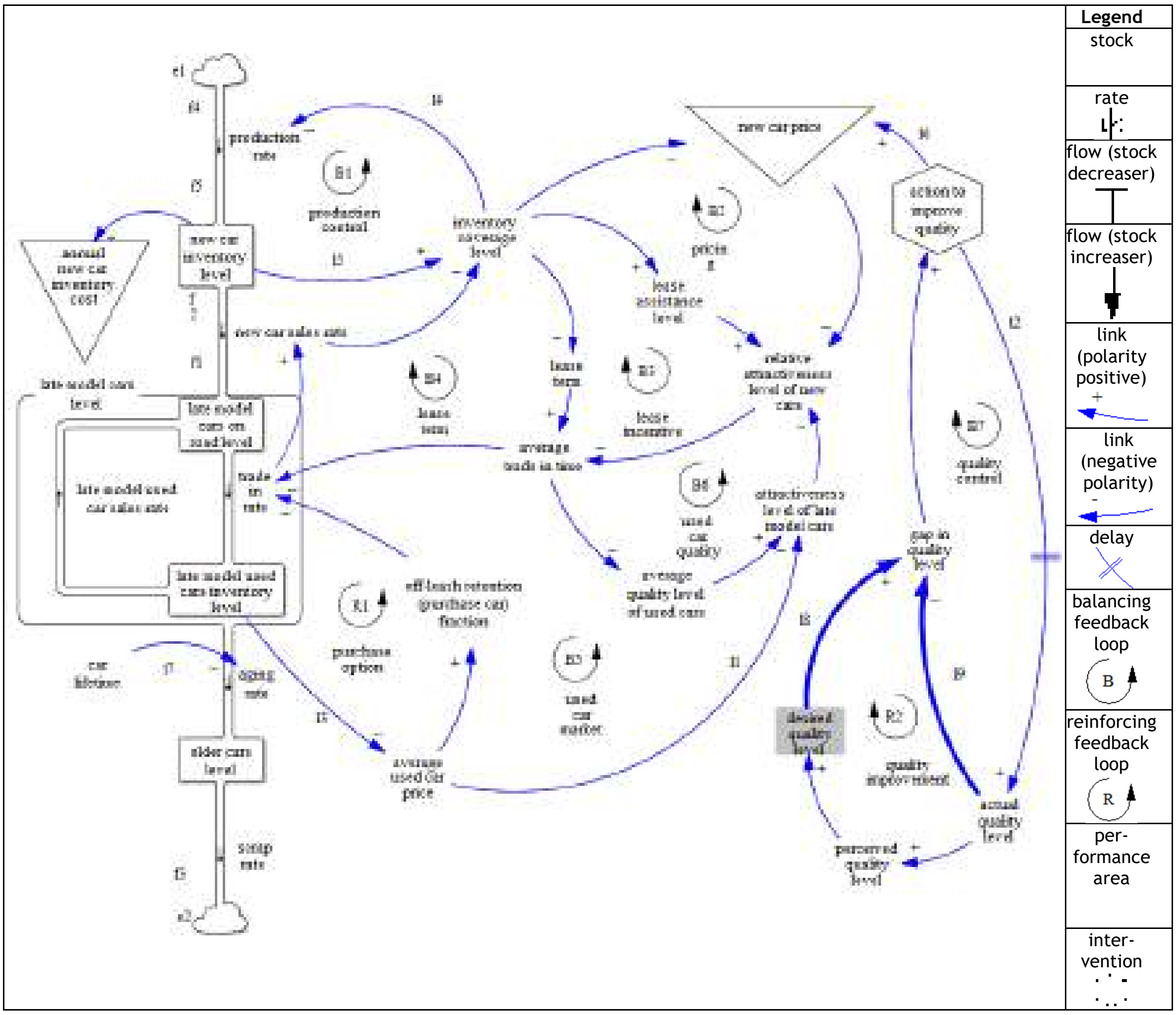

Figure 4: The ESDM, represented as CLSFD, based on the case presented by [5]

Table 3: MMESD concepts instantiated in Figure 4

Types	Instantiation examples in Figure 4
FACET (AS VARIABLE)	Instantiation examples are given for all subtypes of FACET.
QUANTITY	*quantity* average used car price **exists**
TIME STEP	*time step* 1 **exists** <not shown explicitly> % Note that time step is month %
DERIVED VALUE	<not shown explicitly>
VALUE PER TIME STEP value	<not shown explicitly> <not shown explicitly>
REALITY ASPECT	<No example of an instantiation>
REALITY QUANTITY reality indicator	*reality quantity* actual quality level **exists** *reality quantity* desired quality level **exists** **the** *reality indicator* **of** *reality quantity* actual quality level **is** actual <not shown explicitly> **the** *reality indicator* **of** *reality quantity* desired quality level **is** desired <grey-shaded>
STOCK	*stock* new car inventory level **exists** **Container example:** late model car level **contains** set of late model car on road level **and** late model used car inventory level
FLOW RATE	*rate* production rate **exists**
FLOW stock increaser stock decreaser flow rate affector flow rate effector environment increaser environment decreaser	*flow* f1 **exists;** *flow* f2 **exists;** *flow* f3 **exists;** *flow* f4 **exists** **the** *stock increaser* **of** *stock* late model cars on road level **is** f1 **the** *stock decreaser* **of** *stock* new car inventory level **is** f2 **the** *range* **of** stock decreaser **is** stock **the** *flow rate affector* **of** *flow* f2 **is** new car sales rate **the** *flow rate effector* **of** *flow* f1 is new car sales rate **the** *environment increaser* **of** *environment* e2 **is** *flow* f3 **the** *environment decreaser* **of** *environment* e1 **is** *flow* f4
INVERVENTION	*intervention* action to improve quality **exists** (graphically indicated with a hexagon)

Types	**Instantiation examples in Figure 4**
PARAMETER	entity *car lifetime* exists
PERFORMANCE AREA ASPECT i.e. PA ASPECT	<No example of an instantiation> see instantiation example of PA QUANTITY
PA QUANTITY	*pa quantity* new car price **exists** (indicated graphically with an up-triangle) **meaning:** car price is quantifiable, and it is also identified as a performance area during enterprise design.
OUTPUT	*output* new car inventory annual cost **exists**
AUXILIARY	<No example of an instantiation>
LINK	*link* l1 **exists;** *link* l2 **exists;** *link* l3 **exists;** *link* l4 **exists;** *link* l5 **exists**; *link* l6 **exists;** *link* l7 **exists;** *link* l8 **exists;** *link* l9 **exists**
facet affector	**the** *affector* **of** *link* l1 is average used car price
facet effector	**the** *effector* **of** *link* l1 is attractiveness level of late model car
link polarity	**the** *link polarity* **of** *link* l1 **is** positive **the** *link polarity* **of** *link* l7 **is** negative
delay	**the** *delay* **of** *link* l2 **is** true; **the** *delay* **of** *link* l8 **is** false; **the** *delay* **of** *link* l9 **is** false
linearity	**the** *linearity* **of** *link* l3 **is** false <not shown explicitly> **meaning:** adding to the *facet* late model used car inventory level does not have a linear impact on *facet* average used car price
FEEDBACK LOOP	*feedback loop* B1 **exists** *reinforcing loop* R1 **exists** *feedback loop* B6 **exists** (Note: B6 neither includes a [flow rate] instance nor a [stock] instance. For simulation further transformation is required to convert some of the [facet] instances into [stock] instances, also adding [rate] instances. B1 **includes** set of links (l4 **and** l5) and a set of flows (f5).
feedback type	**the** *feedback type* **of** *feedback loop* B7 **is** balancing
behaviour	**the** *behaviour* **of** *feedback loop* B7 **is** quality control **meaning:** addressing the “gap in quality level”, the balancing behaviour “quality control” emerges.
ENVIRONMENT	*environment* e1 **exists** *environment* e2 **exists**
SYSTEM	see instantiation example of OPEN SYSTEM
CLOSED SYSTEM	<No example of an instantiation>
OPEN SYSTEM	*open system* Car Industry Case System **exists**

The MMESD, developed as a new artefact, has been validated via a demonstration, indicating that the MMESD concepts, instantiates most of the MMMST expressed in GOSL, except for the *event type*. Since SD models focus on analysing behaviours over long time frames, i.e. not focusing on deterministic state changes when an act causes a new fact to exist, the event type does not exist in the MMESD.

GOSL was used to define the initial version of the MMESD, via a graphical formalism in Figure 3 and textual formalism in Table 4, distinguishing between different SD concepts. Ample resources exist to provide additional guidance to the SD practitioner, when a CLSFD has to be constructed, taking a step-by-step approach, involving SD experts [18, 51, 52, 54, 57].

During the co-development, critique and refinement of the MMESD, a number of concerns were identified regarding existing concepts in use and their symbolic formalism. Our suggestions include:

- *Terminology of discourse*: In the MMESD, we already included alternative labels for types used within the SD community, using FACET, instead of VARIABLE, to include both quantifiable and non-quantifiable facets within the world of SD. Also, some FACETs, such as PARAMETERs may not *vary* (as a VARIABLE) during a simulation run, but remain constant and the use of VARIABLE as supertype is thus misleading.
- *Symbolic distinction:* Highlighting instances on a CLSDF that relate to EE concepts, we suggest that an up-triangle resembles a performance area, whereas a hexagon resembles an intervention. We highlight *desired* realities with grey shading, drawing attention to human agents' goal-linked behaviour on the sub-system analysed.
- *Delay:* According to [22], every stock and flow structure implies a delay, but hiding the stock and flow details, a delay (represented by a double-bar) can be used instead. Yet, since most of the link instances involve a delay, we suggest that the double-bar delay symbol could be deprecated, rather indicating links that have an instantaneous effect. In Figure 4 we used thick lines to indicate an instantaneous effect.

6 CONCLUSION AND WAY FORWARD

Future work requires further validation, using other cases within different industries. Also, we presented the MMESD as a first version artefact, with limited extension from EE concepts, extracted from [12] and [42]. In future, the MMESD could be further extended with new developments in SD. As an example, the criticisms against SD, summarised by [53], call for a formal understanding of how SD considers hierarchy in relationships between constitutional order, institutions, organisations and conventions, since incentives (related to goal achievement) and constraints between hierarchy levels also determine system behaviour.

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8 APPENDIX: TEXTUAL FORMALISM OF THE MMESD

Table 4: MMESD concepts in Figure 3

Types	Further clarification on definition and modelling guidance
FACET (AS VARIABLE)	*entity type* facet **exists** FACET *is a generalisation of* QUANTITY, PERFORMANCE AREA (PA) ASPECT, REALITY ASPECT, INTERVENTION. **Exclusion law in PRN** (in accordance with [52]): FLOW RATE ∩ STOCK ∩ REALITY QUANTITY ∩ REALITY ASPECT ∩ PA QUANTITY ∩ PA ASPECT ∩ INTERVENTION = ø **meaning:** A thing cannot be more than one of the listed types at the same time. **Further explanation:** • An alternative phrase for FACET, used is in literature, is “variable” according to [52]. However, one of the specialisations of FACET is PARAMETER that is by default a “constant” [52]. Since a “variable” cannot also be “constant” we prefer the phrase FACET as the supertype, also retaining the “AS VARIABLE” in brackets to refer to the current language of discourse. • A [facet] instance is a *system thing* that is of interest to the analyst. • A [facet] instance (depicted on a CLD) may be affected via many in-going and out-going [link] instances. See LINK.
QUANTITY	*entity type* quantity **exists** QUANTITY *is a generalisation of* FLOW RATE, STOCK, PARAMETER, AUXILIARY, OUTPUT, REALITY QUANTITY, PA QUANTITY **Modelling guidance:** For each of the subtypes of QUANTITY, the practitioner should use an appropriate label to quantise the instance, so that its value can increase or decrease over time, e.g. “level”, “rate” “percentage”, “fraction”, “unit price” or “probability” as appropriate. Sterman [22, p 200] also provides examples where the value type of the instance is visually displayed in brackets on the diagram, e.g. “unit price ($)”.
TIME STEP	*value type* time step **exists** **Further explanation:** When an SD model is used for simulation a time step should be selected to ensure consistency throughout the model.
DERIVED VALUE	*derived type* derived value **exists** **Further explanation:** A [derived value] instance is calculable for quantised entity types, i.e. specialisations of QUANTITY.
VALUE PER TIME STEP value	*entity type* quantity per time step **exists** VALUE PER TIME STEP *is an aggregation of* DERIVED VALUE and TIME STEP **the** *domain* **of** value **is** value per time step; **the** *range* **of** value **is** base type **Further explanation:** The value of a [value per time step] instance is calculable [51], using a mathematical calculation, based on the values of other quantised instances.
REALITY QUANTITY reality indicator	*entity type* reality quantity **exists** REALITY QUANTITY *is a specialisation of* QUANTITY **Modelling guidance:** • When a desire is compared with an actual or perceived reality, a “gap in” or discrepancy exists. The described pattern should be identified first as a condition for using the specialisation REALITY ASPECT or REALITY QUANTITY. • The [reality quantity] and [reality aspect] instances modelled on a CLD should include the applicable specialisation phrase as part of the naming, i.e. |actual, perceived, desired, gap in|. No specialisation implies the default, where the [reality quantity] or [reality aspect] instance is “actual”. • The model creates more understanding if both a “desired” and “actual” cause a “gap in”, where it is also possible to calculate the “gap in” mathematically for a [reality quantity] as the difference between the “desired” and the “actual”. When the value of an instance can be calculated, the instance can be classified as an AUXILIARY. Meadows [6] use the word “discrepancy” rather than “gap in”. Sterman [22] uses “shortfall”.

Types	Further clarification on definition and modelling guidance
REALITY ASPECT reality indicator	*entity type* reality aspect **exists** REALITY ASPECT *is a subtype of* FACET **the** *domain* **of** reality indicator **is** reality aspect; **the** *range* **of** reality indicator **is** ¦actual, perceived, desired, gap in¦
STOCK	*entity type* stock **exists** STOCK *is a specialisation of* QUANTITY **Further explanation:** • The value for a [stock] instance changes over time through actions of many [flow] instances. • An instance of [stock] can serve as a container of [stock] instances, i.e. [stock] contains [set of stock] • In a systems dynamics project, a [stock] instance's value over time is often portrayed graphically [57], accommodated via VALUE PER TIME STEP.
FLOW RATE	*entity type* flow rate **exists** FLOW RATE *is a specialisation of* QUANTITY **Further explanation:** • A [flow rate] instance is used to indicate a flow rate that exists between two [stock] instances in the CLSFD, where the [flow rate] affects the value of connected [stock] instance or connected [environment] instance. A [flow rate] instance can be affected by a number of other [facet] instances [58] and hence the [flow rate] instance's value is not controlled by a single "controller". • The value of a [flow rate] instance should only be expressed per time step. See VALUE PER TIME STEP. • In a systems dynamics project, the rate's value is often portrayed graphically against time steps [57].
FLOW stock increaser stock decreaser flow rate affector flow rate effector environment increaser environment decreaser	*entity type* flow **exists** **the** *domain* **of** stock increaser **is** flow **the** *range* **of** stock increaser **is** stock **the** *domain* **of** stock decreaser **is** flow **the** *range* **of** stock decreaser **is** stock **Further explanation:** • A [flow] instance is used for material that flows to increase or decrease stock levels, whereas a [link] instance relates to information about a particular status that affects a [facet] instance to increase or decrease its value. • A [flow] instance may increase a [stock] instance. • A [flow] instance may decrease a [stock] instance. • When no relationship exists between entity types, the implication is that the co-existence of the entity types is not mandated. As an example, since no relationship exists between PARAMETER and FLOW, the implication is that existence of a [flow] instance has no bearing on the existence of a [parameter] instance (in accordance with [52, p6]). **the** *domain* **of** flow rate affector **is** flow **the** *range* **of** flow rate affector **is** flow rate **the** *domain* **of** flow rate effector **is** flow **the** *range* **of** flow rate effector **is** flow rate **Further explanation:** • A [flow] instance may affect a [flow rate] instance. • A [flow] instance may be the effect of a [flow rate] instance. **the** *domain* **of** environment increaser **is** flow **the** *range* **of** environment increaser **is** environment **Explanation:** Also called "sink" [22]. **the** *domain* **of** environment decreaser **is** flow **the** *range* **of** environment decreaser **is** environment **Explanation:** Also called "source" [22]. **Exclusion law in PRN:** $\forall$x,y: stock increaser (x,y) $\Rightarrow$ stock (x) $\wedge$ flow (x) $\forall$x,y: stock increaser (x,y) $\Rightarrow$ $\neg$ stock decreaser (x,y) $\forall$x,y: stock decreaser (x,y) $\Rightarrow$ $\neg$ stock increaser (x,y) **Exclusion law in PRN:** $\forall$u,v: flow rate affector (u,v) $\Rightarrow$ flow rate (u) $\wedge$ flow (v) $\forall$u,v: flow rate affector (u,v) $\Rightarrow$ $\neg$ flow rate effector (u,v)

Types	Further clarification on definition and modelling guidance
	∀u,v: flow rate effector (u,v) ⇒ ¬ flow rate affector (u,v) **Exclusion law in PRN:** ∀w,z: environment increaser (w,z) ⇒ stock (x) ∧ environment (x) ∀w,z: environment increaser (w,z) ⇒ ¬ environment decreaser (w,z) ∀w,z: environment decreaser (w,z) ⇒ ¬ environment increaser (w,z)
INVERVENTION	*entity type* intervention **exists** INTERVENTION *is a subtype of* FACET **Further explanation:** Interventions may involve the re-design of some design domains to positively affect performance areas [12].
PARAMETER	*entity type* parameter **exists** PARAMETER *is a specialisation of* QUANTITY **Existence law in PRN:** ∀x,y: parameter facet affector (x,y) ⇒ link (x) ∧ parameter (x) ∀x,y: parameter facet affector (x,y) = ø **meaning:** a [parameter] instance can only have outgoing [link] instances, i.e. no ingoing [link] instances. **Further explanation:** • An alternative phrase used for PARAMETER is “input”, and considered constant, i.e. not varying with time for the duration of a single simulation model run, according to [52]. Thus, the value of a [value per time step] instance at [time step] instance = 0, remains constant for all time steps. • A [parameter] instance is usually in input to a [flow rate] instance or indirectly an input to a [flow rate] instance by way of [auxiliary] instance(s) [52].
PERFORMANCE AREA ASPECT i.e. PA ASPECT	*entity type* performance area aspect **exists** PA ASPECT *is a subtype of* FACET **Further explanation:** A performance area within the discipline of enterprise engineering, is a design intention that needs to be addressed in multiple design domains [12, 42], and can be specified either *qualitatively* or *quantitatively* [42]. When specified qualitatively, we use “performance area aspect”.
PA QUANTITY	*entity type* pa quantity **exists** PA QUANTITY *is a specialization of* QUANTITY
OUTPUT	*entity type* output **exists** OUTPUT *is a specialisation of* QUANTITY **PRN:** ∀x,y: output facet effector (x,y) ⇒ link (x) ∧ output (x) ∀x,y: output facet effector (x,y) = ø **meaning:** an [output] instance can only have incoming [link] instances, i.e. no outgoing [link] instances.
AUXILIARY	*entity type* auxiliary **exists** AUXILIARY *is a specialisation of* QUANTITY **Further explanation:** • An alternative phrase used for AUXILIARY is “converter”, according to [52]. • According to [51], an [auxiliary] instance has a value that is derived, i.e. calculated based on multiple [facet] instances. • An introduction to software Vensim, indicates that the *value type* dimensionless is possible for an [auxiliary] instance’s value [57], where dimensionless is similar to the *base type* real in the base type list of Dietz & Mulder [30, p. 89].

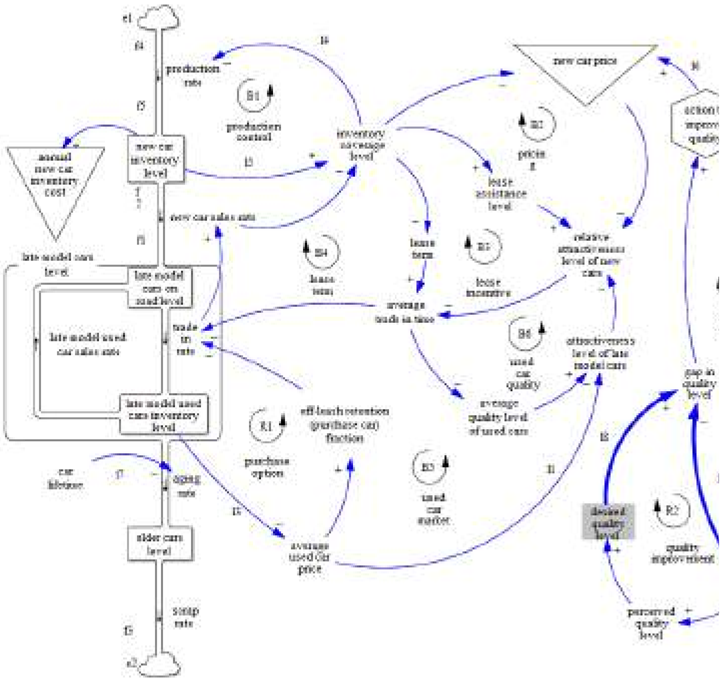
<table>
<tr><th>Types</th><th>Further clarification on definition and modelling guidance</th></tr>
<tr><td>LINK</td><td>entity type link exists
Further explanation:
A [link] instance is an information link [51], affecting a non-stock [facet] instance. Also see STOCK, indicating that a [stock] instance may have an outgoing [link] instance but not an ingoing [link], i.e. cannot affect a [stock] instance.
Since the [link] instance is used between different types of facets, its interpretation in affecting a facet, differs. As an example, l6 in


Figure 4 indicates a hypothesis, i.e. that an action to improve quality may increase the price of new cars.</td></tr>
<tr><td>facet affector</td><td>the domain of facet affector is link
the range of facet affector is facet</td></tr>
<tr><td>facet effector</td><td>the domain of facet effector is link
the range of facet effector is facet
Further explanation:
Literature also refers to “information link” according to [52].
The use of phrases affector and effector is suggested by [52].
The magnitude of effector on the affector is based on a mathematical function that is not shown on a CLSFD.
Modelling guidance:
Since FACET is a generalisation of multiple other subtypes, a [link] instance may be connected to any of these subtypes or the specialisations of these subtypes.
Exclusion law in PRN:
∀x,y: facet affector (x,y) ⇒ link (x) ∧ facet (x)</td></tr>
</table>

Types	**Further clarification on definition and modelling guidance**
	$\forall$x,y: facet affector (x,y) $\Rightarrow \neg$ facet effector (x,y) $\forall$x,y: facet effector (x,y) $\Rightarrow \neg$ facet affector (x,y) **meaning:** An incoming facet link cannot also be an outgoing facet link. An outgoing facet link cannot also be an incoming facet link. **Exclusion law in PRN:** $\forall$x,y: stock facet affector (x,y) $\Rightarrow$ link (x) $\wedge$ stock (x) $\forall$x,y: stock facet affector (x,y) = $\emptyset$ **meaning:** if the [facet] instance is a [stock] instance, the [link] instance cannot be a stock facet affector, i.e. a [link] instance cannot be an ingoing [link] instance into the [stock] instance (see [52, p6]).
link polarity delay linearity	**the** *domain* **of** link polarity **is** link **the** *range* **of** link polarity **is** polarity sort; i.e. ⊦positive, negative⊣ **the** *domain* **of** delay **is** link; **the** *range* **of** delay **is** Boolean, i.e. ⊦true, false⊣, with default “true”. **Modelling guidance on delay:** • Very few [link] instances are instantaneous, i.e. with no delay. One way to highlight the no-delay link is to use a thick border. An example of an instantaneous effect is that the value of desired [reality quantity] instance and value of actual [reality quantity] instance has an instantaneous effect on the value of gap in [reality quantity] instance. The reason is that the value of a gap in [reality quantity] is the difference between value of desired [reality quantity] and value of actual [reality quantity]. According to [22], the “gap in” can thus be classified as an instance of an [auxiliary]. • According to [22], a delay suggests a stock and flow structure, but hiding the stock and flow details, a delay can be used instead. **the** *domain* **of** linearity **is** link **the** *range* **of** linearity **is** Boolean, i.e. ⊦true, false⊣, with default “true”.
FEEDBACK LOOP	*entity type* feedback loop **exists** **Further explanation:** A [feedback loop] instance has to complete a circle, i.e. it should be possible to start the loop at a particular [facet] instance, ending at the same [facet] instance. References [59] and [52] indicate that for a [feedback loop] instance to facilitate simulation, requires the following cardinalities: • An instance of [fbloop] includes exactly one instance of [<u>set of</u> link] • An instance of [fbloop] includes exactly one instance of [<u>set of</u> flow]
           feedback type	**In addition, using PRN:** $\forall$x,y: flow rate affector (x,y) $\vee$ flow rate effector (x,y) $\neq \emptyset$ $\forall$x,y: stock increaser (x,y) $\vee$ stock decreaser (x,y) $\neq \emptyset$ **meaning:** the feedback loop should at least include one [flow rate] instance and one [stock] instance. **In addition, using PRN:** $\forall$xy: facet affector (x,y) $\wedge$ facet effector (x,y) = $\emptyset$ **meaning:** self-loops involving a single [facet] instance is not allowed [52]. **Modelling guidance:** Differences exist between short term and long-term results of actions; hence short-term loops should be separated from long term loops. **the** *domain* **of** feedback type **is** feedback loop; **the** *range* **of** feedback type **is** feedback sort, i.e. ⊦reinforcing, balancing⊣. **Further explanation:** • Reinforcing lead to exponential increase or decrease of the value of a [stock] instance over time. If the number of negative link(s) is even, the feedback loop is positive/reinforcing/self-multiplying/snowballing/escalating. • Balancing moves towards a goal value for the value of a [stock] instance over time. If the number of negative link(s) is odd, the feedback loop is considered as negative/balancing. • Navigating a full circle of a [feedback loop] instance, when counting positives and negatives for a [feedback loop] instance, movement along the circle, moving in the same direction as the directed [flow] instance is interpreted as a positive polarity [22, p 211]. • Navigating a full circle of a [feedback loop] instance, when counting positives and negatives for a [feedback loop] instance, movement along the circle,

Types	Further clarification on definition and modelling guidance
	moving in the opposite direction of a directed [flow] instance is interpreted as a negative polarity [22, p 211].
behaviour	**the** *domain* **of** signal behaviour **is** feedback loop; **the** *range* **of** behaviour **is** behaviour **Further explanation:** • In addition to the classification as a reinforcing or balancing type, an additional behaviour describes the reinforcing/escalating OR balancing/goal-reaching behaviour. • For a reinforcing loop, starting at any [facet] instance, tracing the effect of a small change should reinforce the original change. • For a balancing loop, the feedback effect opposes the original change. • Behaviour labelling, indicates a rationale for a behaviour and according to [22, p 148]: "When working with a client group, it's often possible to get them to name the loop". • When the feedback loop starts at a [facet] instance that is a [reality quantity] instance of "gap in", i.e. deviation from a goal, the balancing behaviour label indicates the balancing strategy to address the "gap in".
ENVIRONMENT	*entity type* environment **exists**
SYSTEM	*entity type* system **exists**
CLOSED SYSTEM	*entity type* closed system **exists** closed system *is a specialisation of* system **Existence law in PRN:** $\forall x,y$: (environment increaser (x,y) $\vee$ environment decreaser (x,y)) = ø **meaning:** a [closed system] instance exists if no inflows into [environment] instances or outflows from [environment] instances exist.
OPEN SYSTEM	*entity type* open model **exists** open system *is a specialisation of* system **Existence law in PRN:** $\forall x,y$: (environment increaser (x,y) $\vee$ environment decreaser (x,y)) ≠ ø **meaning:** an [open system] instance exists if some inflows into [environment] instances or outflows from [environment] instances exist. **Exclusion law in PRN:** OPEN SYSTEM ∩ CLOSED SYSTEM = ø **meaning:** a system cannot be classified as both an [open system] and a [closed system].

THE CHALLENGES OF ADOPTING LEAN MANUFACTURING FRAMEWORKS IN STATE-OWNED ENTITIES- A LITERATURE REVIEW

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ABSTRACT

This study reviewed the extent to which lean manufacturing frameworks can be adapted for implementation in state-owned entities. Lean manufacturing principles such as customer value, flow and waste reduction are translated differently in the state-owned entities than those in the private sector environment. Many of the frameworks analysed were prone to a top-down approach, which may be limiting in the case of the state-owned entities due to restrictive policies and some legislative requirements driven by Public Finance Management Act. Drawing from contingency theory, the prospects, and challenges of adapting lean manufacturing frameworks to SOEs in South Africa were identified. The study also highlighted the need to adopt a bottom-up approach which could effectively assist in adapting lean manufacturing frameworks to the state-owned entities through the involvement of employees at all levels of the organisation. The knowledge and experience of the employees can be leveraged to identify and address issues and specific challenges faced by different departments or business units within the SOE that may have been overlooked in a top-down approach. This study focused on SOEs from the red zone category. Future studies may consider additional SOE categories

Keywords: Lean manufacturing, adaption, state-owned entities, contingency, viable systems

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1 INTRODUCTION

The state-owned entities environment has different types of wastes identified by Mungovan [1] that are more prevalent throughout different government spheres around the world [2,3]. In South Africa, much of these wastes are present in all state-owned entities environments [4] and have resulted in R51 billion total audited irregular expenditure. In addition, operational waste still poses a great burden in state-owned entities (SOEs) where losses total R1.168 billion caused by rising spending on duplicate work, irregular expenditure, and defects. Unfortunately, in most state-owned entities in South Africa this trend continues to grow and has profound implications for fulfilling organisational mandates and creating value for the customers [5].

The emergence of the global economy developments culminates in the use of technology and there are increasing demands from the consumers for effective delivery of public services that has resulted in efforts that have given more impetus to improve service delivery moving the focus away from reducing waste [6]. Debate continues about the best strategies that SOEs in South Africa should use to provide service delivery effectively and efficiently [7] but not at the cost of reducing waste.Adopting lean principles to reduce waste and improve service delivery is one strategy that is receiving increased attention. There is a body of literature regarding lean manufacturing principles and how they can assist in innovative service delivery processes while creating value for customers [8]. To reap the benefits of lean manufacturing principles, several lean manufacturing frameworks have been researched and developed over the last decade. These frameworks offer a good platform for improving the understanding of the application of lean manufacturing principles in state-owned entities such as hospitals, electricity, railway, and transportation.

However, the extant literature about the application of the frameworks ignores the adaptation needed to fit the specificities of the state-owned entity's environment in South Africa as compared to elsewhere in the world [9]. For example, creating value for the customer is one of the core principles of lean manufacturing, which defines value in terms of a specific product with specific capabilities offered at a specific time [10]. Translating value to the state-owned entity's context must be done with the consideration that customers in public services for whom value is identified and then delivered, do not have the liberty to choose between different products and suppliers and spend their money according to the offering that delivers the greatest perceived value. Arlbjorn et.al [11] assert that customer value in state-owned entities is heavily linked to social value and the equitable provision of services. Other characteristics of the state-owned entities point to organisational culture, political mandates and bureaucracy that must be taken into consideration in the application of the lean manufacturing frameworks.

Previous researchers have relied on the resource-based theory to examine the relationships between organisational resources and creating customer value in lean manufacturing applications [12]. Principal-agent theory has been used to understand the headquarter–subsidiary relationship with the lens of principal–agent to successfully adopt lean manufacturing principles to their organisations [13]. However, the theories neglect the rationale that simply the processes of another organisation to replicate or mimic their successful path and may be inappropriate for SOEs due to the different organisational contexts. There is a need to improve the understanding of how the configuration of lean manufacturing principles is appropriate to different state-owned entities contexts in different countries, particularly in South Africa. To expand our understanding of the dynamic relationship between lean principles and state-owned entity's organisational contexts, our study examines three contingencies of the state-owned entities organisation in relation to lean manufacturing principles namely, organisational strategies, context of the organisation and the notion of adaptability.

Lawrence and Lorsch [14] established a comparison between successful organisational structures, by observing the interaction of its internal divisions and the factors derived from the external environment. Their findings suggest that the crucial factor for success is not only in management, but also in the environment or context in which organisations are embedded. Furthermore, in recent years there is a growing significant body of research using contingency theory, that shares the common view that organisational structures are contingent on contextual factors such as the environment, technology, and the size of the organisation [15]. Therefore, to expand on this exploration, this research considers the notion of the fit between lean manufacturing principles and the context of the state-owned entities organisation recognising that each organisation operates within a distinct context, influenced by factors such as the political landscape, regulatory environment, and stakeholder expectations. Despite some state-owned entities in South Africa starting to implement lean manufacturing principles, this concept has not yet has yet been properly explored for state-owned entities.

Because state-owned entities must create or improve value for the customer as opposed to driving profits as their core reason for existence, the researcher employed a qualitative research methodology to explore the understanding of value creation, waste (non-value adding activities) elimination strategies in the state-owned entities, and critical contextual factors (such as regulations, political priorities, limited organisational and financial resources) that determine the applicability of lean manufacturing frameworks to a new setting. National Treasury has classified the major state-owned entities organisations into three board management categories in terms of their performance [16] namely:

- Urgent Management Attention (Red Zone):
  (Eskom, Post Office, SABC, Sentech, Denel, SAA, Transnet, IDT).
- Close Monitoring (Yellow Zone):
  (Land Bank, DBSA, ACSA, TCTA, ATNS, Infraco, SAX).
- Ongoing Monitoring (Green Zone):
  (Armscor, IDC, SAFCOL, NECSA)

With such a large portfolio of state-owned entities, the researcher considered state-owned entities from the red zone category as classified by the Public Finance Management Act No. 1 of 1999 (PMFA) in terms of their performance. The purpose of the study was to explore how lean can be used within state-owned entities to create value in terms of SOEs' mandate to deliver services and to reduce waste. The contingency theory was used as a lens for the research.

Based on the review of the literature and initial interviews conducted, this study makes two major contributions to understanding whether lean manufacturing frameworks can be adapted for state-owned entities. First, the research suggests that contextual factors affect the way in which an organisation is designed and ultimately the ability of the organisation to create value for the customer. For example, one external issue within state-owned entities is the multiple and quite fragmented stakeholder groups that each place different demands on the SOEs and can affect its intended results. Factors to contextualise information or knowledge to a specific environment were found to influence the working and management of organisations leading to different organisational behaviours. Secondly, in terms of creating value, the researcher found that value creation is solely left as a top management input in strategic planning, and this does not allow for value creation to flow from employees as an input to strategy development. The paper is structured as follows: an overview of lean manufacturing in state-owned entities, a review of lean manufacturing frameworks, a discussion, and a conclusion.

2 LEAN MANUFACTURING IN THE STATE-OWNED ENTITIES

Lean manufacturing is an integrated socio-technical system which comprises principles, practices, tools, and techniques that improve the speed, cost, and quality of any process by eliminating waste, synchronising workflows, and managing service flows [17]. The reduction of waste is the cornerstone of the lean approach where waste comprise all non-value-adding activities [1]. Lean has been a topical issue of discussion over the last decade across different fields of application which have resulted in a plethora of lean concepts with different objectives and scopes [18]. The implementation of lean manufacturing principles in state-owned entities is part of a growing trend of management tools designed to reduce costs and improve the efficiency of operations [20].

However, despite a broad consensus about the steps to be followed by an organisation that is implementing lean manufacturing principles, many organisations still struggle to yield the results from the application of lean principles to their processes [21]. To facilitate the implementation of lean manufacturing principles, researchers have suggested an array of lean manufacturing frameworks that provide a structured systematic way of implementing lean manufacturing principles to lament the gap between theory and practice [21, 22]. However, a review of these frameworks revealed that they suffer from several limitations.

Although existing lean manufacturing frameworks have led to an understanding of the application of lean manufacturing principles in different contexts, they are limited by the lack of validation and flexibility to suit the state-owned entity's context. From the literature reviewed [23,24,25], the frameworks propounded by researchers are significant, but they principally focus on highlighting the sequence of the lean manufacturing principles to be introduced in the organisation [26] and, in some cases, the success criteria which are questionable with specific reference to how contingency factors such as bureaucratic processes, political interference, competing stakeholder expectations and resource constraints [27; 4] may limit the applicability of the proposed lean manufacturing frameworks to the state-owned entities environment.

Another framework is proposed by Aivazian, Yin and Qiu [28] who developed a framework to help organisations view the degree of fit between their organisation and the elements of lean manufacturing. The framework proposed by Anand and Kodali is limited when it comes to state-owned entities organisations in that it does not specify the dynamic interaction between the state-owned entities organisation and its external context (stakeholders, shareholders, political influences amongst others) but narrowly focuses only on the internal stakeholders. This is unfortunate, considering that state-owned entities organisations in South Africa operate within a framework of multiple pieces of legislation, which are often imposed from the external stakeholder component of the organisation that are at times in conflict with the broad strategic mandates of the organisation [27]. Other countries such as China do not operate using multiple legislations to manage state-owned entities [29]. The multiple legislations used in SOEs as well as the political climate in South Africa create a very complex environment.

In a similar study, Ngonini [30] conducted an analysis of lean implementation frameworks to investigate the shortfalls in the current lean implementation frameworks. The researcher's critique of most of the current available lean manufacturing frameworks is their focus to on a top-down approach (using strategic plans to drive profit) but not a bottom-up approach (using inputs from staff to improve service delivery). This view is of relevance to this paper, as the selection and interaction of suitable lean tools are most viewed from the operational or shop floor levels of the organisation where employees conduct root cause analysis, sorting and identifying waste and will be better suited to provide immediate feedback on the interaction of the lean tools with certain aspect of the operative processes in the organisation (SOE).

The research of insert author Ngonini [30] identified that one of the reasons for inefficient lean transformation is the shortages in frameworks or plans for implementing lean. Furthermore, the researchers analysed shortfalls in several lean implementation frameworks and found the following:

- Most of the current available lean frameworks were prone to a top-down approach but not bottom-up (see Table 1).
- Improvement initiatives from the shop floor employees were often overlooked by researchers.
- In proposing their frameworks, most of the researchers had neglected the importance of the "Why" aspect in the adoption of tools, techniques, and practices (TTPs) of the framework itself without giving the "reason "for each of the elements in lean implementation.
- The current frameworks were prone to a "one-best-way "approach with lacking contingency which is one of the common criticisms against a lean.

Although the frameworks differ, a common recurrence from their findings appears to be limited by their lack of focus on contextual variables of the state-owned entities and that most frameworks are prone to top-down approached as opposed to bottom-up approaches. In South Africa, state-owned entities organisations with the government as the sole or majority shareholder of many SOEs, often enter into a shareholder's compact or agreement with the respective SOEs. This compact outline the strategic objectives, performance targets, reporting requirements, and governance arrangements for the SOE. It serves as a tool to enhance transparency, accountability, and performance of the SOEs [31]. Unfortunately, these strategic objectives are often driven from the top down and poor conception as well as agreement about the strategy often leads to one-dimensional and narrow perceptions that negatively affect implementation.

To overcome the limitation of the reviewed lean manufacturing frameworks, the existing lean manufacturing frameworks may need to be adapted so that they can help to simplify and streamline the processes in the state-owned entities organisations making them more prone to the identification and creation of value for the customer, while reducing waste which is the overall aim of the lean approach. A further consideration is how the contingencies of the state-owned entities context can aid the adaption of lean manufacturing principles within the SOE environment. The synopsis of the frameworks is presented (see Table 1).

Table 1: Consolidated view of the lean manufacturing frameworks reviewed

Author	**Description of lean framework**	**Findings**	**Limitations**
Xu, Tiwari and Chay (2015:1031)	Provide an analysis of existing lean implementation frameworks	Through the analysis of different frameworks, the researchers found that, some of the lean production principles were often overlooked by the researchers hence they failed to deliver the gist of lean	Most of the analysed frameworks were prone to top-down approach, neglecting to include shop floor workers and supervisors from the onset.
Anvari *et al.* (2010)	Lean framework with 3 implementation stages (preparation, design and implementation).	Framework provides a contingency approach or a dynamic lean	Worth to note, the framework presented biased towards top-down approach and carried out on discrete

		pathway for different types of industries based on "understanding your current state and your desired future state".	project basis where the implementation initiatives are mostly from the top management.
Karim & Arif-Uz-Zaman, (2013)	Effective framework for implementing lean manufacturing strategies	Proposed methodology can systematically identify manufacturing wastes, select appropriate lean tools, identify relevant performance indicators, achieve significant performance improvement and establish lean culture in the organisation.	Method developed has been demonstrated by applying it in real life assembly process and not in a continuous flow process which is a setting for some South African state -owned Enterprise (SOE).
Belhadi, Tourki &Fezazi, (2016:86)	Framework for lean production systems.	The proposed frameworks provide an overcoming for the gap identified in existing frameworks. It also brings together a set of critical elements for lean implementation in SME's.	The study is limited by the fact that its applicability is only favourable to implementation only in SME and is not general enough to suite differing contexts.

3 LEAN MANUFACTURING CONCEPTUAL FRAMEWORK

Several lean manufacturing frameworks have been developed and used in different industries, drawing inspiration from the Toyota Production System (TPS) and other comparable approaches. The potential of frameworks such as Value Stream Mapping (VSM), Six Sigma, Kanban, and Total Productive Maintenance (TPM) has been demonstrated in various studies [21, 22, 23]. These frameworks have shown effectiveness in streamlining processes, optimising resource utilisation, and reducing non-value adding activities. Nevertheless, the use of these frameworks in the public sector requires meticulous examination due to the distinct attributes and dynamics inherent in the public sector environment.

Put simply, the application of lean manufacturing principles in the public sector poses unique problems and opportunities. The public sector is distinguished by its focus on providing services to residents and stakeholders, and functions under a framework that is notably distinct from profit-oriented private firms. Consequently, the use of conventional lean approaches may necessitate modifications to address the intricacies inherent in the public sector. Some of the intricacies in the public sector include a multitude of stakeholders, a wide range of service offerings, and a primary emphasis on generating public value rather to solely pursuing financial benefits. From the contingency perspective, which emphasises the need to match organisational practices with the specific context [14], this study argues that a bottom-up framework offers a more suitable path for lean implementation within the public sector. Bottom-up lean implementation allows for flexibility and adaptability, enabling departments and units to tailor lean principles to their specific needs. This approach acknowledges the diversity of services provided by the public sector and empowers frontline employees to devise solutions that are best suited to their operational context [34, 35].

Figure 1 has been constructed by the researcher for this study. The relationship between the concepts, theory and variables in the framework were established from the review of literature and existing lean manufacturing frameworks that have been developed for the application of lean principles in different organisations and industries. From the critical review of the existing lean manufacturing frameworks, there are similar approaches to the implementation of lean, however the growing complexity and variability of the SOE environment, requires an understanding of the strong interactions among the organisational context and the lean principles. The conceptual framework indicates the conceptualisation of lean manufacturing principles through adopting Albjorn's [10] model that presents three layers of lean conception namely, lean philosophy, lean principles, and lean tools. The layers of lean are explored using the contingency theory and were used in formulating Figure 1. The proposed conceptual framework integrates leadership, strategy, organisational context, and concepts of fit and adapt to guide the effective adaptation of lean principles in the state-owned entities. By emphasising the importance of leadership buy-in, stakeholder engagement, and strategic alignment, the framework promotes a holistic approach to lean implementation.

3.1 Leadership and Stakeholder Alignment

The leadership style of public sector leaders plays a crucial role in initiating and sustaining lean initiatives. Leaders should advocate for lean principles and engage stakeholders to provide the necessary support [36]. Organisational leadership is an important aspect of adapting lean manufacturing principles to an organisation and without committed leadership who understands and translates lean into strategic lean programmes, such initiatives will likely fail [4].

3.2 Strategy

Lean principles should be integrated into the organisation's strategic plan to ensure congruence between lean initiatives and the organisation's overarching goals [36]. Lean initiatives must align with the unique goals, priorities, and mandates of public sector organisations [12]. Secondly, through the proposition of contingency theory includes the design of organisational inputs, and processes to meet requirements of the customers or citizens for the successful development of a lean implementation strategy for the organisation [25,18].

3.3 Organisational context

Regulatory and Political environment recognises the influence of regulatory constraints and political dynamics on lean implementation. Adapting lean strategies includes the ability of the organisation to navigate these challenges while ensuring compliance [37]. In addition, the context of the organisation entails, the analysis of the internal and external issues [15].

3.4 Fit and adaptability

Finally, the tools are selected to the specifics of the organisation and may enable employee participation in fault finding, reduction of waste, process improvement and organisation wide learning. For example, gemba walks can be implemented in one organisation for process improvement whereas another organisation may find 5S tool for sorting more effective[37].

SOE can therefore tailor lean principles to accommodate the regulatory, political, and service diversity challenges of public sector entities. This will incorporate flexibility into lean initiatives to navigate the evolving needs and expectations of stakeholders [15].

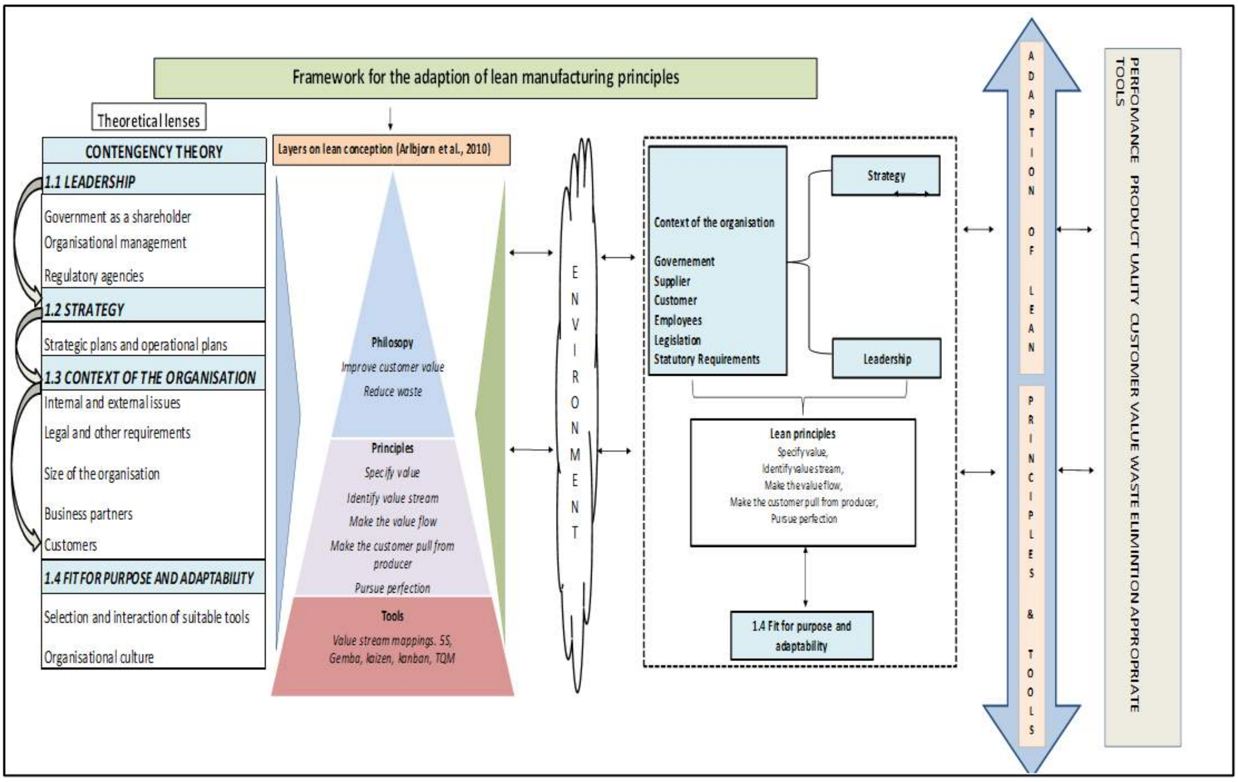

Figure 1: Conceptual framework (Author's compilation)

4 METHODOLOGY

The objective of this study was to examine the difficulties associated with the implementation of lean manufacturing frameworks within state-owned entities. The selection of a qualitative case study methodology was deemed suitable for this study to investigate the distinctive characteristics of public sector contexts and to obtain rich descriptions and in-depth understanding of how lean can be used in SOEs. The appropriateness of employing qualitative research methods to generate comprehensive and detailed portrayals of how lean manufacturing frameworks can be extended to state-owned entities (SOEs) within their existing settings. This includes examining how value is created and their interactions with the public, as extensively discussed by Clark and Creswell [38].

4.1 Sampling strategies and sample of the research

Three state-owned entities classified as being in the red zone category were purposively selected for this study due to their representation of complex service networks that typically extend over many geographical regions. This complexity introduces unique operational challenges that are representative of public sector organisations in the red zone category [16]. Examining how these organisations effectively manage challenges such as operational waste, service availability, and resource utilisation yields significant knowledge regarding the creation of value. One of the benefits of purposive sampling is that it entails the deliberate identification and selection of individuals who possess a high level of proficiency and knowledge regarding a certain phenomenon of interest [39].The researcher adhered to the fundamental principle of the purposive sampling technique, which involves selecting samples based on their ability to offer important information rather than their representation of a larger population [40]. In this study, a total of twelve employees were selected from the list of employees provided by the organisational gatekeepers. The selected employees represented a diverse range of positions, including male and female managers, officers, engineers, administrative people, and plant staff assistants. These employees were selected by the gatekeepers from organisations A, B, and C, respectively.

4.1 Data collection methods

A semi-structured interview guide was employed to elicit and investigate insights concerning the challenges encountered in the adoption of lean manufacturing frameworks within state-owned entities. Scholarly work by Saunders et al. [40] and Yin [39] extensively discuss the benefits of employing semi-structured interviews to prompt and explore essential information relevant to a specific phenomenon. The interview guide encompassed questions pertaining to leadership, strategy, context of the organisation, and fit of strategies as aligned with the constructs of the contingency theory. The interviews were conducted using a qualitative methodology. All interviews took place virtually through Microsoft Teams due to the restrictions induced by the Covid-19 pandemic. These semi-structured interviews were supplemented by document analysis from the websites of the state-owned entities. The interviews were substantial in length, ranging from 40 to 45 minutes, ensuring comprehensive insights into the challenges faced by state-owned entities and their understanding of the intricacies of lean manufacturing frameworks. Despite the inherent diversity in state-owned entities, a purposive approach was adopted to ensure a degree of homogeneity among interviewees. This approach specifically focused on selecting entities with similar business characteristics, including employee count (a determinant of state-owned entities' scale), classification of lean implementation (organisational level or specific process improvement), and homogeneous sector attributes (such as energy production or transportation services). This concerted effort aimed to ensure that the challenges and adaptations discussed are pertinent and aligned within the context of state-owned entities adopting lean manufacturing frameworks.

5 DISCUSSION

The review of the literature regarding lean manufacturing frameworks has indicated that lean should be adapted to suit different contexts. Although the reviewed frameworks offer a significant contribution, most of the frameworks reviewed presented bias towards a top-down approach [32]. One problem with the top-down approach is that it creates a lack of accountability and lack of innovation and ownership where employees of the organisation lack taking initiative. Furthermore, the top-down approach introduces agency problems caused by the agents (managers of the organisations) focusing on their own interests to the detriment of organisational goals [33]. In the absence of strong leadership providing direction to employees, employees may squander and mismanage input resources, not attend to undirected requirements, and place heavy reliance of the PFMA (National Treasury, n.d.) without showing some initiative to resolve some issues which can lead to unjustified delays, long turnaround times, increased waste and less continuous improvement strategies implemented. Lack of direction can also lead to feelings of apathy, low morale and not creating value for the customers of the state-owned entities.

The external environment affects the operational and strategic objectives of the organisation. The researcher argues that the adaptation of lean principles for state-owned entities in state-owned entities must be adapted to incorporate contextual factors (stakeholders, shareholders, political influences amongst others). One external issue within state-owned entities is the multiple and quite fragmented stakeholder groups that each place different demands on the SOEs and can affect its intended results. The internal environment of state-owned entities will dictate the applicability of the different types of lean tools that can be used given the availability of resources and other factors. There is no one size fit all solution of lean principles that can be used across state-owned entities. In fact, lean principles may differ from one business unit to the next within one state-owned entity.

The researcher argues that a bottom-up approach allows for the consideration of the local context and specific challenges faced by different departments or teams within the SOE. Furthermore, employees working on the frontlines often possess valuable knowledge about the organisation's operations, processes, and inefficiencies. By involving them in the improvement process, their expertise can be leveraged to identify and address issues that may have been overlooked in a top-down approach. The bottom-up approach also encourages employees who are closest to the work processes to identify opportunities for improvement and suggest innovative solutions. This can lead to the development of new ideas, techniques, and approaches that may have a significant positive impact on the SOE's efficiency and effectiveness.

5 CONCLUSION

The study outlines contingency theory as the theory that underpins the adaptation of lean within SOEs. SOEs must deliver services by creating value for the public through continuous improvement efforts and reduction of waste. The adoption of lean manufacturing principles in the state-owned entities should be adapted to suit contextual factors that are influencing specific state-owned entities and their business units. The contingency lens provides the impetus to drive specific strategies, policies, and resources that can interact with the lean socio-technical system to reduce waste and improve the processes within SOEs. The study argues that adapting lean principles for SOEs requires a bottom-up approach in adapting lean principles to an organisation and considers empowering employees to contribute to creating customer value and elimination of non-value-adding activities.

The bottom-up approach can drive positive employee performance through active involvement and proper engagement which in turn could lead to continuous improvement initiatives and improved value creation. It is recommended that SOEs should adapt lean principles subject to internal and external contextual factors that may impact business processes. Future studies may incorporate SOEs in the yellow and green categories to identify how the use of lean principles and tools may differ across these different categories of SOEs. The study may be of value to SOEs, in adapting the lean principles to the specific contexts and processes particularly considering incorporation the feedback from their employees.

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DEFINING AND QUANTIFYING VENTILATION MODELLING ERROR FOR DEEP-LEVEL MINES

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ABSTRACT

In deep-level mines the ventilation network plays a critical role in sustaining a safe and productive work environment for personnel underground. The ventilation system is planned using simulation packages to ensure that legal requirements are met regarding volumes and temperature limits. Even though the theory of such networks is well understood, the propagation of error from the inputs to the outputs are uncertain which undermines the aim of ventilation planning. This study modelled an underground ventilation network and identified possible ranges for the inputs. A Monte Carlo simulation was used to test the sensitivity of different error metrics for use in model validation. Differential entropy was used to quantify the sensitivity of the metrics. The two proposed metrics were the most sensitive, with differential entropies of -1.70 bits and -1.41 bits, respectively. This is an improvement over MAE and MAPE, with differential entropies of -2.84 bits.

Keywords: Mine ventilation, simulation, error metrics, information entropy

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1 INTRODUCTION AND LITERATURE:

The ventilation network in deep-level mines plays a critical role in maintaining a safe working environment underground [1]-[3]. Ventilation planning is required to provide the necessary environmental conditions underground and benefits the mining company since insufficient planning might lead to production delays and increased operating costs [4], [5].

The typical deep-level mine ventilation system is quite complex. This requires mathematical modelling and simulation for planning, which is not as resource-intensive as field experiments [6]. Mine ventilation modelling has now been established as the primary tool in modern mine ventilation planning [7]–[9].

The model builder needs to specify accurate inputs in order for the model to give accurate outputs (GIGO) [7]. This is not always the case, with the most common error in mine ventilation simulations stemming from inaccurate estimations of airflow resistance [7]. To make appropriate decisions when using predictions from a simulation model, knowledge of the accuracy and uncertainty of those results are required [10]. This problem of accuracy and uncertainty is addressed in model validation, which by definition is the process of determining whether a mathematical model is an accurate description of a process or system [11]-[16]. It is therefore essential that the ventilation model be validated [9].

There is little to show on the validation of mine ventilation simulations. Wallace *et al.* [9] only recommends the comparison of model outputs against empirical data. Similarly, Labuschagne [8] proposes the comparison of model outputs against empirical measurements using mean absolute percentage error (MAPE). Labuschagne [8] recommended that any areas that displayed a MAPE higher than 10%, should be investigated for modelling errors. A similar procedure was used for the validation of computational fluid dynamics (CFD) models used in mining by Xu *et al.* [17]. This procedure quantified the difference between the measured values and predicted values using the root mean square error (RMSE). Another study that focused on mine ventilation modelling used mean square error (MSE) and the coefficient of determination (R^2) to validate the model [18]. No accepted value of the RMSE was given by Xu *et al.* [17] or for the MSE used by Fair *et al.* [18].

The use of error metrics is well suited to the validation of mine ventilation simulations since multiple simulation runs and measurements are either prohibitively expensive or unavailable. This means that statistical validation techniques are largely redundant because multiple simulation runs or measurements are required to build statistical models.

Ventilation modelling is an essential tool in ventilation planning, but the accuracy of the model is unknown [7]. An understanding of the model accuracy is essential when basing decisions on simulation results [10], [13], [19]. Thorough validation practises are therefore required if decisions are to be guided from simulation results. This requires the use of sensitive error metrics to compare predictions against measurements. Given a likely range of errors, metrics are less sensitive to simulations that fall into this range. This problem leads to:

- insensitive validation criteria—when based on the metric,
- the faulty acceptance of models as valid, and
- overconfidence in the model.

This suggests the use of information entropy, which describes the uncertainty or information content of a variable [20], [21]. A metric that has higher information entropy will be more sensitive than one of low information entropy. A sensitive metric aids the model builder by distinguishing better between models by error. This reduces the risk of faulty model acceptance.

This paper aims to evaluate and recommend different validation metrics for use in mine ventilation modelling based on their sensitivity. This was done by comparing the information content or information entropy of the probability distribution function (PDF) of four chosen metrics for a mine ventilation circuit.

2 METHOD

A controlled experiment was used to test the following hypothesis [22], [23]:

The model builder can improve the validation test by choosing a more sensitive metric.

The validation test refers to whether a model is rejected if the error metric is larger than a chosen threshold, or accepted when below a chosen threshold. The validation is improved when it employs a more sensitive metric. This study will define the sensitivity of the metric as its ability to differentiate between simulations, based on their errors. This formulation implies the metric takes both the magnitude and probability of the errors into account. The sensitive metric would then give an output that is:

1. Proportional to the error.
2. Increases differences between errors that are more probable to occur.

By extension, statement 2 increases the difference between two probable simulations and therefore the sensitivity of the validation test. This is explained with a simple example. Consider a probability distribution function (PDF) of errors for a simulation which is quantified using two different error metrics: metric A and metric B. Figure 1 and **Error! Reference source not found.** show the PDF of metric A and metric B, respectively.

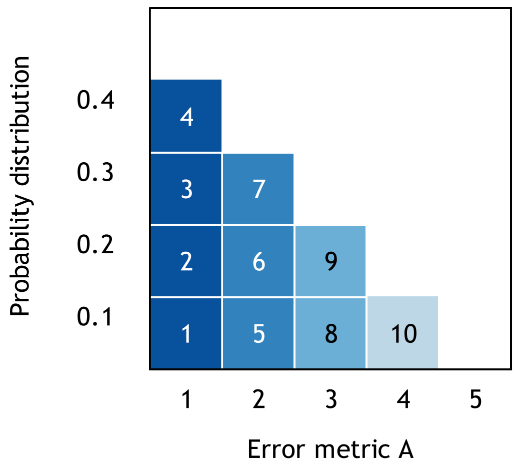

Figure 1: PDF of metric A

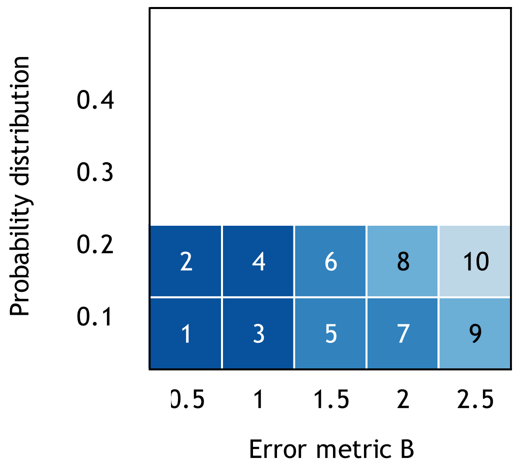

Figure 2: PDF of metric B

From the definition proposed, metric B is more sensitive than metric A. This is because metric B has more resolution to the smaller errors: squares 1-4. This allows a validation test that uses metric B to differentiate between squares 1 and 2 against 3 and 4. A similar phenomenon occurs with squares 5-7. Metric B can differentiate between squares 5 and 6 against 7, whereas metric A cannot. This definition corresponds to the information entropy of a metric. Metric B has higher entropy than metric A, because on average there is less certainty in the probability of individual bins occurring than in metric A.

2.1 Data generation

The controlled experiment compares the information content of four different metrics. The independent variable is the error metric used, which results in an information entropy value for each. Therefore, the information entropy calculated is the dependent variable.

The error of the simulations was based on the air flows, since it is also the quantity of interest. Oberkampf and Roy's [24] definition allows us to write this using Equation 1:

$$E_{sim} = Q_p - Q_m \tag{1}$$

Here, E_{sim} is the error of the simulation, Q_p is the predicted air quantity and Q_m is the "correct" or measured air quantity. The four metrics tested were the mean absolute error (MAE) as given by Equation 2:

$$\text{MAE} = \frac{1}{n}\sum_{i=1}^{n}\left|Q_p^i - Q_m^i\right| \tag{2}$$

The mean absolute percentage error (MAPE) as given by Equation 3:

$$\text{MAPE} = \frac{100}{n}\sum_{i=1}^{i}\left|\frac{Q_p^i - Q_m^i}{Q_m^i}\right| \tag{3}$$

Two proposed metrics, the mean logarithmic absolute error (MLAE) as given by Equation 4:

$$\text{MLAE} = \frac{1}{n}\sum_{i=1}^{n}\log\left|Q_p^i - Q_m^i\right| \tag{4}$$

As well as the mean square root absolute error (MSRAE) as given by Equation 5:

$$\text{MSRAE} = \frac{1}{n}\sum_{i=1}^{n}\sqrt{\left|Q_p^i - Q_m^i\right|} \tag{5}$$

Many such metrics exist, but MAE and MAPE was chosen since they are popular [8], [25]-[27]. The proposed metrics of MLAE and MSRAE was chosen because of the logarithmic and root function's shape: a large derivative near zero, that steadily drops off for larger values.

The MAE is the absolute value of E_{sim} whereas MAPE expresses E_{sim} as an absolute percentage of the measured value. MAPE is the absolute value of the relative error (RE). The proposed metrics, MLAE and MSRAE, passes E_{sim} to a function. For MLAE this function is logarithmic, while for MSRAE it is a square root.

Note that these metrics are expressed as a mean but was tested for only distributions of one error pair of Q_p and Q_m. This simplifies the analysis to the effect of different functions on individual errors, rather than the additional effect of different averaging techniques over many errors. Therefore, the proposed metrics employ a simple expected value or mean when used over many errors, similar to MAE and MAPE.

The metrics are then calculated over many different simulations. This allows the construction of a PDF for each metric, similar to Figure 1 and Figure 2, but requires the use of a Monte Carlo simulation.

2.1.1 Monte Carlo simulation

The study used a Monte Carlo sampling method, since it can be considered the most accurate for uncertainty propagation methods [14]. This method consists of repeatedly sampling inputs from predetermined PDFs and calculating the output to generate the data. The simulation consisted of a hydraulic network which was solved using the Hardy-Cross method as outlined by Sereshki *et al*. [3], and du Plessis [5] for different sets of inputs and represent steady state air flows.

To calculate the error, an accepted value for each branch is required [24]. Rather than opt for the periodic measurements by the case study mine, a "standard" ventilation simulation method was taken to represent the "correct" air flows. This evades the problem of measurement errors and assumes the model builder has an "accepted" value to assess predictions with. This can be a mean of multiple measurements, expert opinion, legally reported value, or combinations thereof.

2.1.2 Probability distribution functions

To construct the Monte Carlo simulation, the uncertainty of the different inputs had to be considered. When describing the uncertainty in inputs for the simulation, the following sources of uncertainty were included:

1. Numerical error due to iterative solutions or interpolation.
2. Ranges of friction factor reported in the literature.
3. Possible misplacement of nodes on ends of haulages (affects length used).
4. Possible curvature of haulages (affects length used).
5. Range of haulage dimensions (affects both perimeter, area and friction factor).
6. Reported uncertainty of minor resistances.
7. Performance of fans.

This was done by specifying PDFs for the different inputs to the model. The air flows are calculated by sampling the inputs and solving the network for each run of the simulation.

2.2 Entropy calculation

Information entropy is defined differently for the discrete and continuous cases, but this study will use the formulation for the continuous case (differential entropy) as defined by Jaynes [29] and is given by Equation 6:

$$H(x) = -\int p(x)\log\frac{p(x)}{m(x)}dx \qquad \textbf{\textit{(6)}}$$

Here, $H(x)$ is the information content and its units depend on the logarithm. For this study the base-two logarithm will be used, resulting in units of bits. $H(x)$ directly corresponds to the difference in bits required to encode the event $p(x)$ against $m(x)$. $p(x)$ is the probability density function (PDF) of x and $m(x)$ is a uniform probability density of the input x [29], [30]. $H(x)$ was calculated by estimating $p(x)$ and $m(x)$ from a histogram constructed using the results of the Monte Carlo simulation.

The maximum entropy for any metric is zero, with smaller values indicating less entropy. Therefore, metrics that have differential entropies of zero requires as many bits to encode as $m(x)$, with negative values meaning less is required.

3 RESULTS AND FINDINGS

The method was implemented for a section of a case study mine which is shown in Figure 3. It constitutes a development end where fans are extensively used to ventilate the working areas. The section is located on one level with little to no height difference, therefore the effect of natural ventilation pressure was neglected. Additionally, the air density was assumed constant, at 1.2 kg/m^3, and the pressure drop over the entire section was calibrated to 700 Pa beforehand. This represents a small pressure drop, with little to no vertical changes which supports the assumption of constant density [5], [28], [31]–[33]. It was assumed that the ventilation door forms a seal making its branch resistance arbitrarily large.

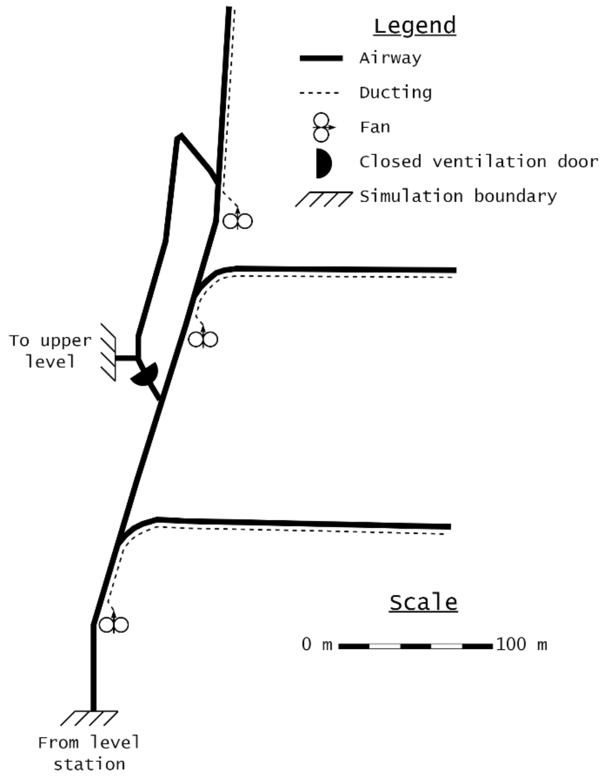

Figure 3: Case study ventilation network layout

3.1 Monte Carlo simulation

The Monte Carlo simulation was constructed by quantifying the uncertainty of the different sources from the method. Therefore, knowledge of how the hydraulic network was created is necessary. The pressure loss along the length of a haulage was calculated using the Atkinson equation as given by Equation 6 [5], [7], [8], [28], [34], [35]:

$$\Delta P = \frac{k_{1.2}LP}{A^3} \times \frac{\rho}{1.2} Q^2 \qquad (6)$$

Here, $k_{1.2}$ is the Atkinson friction factor, L is the length of haulage or duct, P is the perimeter, A is the area, and Q is the volumetric flow rate. Note that the Atkinson friction factor is typically calculated for an air density of 1.2 kg/m^3. For the calculation of minor losses through contractions, expansions, bends and tees, the methods of Rennels and Hudson [36] were employed. Using these inputs, a breakdown of the uncertainty is given below.

3.1.1 Numerical error

To limit the numerical error, convergence was achieved only when the maximum adjustment in flows from one iteration to the next was less than 0.002 m^3/s. The fan curves had to be interpolated and was calculated with increments of 0.001 m^3/s. Therefore, the error introduced by interpolation cannot be larger than the 0.002 m^3/s allowed for convergence.

3.1.2 Friction factors

A wide range of friction factors were found in the literature, spanning orders of magnitude for similar descriptions. This is shown in Figure 4 using only one axis to represent the friction factors. This constitutes an enormous amount of uncertainty but should be expected since the friction factor depends on [5], [37]:

1. Mining method.
2. Supports and lining present.
3. Rock characteristics.
4. Haulage size and shape.

The suggested values of Montecinos and Wallace [37] were employed in the simulation since it takes the type of support into consideration and is independent of haulage sizes.

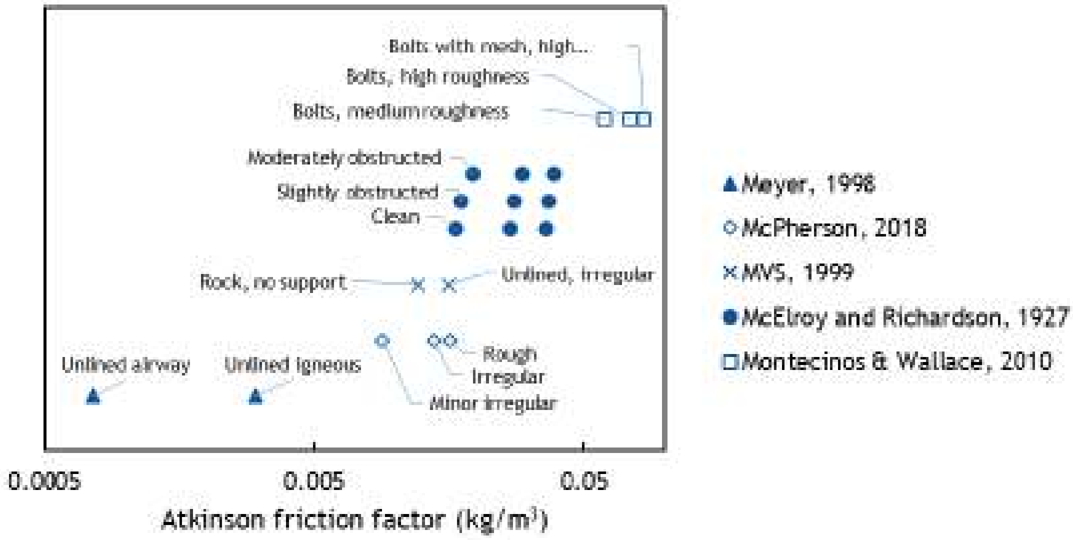

Figure 4: Comparison of Atkinson friction factors in the literature [5], [34], [37]-[39]

3.1.3 Haulage length

The length of the haulages was measured from layouts with uncertainty up to one haulage width in case the node was offset during model development. Similarly, possible curvature of the haulage was included as uncertainty in its length. This was calculated based on the assumption that the curvature was similar to that of a circle with a radius equal to the measured haulage length. The uncertainty in the length of ducts was specified using the standards of the case study mine and the smallest duct length with which to comply with the standards.

3.1.4 Haulage dimension

Measurements were used to construct a uniform distribution for both the width and height. This would then be sampled for each branch separately between different simulation runs to calculate the area and perimeter.

3.1.5 Minor resistances

Rennels and Hudson [36] recommends uncertainties for different minor losses. This was used to construct distributions for the minor losses in the simulation.

3.1.6 Fan performance

The fans were specified using performance reports of four similar fans obtained from the case study mine. The variance and mean of the four fan performance curves were used to construct confidence intervals (CI) using the t-distribution as shown in Figure 5. It is important to note that the curve does not describe the actual fan performance data, but rather the fan performance data as calculated using the fitted parabolas from the performance reports. This includes estimates of the maximum measurement error as recommended by Daly [40] for standardised tests.

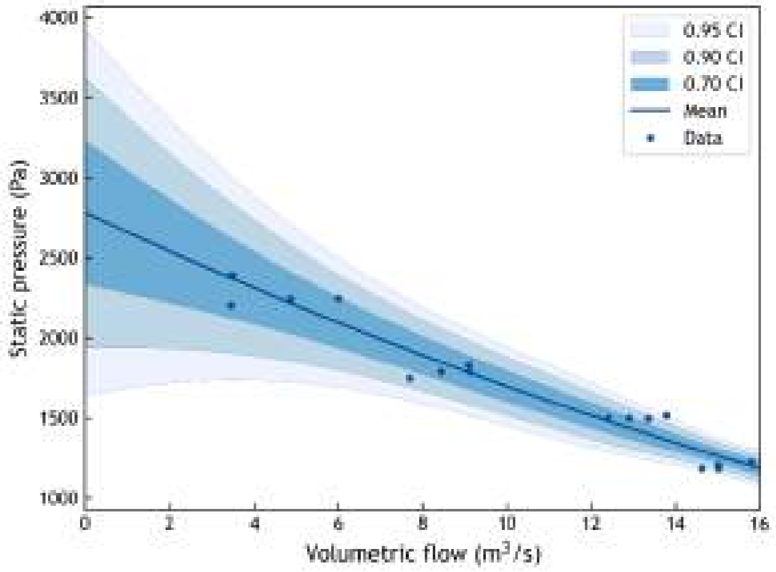

Figure 5: Fan characteristic curve with confidence intervals

3.2 Entropy calculation

The air flows for both the Monte-Carlo and standard simulation method were simulated and is shown in Figure 6 for the inlet to the area. This PDF represents 99 846 different runs, with a minimum air flow of 15.88 m^3/s and a maximum of 18.23 m^3/s. The standard simulation showed an airflow of 17.91 m^3/s, which is close to the mean of the Monte-Carlo simulation, at 17.87 m^3/s. This difference was expected since the mean of the inputs do not necessarily map to the mean of the output [24]. All the figures and differential entropy calculations use histograms with 100 bins. This corresponds to a maximum entropy of 6.64 bits when encoding the 100 different bins.

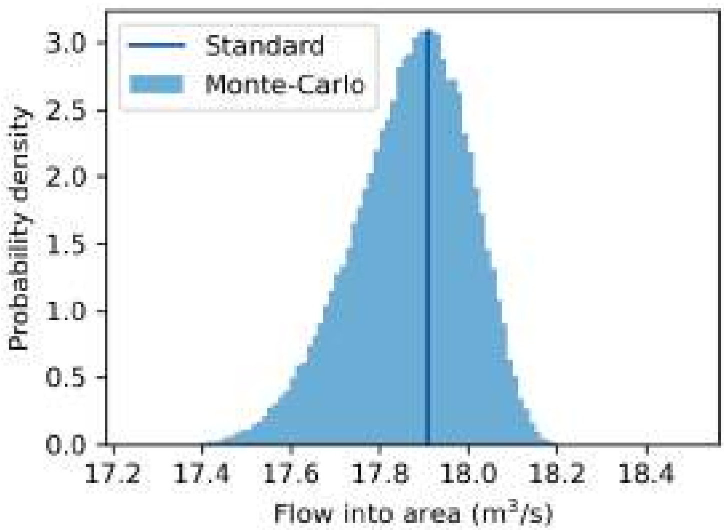

Figure 6: PDF of air flow into section

Figure 7 and Figure 8Figure 8 show the PDF for MAE and MAPE, respectively. The differential entropy for both MAE and MAPE was calculated at -2.84 bits. This makes sense when comparing Figure 7 and Figure 8Figure 8: their distributions are similar with only scaling in axes. This indicates their information content is similar and there is no benefit in using one to the other for the single location being compared. Note how small errors are more likely than larger errors, which reduce the information entropy for the metrics since there is less uncertainty in the result of the metric.

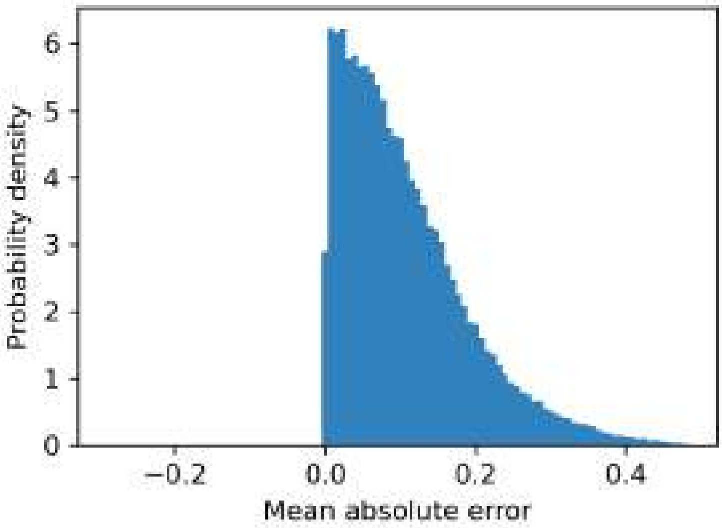

Figure 7: PDF of MAE

One might have expected that MAPE, like relative error (RE), should flatten the probability distribution and increase the differential entropy. Keep in mind that the figures compare only one location and therefore scales all the errors with one accepted measurement.

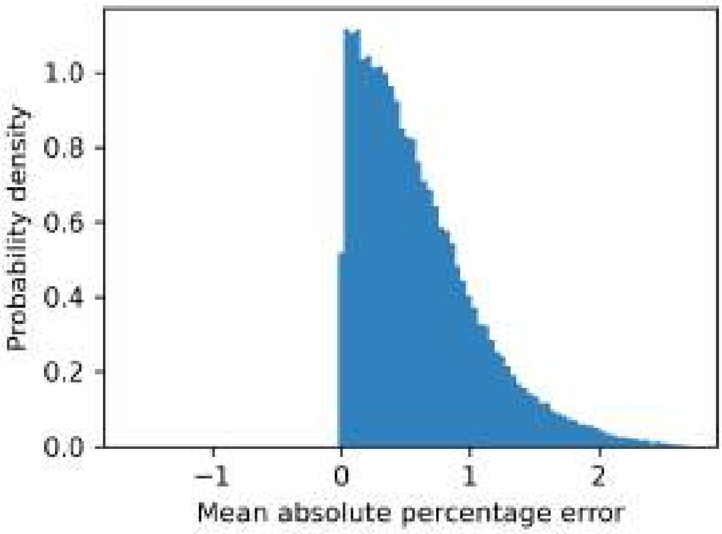

Figure 8: PDF of MAPE

When more than one location is included, the different measured values do change the distribution of errors over multiple simulations. This can be generalised to Equation 7:

$$M = \sum_{i=1}^{n} \frac{c_i}{n} f\left(x_p^i - x_m^i\right) \tag{7}$$

Here, C_i are constants used to change the final metric, M. In the case of a mean, $C_i = 1$. Therefore, MAPE can be seen as a weighted average of the errors where $C_i = \frac{1}{Q_m^i}$. Relative error-based metrics therefore do not change the information content of $f(x_p - x_m)$ but rather that of M by weighting with different C_i.

Figure 9Figure 9 and Figure 10 show the probability density distributions for the two proposed metrics, MLAE and MSRAE. The differential entropy of MLAE and MSRAE was calculated at -1.70 bits and -1.41 bits, respectively. The differential entropy of MSRAE was the lowest, at -1.41 bits. This is an improvement of 1.44 bits over MAE and MAPE, indicating the metric has the highest differential entropy of the four metrics tested and is therefore the most sensitive.

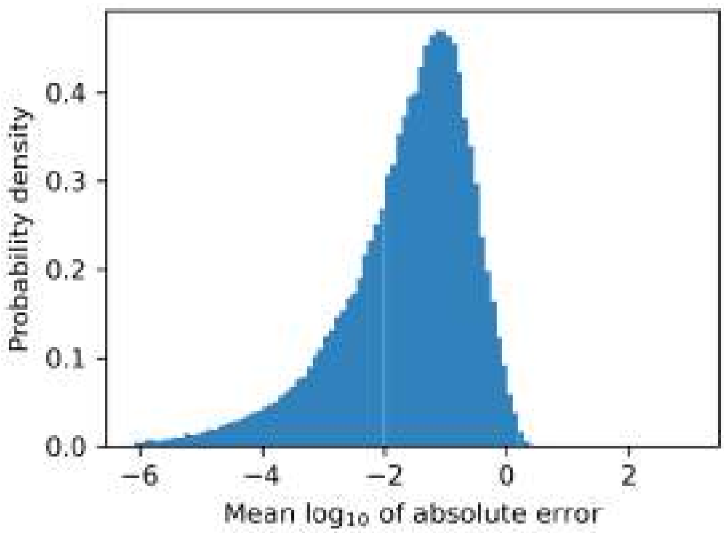

Figure 9: PDF of the $\log_{10}$ of the absolute error

When comparing Figure 9 and Figure 10 against that of Figure 7 and Figure 8, the difference in differential entropy is apparent. Even when considering the scaling of axes, the PDFs of MLAE and MSRAE is more distributed than that of MAE and MAPE. This increases the uncertainty in the final metric and therefore the information entropy.

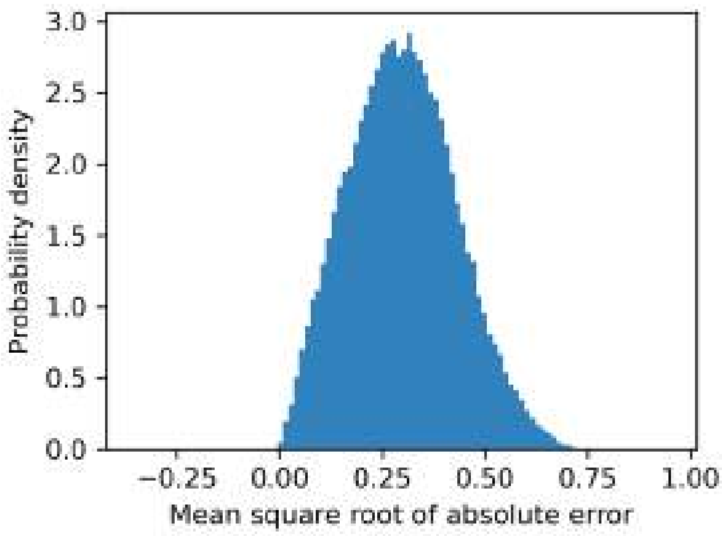

Figure 10: PDF of the square root of the error

As explained, the differential entropy is the difference between the number of bits required to encode $p(x)$ as compared to $m(x)$. For the case of 100 bins, 6.64 bits is required to encode $m(x)$. Taking this into consideration, MAE and MAPE requires 3.80 bits whereas the MLAE and MSRAE requires 4.94 bits and 5.23 bits respectively. This is a large improvement, but is sensitive to the presence of outliers in the data.

Note that the MLAE and MSRAE do not consider the underlying PDF of the error. This was a necessary criterion since the underlying PDF is not known in advance and at best for only a few simulations. Therefore, parametric information cannot be used to construct a tailored metric to flatten the PDF.

The effectiveness of the metric is also dependent on the mean error and its variance. The MLAE and MSRAE naturally increase the differential entropy when small errors are more probable than larger errors as in the case of Figure 6. This is because the derivative of both the logarithm and square root function is large near zero, but decreases for increasing values. This allows smaller errors to spread out more than the larger errors—increasing the differential entropy. The model builder should be cautious when choosing error metrics during model development since this condition might not be valid.

Other methods, such as those outlined by Oberkampf and Roy [24], detail the properties that a metric require: it has to be positive, objective and measure some difference between simulation and measurement. Compared to this, the results quantify the difference in sensitivity between metrics that all fulfil the properties required. This allows the most sensitive metric to be identified.

4 CONCLUSION

The sensitivity of MAE, MAPE and two proposed metrics—MLAE and MSRAE, were tested for use in mine ventilation simulation. From the difference in differential entropy for the metrics the hypothesis was confirmed: the validation test can be improved when employing more sensitive metrics. Both the MAE and MAPE had differential entropies of -2.84 bits. This was improved upon by the MLAE, having a differential entropy of -1.70 bits. The MSRAE had the smallest differential entropy from the metrics tested, at -1.41 bits. This means the MSRAE had the highest information entropy between the metrics considered and was therefore the most sensitive.

The proposed metrics, MSRAE and MLAE, can therefore assist the model builder by distinguishing better between different models. This reduces the risk of faulty model acceptance. The scope for future research includes larger ventilation models and comparing the error of multiple locations. This would give a more complete understanding of different error metrics and explain the effect of varied air flow magnitudes and averaging techniques.

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INTELLIGENT OEE BASED DASHBOARD DESIGN FOR UNDERGROUND MINING APPLICATIONS

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ABSTRACT

Smart solutions are technology driven platforms driving innovation. These solutions have enabled the development of an intelligent dashboard. The purpose of the dashboard is to provide real-time insights into the performance of mining equipment and processes, enabling mining companies to optimize production, reduce downtime, and increase efficiency. The dashboard uses analytics and data visualization techniques to provide a user-friendly interface for mining operators, supervisors, and managers. Mining operations are highly dynamic necessitating timeous decision making. Decisions in underground mining can range from a simple operations decision to a complex life-threatening safety decision. This study focuses on the development of an intelligent overall equipment effectiveness (OEE) based dashboard as an integral part of mining operations decision support system.

Keywords: Overall Equipment Effectiveness (OEE), Dashboards, Mining

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1 INTRODUCTION

Overall Equipment effectiveness (OEE) is a frequently used benchmark for determining the effectiveness of a production system; it evaluates the equipment's availability, performance, and output quality [1], [2], [3]. Mining companies can rely on key performance indicators (KPIs) such as OEE to monitor and control production, operational efficiency, and safety. The latter also contributes to sustainability efforts in the mining industry. Mine management have always had to deal with elevated levels of uncertainty and delayed/inadequate operational information, compromising decision making [4]. Traditional management information systems focused on historical reports may not be adequate in the current fast paced competitive operational environment. Management decision support systems may be enhanced through availability of real time operational data/information to management. This enhances agility effectiveness and operational efficiency. Dashboards in their various forms provide timeous data to decision makers. Dashboards have evolved in sync with technological developments, from signal and data presentation to data processing and intelligent manipulation/ presentation of input data.

An OEE based intelligent dashboard can provide comprehensive data collection and timeous visibility into the operational equipment and processes. Industry 4.0 driven technologies have facilitated the evolution of dashboards enabling real time data presentation [5].

Industry 4.0 has steered research studies in OEE [6] and mining as researchers attempt to establish frameworks and assess the applicability of industry 4.0 technologies. Industrial Internet of Things (IIoT) and Machine Learning are among the top technologies facilitating improved remote process monitoring and control. Smart data exploitation offers numerous competitive advantages that influence key performance measures like quality, productivity, and efficiency [5].

The study seeks to design an intelligent OEE-based dashboard that integrates data acquisition, processing, and visualization for real-time monitoring and decision making. To identify and integrate applicable 4IR technologies in dashboard design and development as an integral part of decision support systems.

The case company faces difficulties with timeous capturing, validating, and processing manually captured operational data. The over reliance on radio/telephonic communication through control rooms to report incidences is problematic and inefficient. We seek to automate the fault/incident sensing, identification, communication, recording and presentation processes in underground mining. Appropriate enabling technologies have been identified.

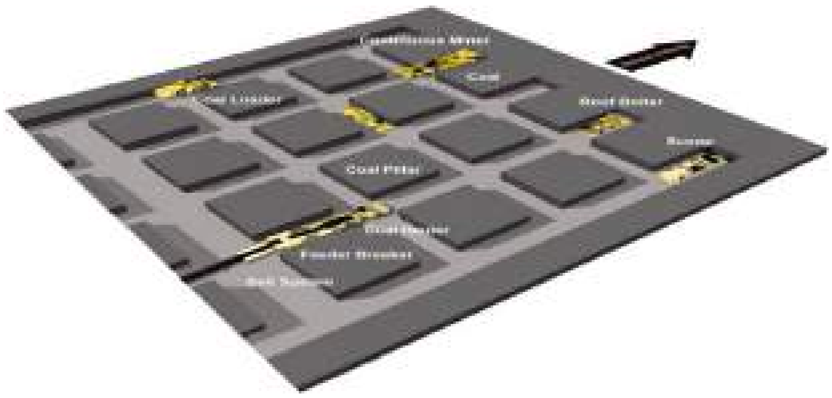

Figure 1: Example of coal production setup [7]

Mining companies place a high priority on the safe extraction of minerals during each scheduled operation. Mining firms' productivity, on the other hand, is determined by the availability and performance of mine operational equipment and the quality of the product.

Efficient monitoring and management of operations are key to improving productivity and profitability in underground mining applications. OEE has drawn a lot of attention as a critical performance measure for measuring the effectiveness of equipment and manufacturing processes [5]. It is made up of three major indicators: availability, performance, and quality [5]. The availability factor includes both unplanned and scheduled stops; performance considers actual versus design capacity utilization of plant whilst quality considers defects [3], [6], [8] The three main indicators are calculated as follows [9]:

Availability

$$[Availability] = \left[\frac{Run\ Time}{Planned\ Production\ Time}\right] \tag{1}$$

Where:

$$[Run\ Time] = [Planned\ Production\ Time - Stop\ Time] \tag{2}$$

Performance

$$[Performance] = \left[\frac{(Ideal\ Cycle\ Time \times Total\ Count)}{Run\ Time}\right] \tag{3}$$

Rate is the reciprocal of time; therefore, performance may be calculated as follows:

$$[Performance] = \left[\frac{(Total\ Count\ /\ Run\ Time)}{Ideal\ Run\ Rate}\right] \tag{4}$$

Quality

$$[Quality] = \left[\frac{Good\ Count}{Total\ Count}\right] \tag{5}$$

OEE

$$OEE = Availability \times Performance \times Quality \tag{6}$$

In simplest terms OEE is reduced to:

$$OEE = \left[\frac{(Good\ Count \times Ideal\ Cycle\ Time)}{Planned\ Production\ Time}\right] \tag{7}$$

2 LITERATURE REVIEW

2.1 OEE in mining

OEE implementation has continued beyond manufacturing and has been adopted by many industries including mining. However, several scholars believe that the application of OEE in the mining and excavation industries has not been sufficiently adopted [1], [10]. In the effort to implement OEE in mining, the OEE generic model is modified to adapt to mining equipment and dynamic mining environment [1], [10], [11]. The OEE model was revised to consider the operational time, speed, and bucket capacity utilization losses [10]. Similarly, [1], revised the quality parameter to consider the bucket fill factor. Most [1, 2] studies that evaluated OEE in mining considers the ability to load the bucket to full capacity as good quality, and anything below as poor quality. However, [11] account for quality differently. They consider the number of loads of mineral that were transferred effectively without delays caused by stoppages or equipment breakdown [11]. It is evident that the challenge in adopting the OEE metrics in mining is subject to the quality parameter.

Durrant-Whyte et al. [12] ,proposed comparing mining to other industries such as upstream oil and gas, steel, and oil refinery to have a better understanding of the scale. According to their benchmarks, the global average OEE performance for underground mining was 27 percent, whereas upstream oil and gas was 88 percent, steel was 90 percent, and oil refining was 92 percent [12].On the other hand, it is argued that OEE should be used as a statistic to identify opportunities for improvement rather than as a tool or approach to compare one facility to a different one [13].In [12],the mining industry is approaching a point in time where technological advances have an opportunity to unearth new ways of controlling uncertainty and improving productivity [12]. They point out how OEE is a solid foundation for operational improvement [12].

An important aspect in collection of data necessary to conduct OEE computations is the accuracy of the data and the reliability of the data collection method [3]. Arunabh et al. [13], studied the OEE losses of a blast furnace. They used the processed data to develop an online dashboard to measure OEE for blast furnaces. The dashboard would alert them of significant OEE losses and give directions to areas of focus for improvement [13]. When the identified OEE losses were addressed, a 5% OEE increase was recorded [13]. According to Arunabh et al, [13], proactive decisions on the shop floor can be taken to maximize plant OEE if they are monitored daily using digital technologies such as online dashboards and then analyzed using data mining and machine learning techniques.

2.2 Decision support system

Decision support systems are computer-based systems that display and process data to enable more productive, effective, imaginative, and informed decision making [14]. A dashboard is a component of a decision support system that allows decision makers to access information necessary for decision making. Corresponding to [15], the design of a meaningful dashboard should be informed by user objectives and aims. Hoelscher et al. [16],mentioned that users of intelligent dashboards can see and comprehend data in ways that were previously only possible using complex queries and time-consuming manipulation. In a different research investigation, Lindgren et al. [17] proposed and demonstrated a data-driven approach to improving OEE (Overall Equipment Effectiveness). The data was gathered over a two-month period from the case study company’s Enterprise Resource Planning / Manufacturing Execution System [17]. In the context of Industry 4.0, [17] created an overview of production failures and made it possible to identify the occurrences of each failure in connection to the others by utilizing combined simulation and data analytics (PowerBi) software.

The SCADA system and PLC HMI are one of the legacy systems carried over into the 4IR world [18] . SCADA (supervisory control and data acquisition) is an abbreviation for a system of software and hardware components that enables industrial enterprises to operate industrial processes locally or remotely [18]. The HMI is a Human machine interface that connects the operator to the machine [18]. Maharaj et al. [19], supplement SCADA with an OPC server, an HMI, and an optional SQL database, referring to the configuration as a typical modern-day process control system. Yuan et al. [5], integrated OEE in SCADA system to provide insight into the Manufacturing Executive System (MES). The functionalities of MES system although initially designed for manufacturing environment can be tailored in the context of mining [20]. It enables better decision-making and increased visibility into operations [20]. Younus et al. [20], concludes 61 percent average reduction in paperwork between shifts, 75 percent reduction in data entry time and a 56 percent average reduction in lost paperwork amongst other benefits with implementation of MES in manufacturing, however also advocating for implementation in other industries.

Figure 2: Data processing [21]

According to Pham and Liao [21], a high-level data processing diagram would include data source, processing, and products steps, where dashboards feature in the products phase. The processing phase would first extract data from the data source phase then filter and validate. Once the data has been validated, it is entered into a database for later report preparation [21].

2.3 Dashboards

Dashboards can be used to integrate a wide range of data concerning organizational performance into a single comprehensive visual presentation to monitor and enhance performance [22]. Tokola et al. [23], used survey results to design a hierarchical dashboard. Their research found that different key performance indicators are desired for dashboards at different hierarchy levels, and that mobile dashboard usage, particularly on tablet computers, is preferred [23]. Earlier research by [21], agrees with the different KPIs for different levels notion and caters for this need by developing a web-based dashboard. The main purpose being to make the dashboard accessible at all locations by all stakeholders to facilitate effective response to anomalies reported and many other monitored parameters [21]. The design principles include: [23]

- customizing metrics,
- use of existing data resources for selecting metrics, linking performance metrics to the overall processes and procedures,
- analyzing the effects of alternative improvement options, visual communication briefly for monitoring, analyzing, and assessing performance,
- integrating several small dashboards into one dashboard,
- data interpretation support and
- learning and growth.

3 METHODOLOGY

The research adopted the mixed method research approach applied in a case study involving a coal mine. The primary goal of this project was to create a dashboard that integrates data acquisition, processing, and visualization enabling real-time monitoring of mining processes. The methodology considered four key steps namely, problem identification, planning, design architecture, data capture and prototype review in the context of mining operations.

Following up on the dashboard conceptual design and subsequent design architecture, the researcher undertook study visits to the case mine. During the visits, detailed observations on mine processes, management information systems and decision support systems were recorded for review. Supporting quantitative and qualitative data were also gathered through structured and unstructured interviews with mine operatives, supervisors, and management. Secondary data on production, equipment maintenance, failure and performance data were acquired from company databases.

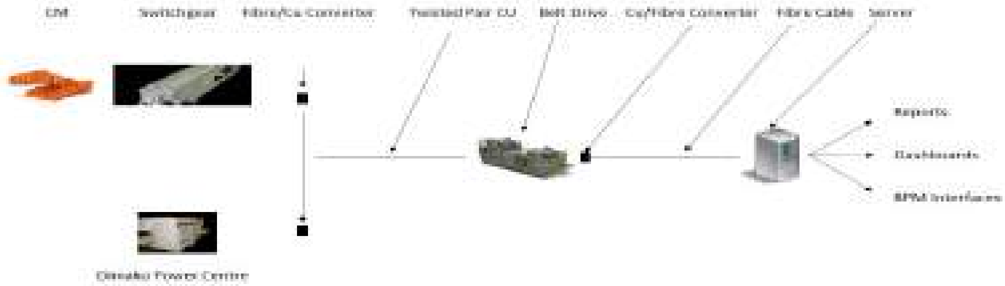

Figure 3: Current CM system data collection architecture

A needs analysis on current systems and processes was carried out with a view to identify unique needs and requirements of the case mine. The data/information acquired was integrated into the base dashboard design. The objective being to enhance relevance and usability of the ultimate dashboard. The user needs identified assisted refine the core dashboard design architecture. A detailed functional dashboard was subsequently developed. The Tableau data analytics and visualization application was used.

Live maintenance, production and quality performance rectangular data files are extracted from the mine loaded onto excel files and subsequently imported into the Dashboard. Then verification was done to ensure that the data types are correctly identified and assigned to the appropriate data roles to the fields. The conditioned data was then used to create calculated fields for the availability, performance, quality, and the overall equipment effectiveness. In addition, we used Tableau's built-in analytics functions can be used to gain insights from the data. Successful trial runs were conducted. The dashboard outputs were validated using current management reports.

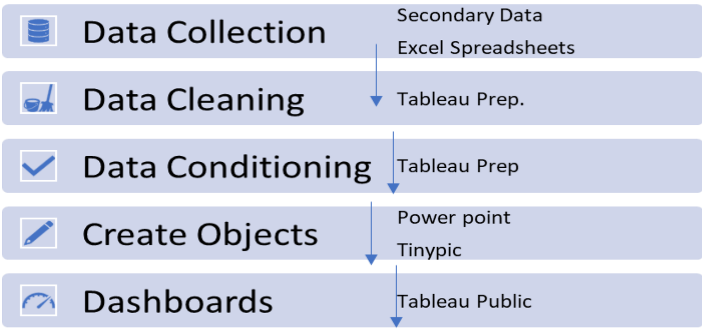

Figure 4: Data management

Components of the dashboards were designed inside of Tableau public worksheets. Each worksheet constituted a chart which was later integrated into the dashboard. The type of charts used were selected based on the type of information we intend the user to draw from the visuals. During the problem identification phase, the user needs where identified and strategies formulated on how to address these needs. A completed dashboard design was presented for reviews. This stage tested usability (ease of navigation) and functionality of the dashboard. The dashboard was verified for fitness of purpose. The prototype was thus iterated until a final design was approved. Considering that needs change in roles, the dashboards are to be monitored also for design improvement.

4 RESULTS AND DISCUSSIONS

The research results are hierarchical dashboards that correspond with the four levels of management in mining operations.

Table 1: Mapping users to dashboard

User	Dashboard Type
Mine manager	OEE analysis; Shift OEE; Downtime analysis
Section manager	OEE analysis; Shift OEE; Downtime analysis
Shift boss	Shift OEE
Technicians	Downtime analysis

The mapping of users to dashboard is particularly important to manage the information and access to information. This will also assist in ensuring users are not overloaded with information not directly important for their role.

Figure 5: Dashboard -OEE Analysis

The OEE analysis dashboard presents the equipment effectiveness for all the underground sections in the mine. The intended user as specified in Table 1, can monitor performance, availability, and quality parameters of all sections at the same time. The dashboard can be filtered by month and/or section. The set thresholds allow for colour changing to represent alert levels. The OEE percentage and colour status communicates to the user an alert level of equipment. The corresponding display of the percentage and colour code will direct the user to key contributory factors.

The lower horizontal bar-chart labeled “equipment downtime” communicates the highest contributory equipment to aggregate downtime. The month to date (MTD) figure represents total tonnages mined. A filter by month/section will alter the text to display the contributing tonnage contribution per section per month. All the charts in the OEE analysis dashboard are linked and the selection of a component within a chart will alter the view to correspond to the selected item. At any point the user can switch the dashboard back to the default view.

The downtime analysis dashboard presents a detailed view of downtime per month/section. At a glance the user can see the equipment with highest downtime from the heat-map chart (the bigger the square the higher the downtime).

The donut chart report relative contribution of scheduled to unscheduled downtime. The count of downtime chart arranged in descending order details the delay type. The chart has drill down capability to further communicate causal factors, facilitating root-cause analysis.

The percent of downtime tree map chart communicates percent of downtime attributable to mechanical, operational, instrumental, and electrical issues corresponding to the selected equipment. The more intense the colour the higher the measured value in all the charts used in the downtime analysis dashboard.

Figure 6: Dashboard -Downtime Analysis

5 CONCLUSION AND FURTHER DEVELOPMENTS

The dashboards offer a comprehensive perspective of the mining operations by integrating data from the mine databases, allowing decision makers to identify inefficiencies, and potential dangers and/or failures. Thus, providing them the ability to act quickly to maximize equipment utilization, decrease downtime, and increase overall production. The development of an OEE based dashboard for mining applications has the potential to significantly improve operational efficiency, productivity, and safety in the mining industry.

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THE IMPACT OF POOR ERGONOMICS ON EMPLOYEES IN AN AUTOMOTIVE PLANT IN SOUTH AFRICA.

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ABSTRACT

This paper explores the impact of poor ergonomics in an automotive plant in South Africa. Ergonomics is a field of study that focuses on creating workspaces, tools, and equipment to ensure workers' maximum safety and comfort. Poor ergonomics contribute to lower productivity and various health issues, including musculoskeletal disorders (MSDs), fatigue and stress, and poorer levels of employee satisfaction. This study examined the state of ergonomics in an automotive plant and how it affects employees. Data was collected through observations at the final assembly workstation in the automotive plant. Findings revealed that ergonomics had a negative impact on employees due to factors such as static posture and repetitive work at the final assembly workstation. Findings also revealed that employees may suffer from static body posture related to the vehicle interior assembly line environment with poorly designed workstations. Recommendations on how ergonomics can be improved to better the workspace environment were highlighted in this study.

Keywords: Ergonomics, Automotive, Employees

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1 INTRODUCTION

The automotive industry has been essential to the economy of South Africa for decades. The industry has become more competitive; to gain a competitive advantage in the market, manufacturers must carefully study and respond to consumer feedback [1]. This means that automotive manufacturers must always satisfy customer demands by producing more products that meet customer specifications in order to stay competitive.

While striving to remain competitive, automotive companies in South Africa face challenges such as a decline in new local vehicle sales, carbon emissions, technological advances, and lack of infrastructure to support electric vehicles [2]. Inadequate infrastructure and lack of technological advancement could have a negative effect on ergonomics.

This study was carried out to investigate how poor ergonomics can affect employees in an automotive assembly plant in South Africa. Smallwood [3] defines ergonomics as an applied science concerned with the qualities of people that must be taken into account when arranging tools and equipment, they use for employees to interact as effectively and safely as possible. Ergonomics deals with keeping individuals more productive, efficient, safe, and healthy while performing their duties or tasks [3]. Bridger [4] defines ergonomics as studying how people interact with machines and the elements that influence that relationship.

The study was conducted at an automotive plant in South Africa. The plant assembles motor vehicles and distributes them to South African dealerships and over 148 markets around the world [5]. The motor vehicles are assembled manually, and employees are deployed to different workstations in the plant to do specific operations. The plant has multiple stations where a part or multiple parts of a vehicle are mounted in each station until a complete vehicle is assembled [5]. The process of manually assembling multiple vehicle parts on each workstation may lead to more cases of MSDs being reported in the final assembly department. MSDs are injuries, disorders, or conditions that affect and impair the function of the body's nerves, tendons, muscles, and supporting systems [6]. Srikanth [7] stated that MSDs are one of the leading causes of occupational illness and disability in industrialized and developing nations. Srikanth [7] further argued that workers in an automotive assembly line were found to have a significant prevalence of MSDs. This could be due to the type of labour done in automotive industry businesses, which includes repetitive labour, tense postures, and severe exertions. Working posture is critical, especially if one is working for extended periods of time. The task, workstation, working tool design, and anthropometric qualities of the workers all affect posture [8].

Automotive assembly is a major business in some countries. Because of the nature of the duties, workers in this industry are exposed to various working postures that might lead to MSDs [7]. From the three types of ergonomics, physical ergonomics may be necessary when looking at how ergonomics is impacting employees.

Physical ergonomics deals with workplace settings and the human body's responses to physical and physiological stress [9]. Physical ergonomics includes biomechanics, anthropometry, and physiology as they relate to physical activity [9]. Therefore, it can be said that when these physical ergonomics principles are neglected, it could eventually lead to a rise in MSDs in the workplace.

Research in the automotive and manufacturing sectors has shown that absenteeism rates have increased among employees with lower wages and emotional issues [10]. Gellatly [10] further states that employees who receive workloads of an enormous physical nature have an increasing absenteeism rate of 25%. If an operator works in conditions that limit their posture, resulting in muscle fatigue, it contributes to absenteeism [8]. All this shows that poor ergonomics practice leads to absenteeism in the workplace, leading to decreased productivity.

As a result of improved working circumstances, greater ergonomics leads to improved health, reduced absenteeism, increased productivity and quality, and cost savings [3].

In today's business environment, physical, psychological, and organizational working circumstances are considered to be the key barriers that an employee must overcome. Kata & Prasad [11] stated that poor ergonomics puts the workers under physical and psychological strain, and it will eventually have a negative impact on the employee's health and well-being. If an employee's well-being is affected, it would reduce the efficiency of the employee and organization's performance. To avoid this, an automotive plant must have good ergonomics practice, which reduces the risk of musculoskeletal illnesses.

According to a study by Spallek et al. [12], MSDs caused by repeated labour are widespread in the automobile industry. A significant number of repetitive tasks and stressful postures were observed at the automotive assembly plant; therefore, this study aimed to investigate and comprehend the impact of poor ergonomics on employees from a shop floor perspective.

1.1. Aim

The aim of this study was to investigate and evaluate the impact of poor ergonomics on employees in an automotive assembly plant in South Africa.

1.2. Research Question

The main research question for this study is: How does poor ergonomics impact workers at an automotive assembly plant?

2 METHODOLOGY

2.1. Research Approach and Population

This study was conducted using a qualitative research method. The approach used was conducting first-hand observations with 10 employees working at the final assembly workstation within the automotive assembly plant. The final assembly workstation comprises of 10 employees. The 10 employees include 9 general workers who were fitting parts on the roof interior and 1 supervisor to oversee the process. Observations were conducted to observe employees' working environment and activities and to understand the assembly process from a shop floor point of view. The research desired to observe and understand every movement of employees and equipment to see how the working environment impacts the employees.

2.2. Sampling Techniques

A stratified sampling technique was used to identify the workstation in which the observation was conducted. Stratified sampling is based on specific traits, where researchers split a population into homogeneous subpopulations called strata [13]. Using stratified sampling, the research identified the different types of workstations at the plant and chose the busiest one with more difficult work, that is difficult working postures and more repetitive work. Some of the ergonomic flaws in the sampled workstation are also present in some of the workstations along the production line so by collecting data from this workstation, the study was able to address the other ergonomic problems that might be present in other workstations. The workstation or assembly line that was chosen was the final assembly workstation, where they fit vehicle parts under the roof inside the vehicle. The process can be considered complex, as the parts are mounted in a very awkward position. Upon identifying the assembly line, convenience sampling was used to identify 10 employees to be observed from the workstation. Convenience sampling is one in which the members of the target population are simply chosen because of factors such as easy accessibility or availability at a given time [14]. Through convenience sampling, the researcher could observe the 10 employees on duty at the workstation during the day of observation.

2.3. Data Collection

Primary data was collected through first-hand observations to observe the employees' working conditions and their movement around the final assembly workstation. The researcher spent 9 months at the plant and did first-hand observation for 14 days. The researcher spent 4 days at the final assembly workstation observing the roof interior assembly process. This was done to understand the layout of the workstation and the placement of materials and equipment. The researcher then spent 5 days observing employees working and their movement between picking up material and tools and mounting the material on the inner roof of the vehicle. This assisted the researcher in identifying the challenges the workers might encounter while watching their body movements and postures. Then, for 5 days, the researcher focused on the pace at which the employees worked when they were under pressure.

2.4. Data Analysis

Cause-and-effect analysis tool was used to analyse the data collected through first-hand observations in the final assembly workstation. The tool helped to find the root cause of employee ineffectiveness in the final assembly workstation.

2.5. Ethical Considerations

Permission from the plant manager was acquired before the research was conducted in an automotive assembly plant. Therefore, prior to conducting this research, the researcher was invited and given access to the plant by the plant lead engineer. Prior to conducting observations, targeted employees were informed about the purpose of conducting observations at the assembly workstation, and they granted permission to conduct observations while performing their duties.

3 FINDINGS

3.1. Observation of the design of the roof interior workstation

The study observed the design of the roof interior workstation which was being studied. The study found that the workstation was not designed with equipment that would make it easier for the employees to move around inside the vehicle. Employees had to move from their initial position and approach and pick a part to mount; then they would move towards the vehicle and lean inside the vehicle to mount the part using power tools. After mounting all the parts, the vehicle would move to the next workstation, and another vehicle would come in for the employees to repeat the same tasks. This study observed uncomfortable postures during the process of mounting parts under the roof interior. The study further observed a lot of movement between employees picking parts and equipment and approaching the vehicle to mount the parts. These findings imply that employee's health is compromised due to the uncomfortable postures that employees have to endure while mounting the parts.

As Smallwood [3] has stated, ergonomics is concerned with considering the employees' qualities, such as health and safety, when designing and arranging equipment and materials they use. Considering employees health and safety in the design phase will help employees to interact with the equipment and materials more effectively and safely. According to [20], risk assessment is vital in the automobile sector to identify unsafe tasks and establish effective working postures. This means that risk assessments such as virtual assessments must first be completed to have a suitable ergonomically designed workplace. From the current design of the roof interior workstation, it was clear that it was not fully designed so that employees could bring out their best performance.

3.2. Observation of the position and posture of employees while mounting parts

This study also observed the position and posture of the employees while working at the vehicle assembly line. The first posture would be when the employee leans forward to position himself inside the vehicle where he can mount the parts inside the roof interior of a car. The second posture was when the employee raised his hands while holding the power tool, reaching for the area where a part must be mounted. Overhead work can be regarded as awkward postures and can be a risk for upper extremity MSDs [15].

Figure 1: Employee's posture while working on car roof [16].

Figure 1 shows an employee's posture while working under the roof of a vehicle in an assembly workstation of an automotive plant in South Africa. Nussbaum, et al. [17] highlighted that risk factors such as static loads and overhead work may contribute to shoulder musculoskeletal disorders. Therefore, working in a position like the one indicated in Figure 1 daily may impair employees' health, leading to a rise in MSD reports; employees must not adopt the posture depicted in Figure 1 when mounting part on the interior of a car roof.

3.3. Observation of employees working under pressure

This study also observed how employees work faster when they are behind schedule or target, as every workstation only has approximately two minutes to work on one vehicle before it leaves the station. If an employee loses time for whatever reason, such as finding a tool or a part or doing something outside of the standard operating procedure (SOP), they begin to work under pressure to finish on time. The cycle time is two minutes, and the employee work overload is benchmarked on the two minutes cycle time, but once it goes above two minutes, there is a bottleneck on that workstation. Line balancing will then be performed on that workstation to reduce cycle time to two minutes. Line balancing can be done by adding more personnel to the workstation or reducing the number of tasks done. The tasks can be moved to another workstation where they can be completed in just the two minutes cycle time.

3.4. Observation of the final assembly workstation

Findings from observations reveal that the workstation is poorly designed because of how employees are positioned when they are working; this was seen from the employee posture. The employee's body must be supported when working in a situation such as the one depicted in Figure 1. Instead of reaching overhead, employees may operate while seated and facing upward. Findings also reveal that some ergonomics factors that were listed by Stock [18] such as repetition, force, static posture, and extreme joint position were not considered and [18] further added that these could contribute to development of muscle, tendon, and peripheral nerve entrapment disorders of the neck and upper limbs, leading to musculoskeletal disorders.

3.5. Cause-and-effect of how poor ergonomics leads to MSDs and low production

The cause-and-effect diagram shown in Figure 2 displays all the ergonomics factors that lead to MSDs, employees' ineffectiveness and eventually slowing down production. The information displayed in the cause-and-effect diagram was collected through first-hand observations at the automotive assembly plant by observing employees performing their duties in the final assembly workstation. This study identified 5 categories, with each having different possible causes that could lead to MSDs and employees' ineffectiveness as they work.

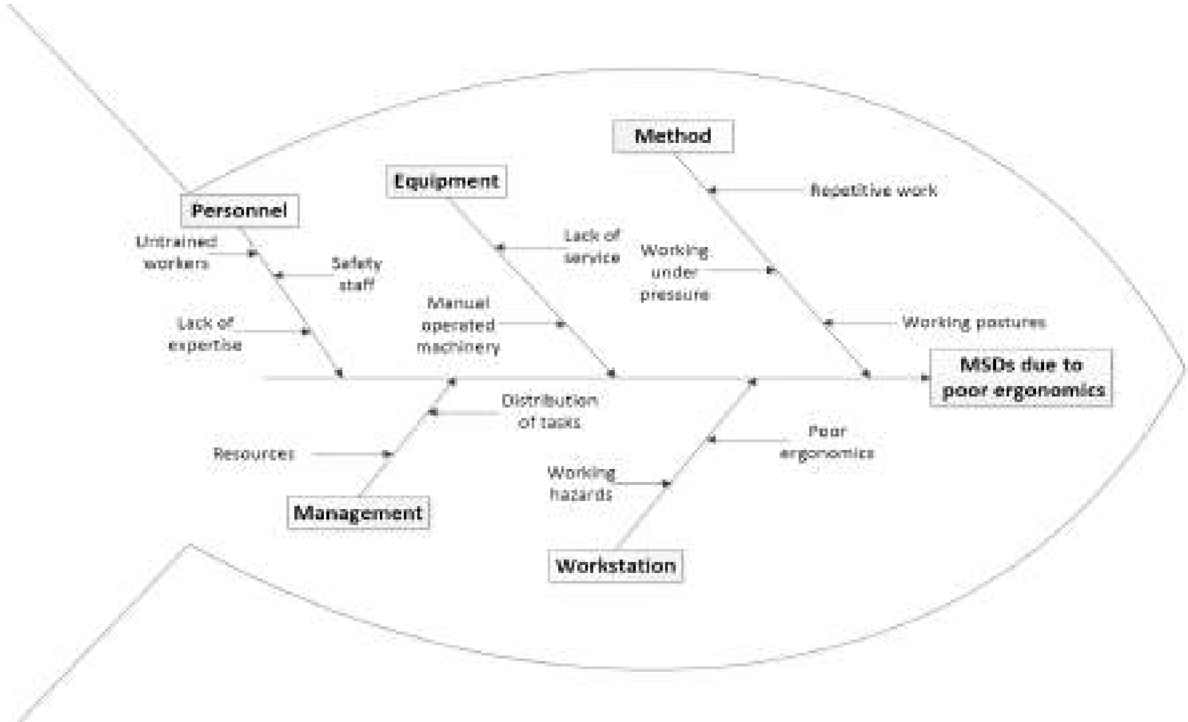

Figure 2: Causes of MSDs and employees' ineffectiveness at the final assembly plant.

The observation findings revealed that the possible causes for the negative impact of poor ergonomics were the design and arrangement of the workstation, the position of the employees while operating, and the pace at which they work when under pressure. The cause-and-effect diagram in Figure 2 was used to identify which categories the problems or causes fell into. Identifying these categories assisted the research in determining where most problems are coming from and where to apply the improvements. Based on the analysis findings, this research determined that the workstation and methods should be prioritized for improvement within the final assembly plant.

4 CONCLUSION

This study investigated how poor ergonomics affect employees in an automotive assembly plant based in South Africa. Findings from this study revealed that employee's well-being and health is compromised due to the awkward and uncomfortable posture employees take while performing the roof interior mounting operation; repetitive work and employee movement were also found to be contributing to the ineffectiveness of the employees in the final assembly workstation. The literature revealed that poor ergonomics in an automotive assembly plant has a negative impact on the employees' health and performance. Literature concurs that poor ergonomics leads to an increase in MSDs reports. The proposed solution to this is to use virtual assessments to minimize any ergonomic factor from the design of a workstation. After acquiring these assessments, the company can redesign its assembly line layout to make it more ergonomics-friendly to the workers and make a prototype to simulate the whole process. Assessments like the 3D biomechanical model and the Jack-siemens PLM can help improve ergonomics in the assembly lines. Wan & Shan [19] explained that the 3D biomechanical model is applied to identify muscles at risk and prevent injury. This tool would be great to reduce MSDs in the automotive plant. The Jack-siemens is a similar tool that models and simulates a human prototype to improve ergonomics. Since musculoskeletal disorders are very common and high in the automotive industry [7], this study also recommended that the automotive assembly company should provide training for self-musculoskeletal disorder prevention training to the employees. That way, the employees will be able to prevent MSDs and be able to interact with the equipment and machinery around them without causing any harm to themselves. By providing training of how employees should work and position their body to reduce the chances of getting MSDs, it will create a new culture for the company and even new employees that would come after will be satisfied with a company that cares for its employees. In this study, the aim was satisfied as the ergonomics in an automotive assembly plant were studied to find the impact and the source of the poor ergonomics in the assembly line.

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PREDICTION MODEL FOR THE PERFORMANCE OF A METHANE-FUELLED SPARK-IGNITION ENGINE AT A DEEP-LEVEL MINE

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ABSTRACT

This paper presents the development and implementation of an artificial neural network model to predict the power generated by a spark-ignition engine that is fuelled by methane emissions from a deep-level mine. A case study was selected to train the model and evaluate the relationships between the variables. The model was used to investigate the best input operating conditions to improve the engine's power output. After trials, the best performing model consisted of a 6-14-11-1 architecture and was trained using the Levenberg-Marquardt algorithm. The model's prediction performance yielded a coefficient of determination (R^2) of 0.9865 and 0.9803 on the training and testing subsets, respectively. The model was determined capable of predicting the power of the engine accurately and robustly. It was found that an additional energy cost saving of R 2 860 000 per annum can be achieved by running the engine at its best operating conditions.

Keywords: prediction model, engine performance, deep-level mine, spark-ignition engine, artificial neural network

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1 INTRODUCTION

In South Africa, the supply of electrical energy has become unreliable while the cost has, on an annual basis, been increasing significantly. High energy consumers, such as deep-level mines, are especially negatively impacted. Consequently, the reduction of energy costs has become increasingly critical to their life-of-mine [1]. During normal mining activity, deep-seated underground geological sources are intersected from which gases are emitted at elevated temperatures [2]. These gas emissions differ in composition but at certain deep-level mines, the mixture has a fluctuating high methane concentration and trace non-methane hydrocarbons [3]. To utilise the methane-rich emissions from underground, some deep-level mines have implemented systems to capture and feed the emissions to an energy-generation system. An example of such a system is the utilisation of spark-ignition (SI) engines. This allows mines to benefit from hazardous methane emissions by generating power and feeding it back into their system [4].

By generating power using the methane-fuelled SI engine, a mine can partly offset the energy supplied to it by Eskom and circumvent power usage supplied from primarily coal-fired power stations [5]. Mines can thus reduce their energy expenditure using the engine's operation. During operation, the engine offsets carbon by converting the methane-rich mixture from underground into carbon dioxide and other flue gases [6]. Carbon credits are issued to mines for the reduction of methane emissions, a non-carbon dioxide greenhouse gas, by carbon offsetting. Carbon credits can be sold by governments, companies or individuals on national and international markets for financial gain or purchased to reduce their carbon footprint to comply with emission reduction targets [7]. By reducing their carbon footprint and trading carbon credits, high energy consumers, such as mines, improve their compliance to their Environmental, Social, and Governance (ESG) standards and regulations [8].

SI engines are frequently run inefficiently with most operational parameters either at a fixed set point or altered regularly by personnel without taking all parameters into consideration [9]. This may result in ineffective engine operation and substandard performance. The performance of a SI engine is dependent on numerous operational variables. The methane content in the feed to the engine and flow rate are directly proportional to the power generated by the engine [10]. The content of oxygen in the feed stream has an impact on the air-fuel ratio, influencing the mass of fuel in the combustion chamber and affecting the engine's power output and emissions [11]. Fuel temperature influences the operation of a SI engine. An increase in fuel temperature results in an increase in charge temperature, charge density and brake specific fuel consumption (BSFC). SI engines therefore require more fuel at higher fuel feed temperatures to maintain the same power output [12].

Feed flow rate, fuel composition and temperature significantly impact the performance of the engine. To maximise the engine's performance, an optimisation algorithm can be implemented to determine the optimal conditions for these operational variables. Consequently, the set points and operating procedures of the system can be adjusted and adapted to realise the results of the optimisation algorithm and attain the maximum possible output power. Improved power output realises more financial and environmental benefits. These include greater energy savings, less reliance on the Eskom power grid, additional carbon credits and an improved ESG status. Nonetheless, to implement an optimisation algorithm, a model is required that accurately and robustly describes the relationship between the input operational variables and output power for the engine system.

Mathematical models derived from first principles would be effective if the engine was new and operated at its manufactured efficiency. If the engine has accrued declining efficiencies from continual operational, a first-principal approach might prove tedious by requiring multiple assumptions and additional investigations that might not result in sufficient accuracy nor robustness [13]. Modelling the particular SI engine is a complex and strongly non-linear problem, therefore, statistical and basic regression approaches would prove inadequate. An artificial neural network (ANN) approach can sufficiently model the system's complexities and non-linearity [14].

An ANN is a technique that learns the relationship between input and output variables in a data set to model a system and make predictions. The only requirement for an ANN is to provide a data set that adequately describes the relationship between the input and output variables [15]. ANNs are able to analyse large data sets and complex relationships between inter-dependent variables. Furthermore, ANNs are able to ignore minimally important variables and data noise to identify and concentrate on more significant variables [16]. Also known as a "black box" model, ANNs can be applied to any given system without requiring any detailed information on the system. Energy- and engineering systems have been modelled and predicted successfully using ANNs [15].

Çay *et al*. [17] implemented ANNs to predict the effective power of a methanol SI engine from multiple input variables, including fuel flow rate, torque and engine speed. Çay *et al*. obtained a coefficient of determination (R^2) value of 0.9998 on the testing subset. In a study by Özgören *et al*. [18], power and torque were predicted for an experimental helium Stirling engine using its engine speed, compression ratio, heat source temperature, charge pressure and type of piston coating as input variables. The ANN model's power predictions correlated with the experimental targets with a R^2 value of 0.9987. A methane fuelled SI engine was modelled by Kurtgoz *et al*. [10] to predict its BSFC from multiple input variables, including methane content. For the prediction of BSFC, the model achieved a R^2 value of 0.9901. These studies successfully modelled engine performance and related parameters using ANNs for SI engines fuelled by alternative fuels.

From a review of similar aforementioned literature [19]–[27], no prediction model exists for the relationship between the operational parameters and engine performance of a SI engine, fuelled by a dynamic methane-rich gas mixture from the underground sections of a deep-level mine. There is also no similar study that was found that uses a model with the specific combination of operational parameters: fuel feed flow rate, compositions and temperature. Furthermore, no model exists that determines the best operating conditions to maximise the engine's power output for a methane-fuelled SI engine.

The engine's performance must be improved to increase the mine's energy cost savings, obtain additional carbon credits, and reduce its carbon footprint. To achieve this, the engine's operation must be modelled so that an optimisation algorithm can be implemented and the operational conditions, that result in optimal performance, be determined. A "black-box" ANN model is sufficiently capable of modelling such a system. In this study, an ANN prediction model will be developed and implemented to predict the performance of a SI engine fuelled by a primarily-methane gas mixture emitted from a deep-level mine. Using the trained model, the relationships between the variables will be evaluated and the maximum energy cost savings achievable by the engine determined.

2 CONSTRUCTION OF AN ANN MODEL

Neural networks consist of processing elements – called neurons – that are highly interconnected to a form a processor with layers distributed in parallel [28]. The basic structure of a processing element (neuron) is given by Figure 1. Inputs are received (x_j) by the neuron and are attached weights (w_{ij}) which quantify the connection strength of the corresponding input to the neuron. A bias (b_i) is a constant non-zero connection value that acts as a connection weight to the weighted inputs [29].

Two functions occur at a neuron, namely summation and activation. The summation function determines the net input that approaches a neuron and is calculated by the weighted sum for each input with the addition of the bias. The equation to obtain the summation function's output or pre-activation value (u_i) is given by:

$$u_i = \sum_{j=1}^{d} w_{ij}x_j + b_i \quad (1)$$

To account for non-linearity in the model, the pre-activation value is rescaled using the activation (or transfer) function. The selection of activation function (f) significantly affects the performance of the ANN. For this study, the logistic sigmoid was selected as transfer function, as it is commonly for similar applications and is continuous, differentiable and non-linear [21]. The logistic sigmoid function is given by:

$$f(u_i) = \frac{1}{1 + e^{-u_i}} \quad (2)$$

By implementing the activation function, the output (y_i) is computed, as given by:

$$y_i = f(u_i) \quad (3)$$

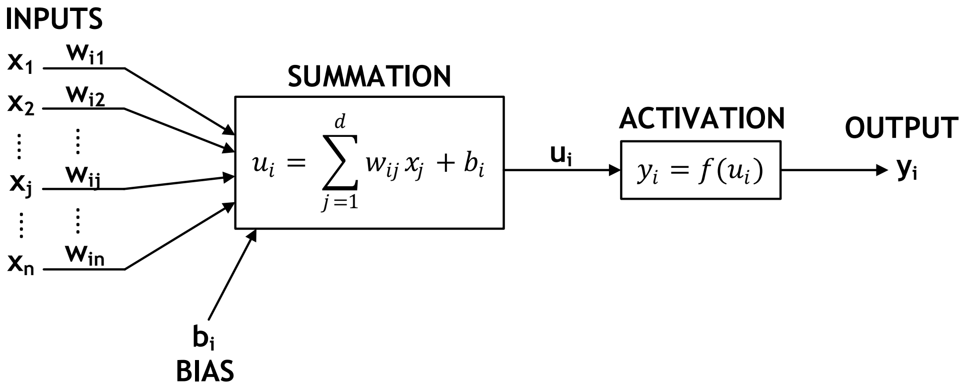

Figure 1: Representation of the basic structure of a neuron (adapted from [30]**)**

A multilayer ANN comprises multiple neurons arranged in parallel layers. These layers are the: input, hidden, and output layers. An ANN may also have more than one hidden layer. The input layer does not process any data and only distributes the input variables' data to the hidden layer. Processing of data occurs in the hidden and output layers using neurons [31]. The number of neurons in the hidden layer will determine how well the ANN learns the relationships between the variables of the system. Too few hidden neurons will underfit the system, while too many hidden neurons will overfit the system. Both the underfitting and overfitting of the system will exhibit poor generalisation and accuracy with high prediction errors [32].

The purpose of training is to determine the optimal weights that minimises the error between the network and data set's outputs. During network computation, activation is propagated forward from the input layer by the hidden layer(s) to the output layer. The error between the network (predicted) output and actual output is determined. The back propagation algorithm (BPA) is one of the most commonly implemented training algorithms for feedforward multilayer neural networks. The error is minimised using the BPA at small increments at a time over numerous iterations or training cycles (epochs) [33].

At the completion of training, the ANN should be capable of predicting the correct output for any input within the range of the training set and generalise to similar unseen cases [15].

Advanced BPAs were implemented in this study, namely the Levenberg-Marquardt (LM) and Scaled Conjugate Gradient (SCG) algorithms. Due to the difference in method between the training algorithms, the type of algorithm implemented will impact the generalisation capabilities of the trained network [34].

The input and output variable data set is divided into subsets to train, validate and test the ANN. The training subset is used by the BPA to adjust the weights of the hidden and output neurons. The validation subset is used to find the best network configuration and prevent underfitting or overfitting by stopping training at the iteration with the minimum error. The test subset is an independent and unbiased data set used to quantify the generalisation capabilities of the trained ANN [35].

The accuracy of the network's predictions (outputs) relative to their targets (data set outputs) are quantified by the root mean square error (MSE) and mean average percentage error (MAPE) [36]. The coefficient of determination (R^2) quantifies the network's generalisation capability. The statistical evaluators R^2, MSE and MAPE are given by Equations (4), (5) and (6). The predicted output is represented by o_j and target by t_j for all data points from $j = 1$ to N [37].

$$R^2 = 1 - \left(\frac{\sum_{j=1}^{N} (t_j - o_j)^2}{\sum_{j=1}^{N} (o_j)^2} \right) \quad (4)$$

$$MSE = \frac{1}{N} \cdot \sum_{j=1}^{N} (t_j - o_j)^2 \quad (5)$$

$$MAPE = \frac{1}{N} \cdot \sum_{j=1}^{N} \left| \frac{t_j - o_j}{t_j} \cdot 100 \right| \quad (6)$$

The network configuration, namely the number of hidden neurons, number of hidden layers and training algorithm, significantly impact the prediction performance of an ANN. The MSE is used in this study to identify the best performing network configuration [32]. A minimum MSE, minimum MAPE and maximum R^2 indicate the best performing network configuration [38].

3 CASE STUDY

The case study SI engine selected for this study is situated at a deep-level mine and uses the methane-rich gas mixture from underground as fuel source. The gas is captured from intersected underground geological sources and extracted to surface by blowers through an extensive pipe network. The set point on the extraction blowers determine the feed flow rate of gas from underground to the engine and flare. The engine receives on average a feed flow rate of 400 m^3/h at a methane concentration that varies between 60% and 80%. A heat exchanger uses chilled water to cool the fuel gas mixture before it is fed to the engine. The methane content of the feed stream varies throughout the day, consequently affecting the power generated by the engine. The engine typically generates 280 000 kWh per month. The case study engine is system schematically represented by Figure 2.

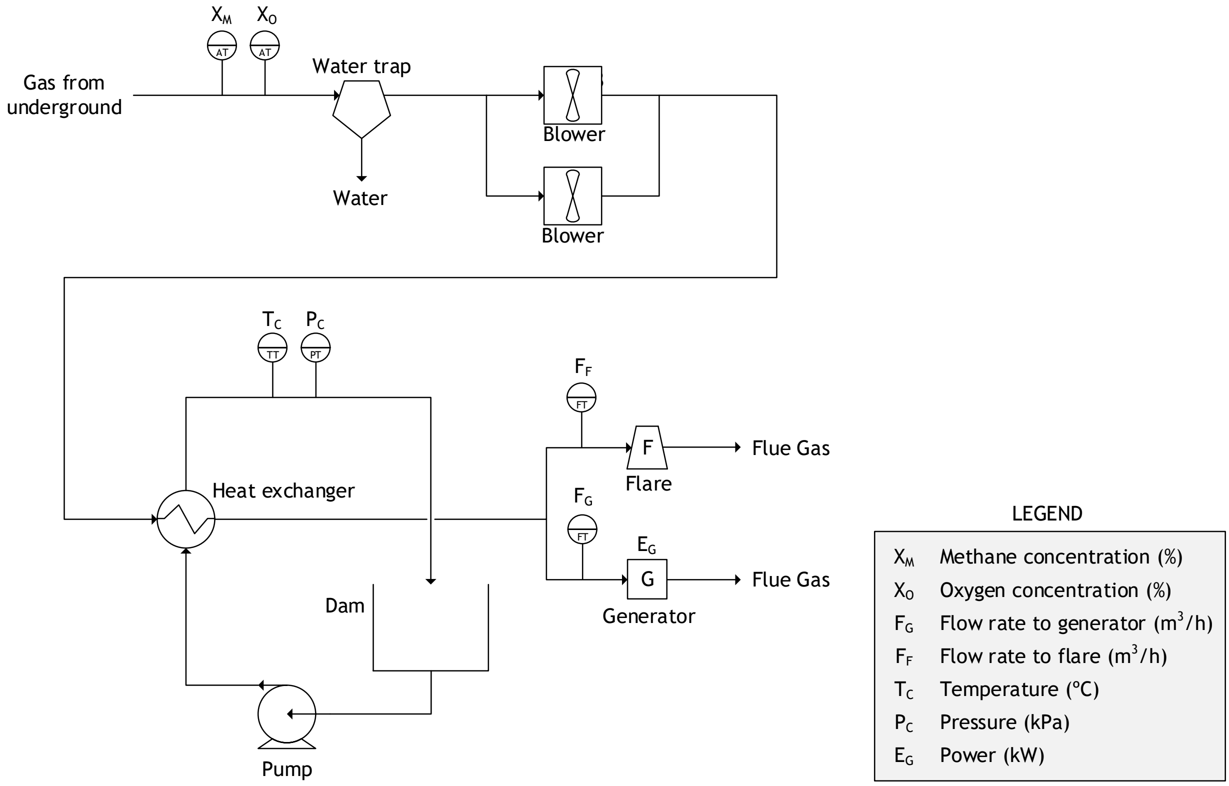

Figure 2: Schematic diagram of the case study SI engine system

4 METHOD

A computer program has been developed in this study using MATLAB to develop and implement the model. The development of the model entails determining the best network parameters and training the network accordingly, while, the implementation involves evaluating the model's prediction performance, the relationship between the variables and the best operating scenario for the engine. The total number of data points used in the development of the model was 23 856 and randomly split into 16 699 (70%), 4 771 (20%) and 2 386 (10%) data points for the training, validation- and testing subsets, respectively. Data points during which the engine was not at steady state (non-operational, starting up or stopping) were removed from the data set. The noise-spike (NS) and exponentially weighted moving average (EWMA) filters were applied to the data. A standard normalisation method was used to convert the data to the appropriate form for training.

To ensure that the minimum MSE for SI engine performance predictions is achieved, the optimal number of hidden neurons, training algorithm and number of hidden layers have to be determined. Trials were performed where in each, the number of hidden neurons, training algorithm and number of hidden layers were varied over pre-defined settings. The best combination was determined as having the maximum R^2 value and minimum MSE over all iterations of the trials. A comparison between the results of the final trials is given by Table 1.

Table 1: Results for the different best-performing ANN configurations

Configuration	One hidden layer		Two hidden layers	
Training algorithm	LM	SCG	LM	SCG
Hidden neurons	20	20	14-11	18-30
MSE Validation	275.2	421.7	260.0	375.4

A 3D surface plot of the R^2 values for the different trials of the number of hidden neurons in each hidden layers is given by Figure 3. The best performing ANN was determined to comprise two hidden layers, with 14 hidden neurons in the first layer and 11 hidden neurons in the second layer, trained using the LM algorithm. The best performing architecture was therefore 14-11 and 6-14-11-1 taking the input and output neurons into consideration. A schematic of the developed model is given by Figure 4.

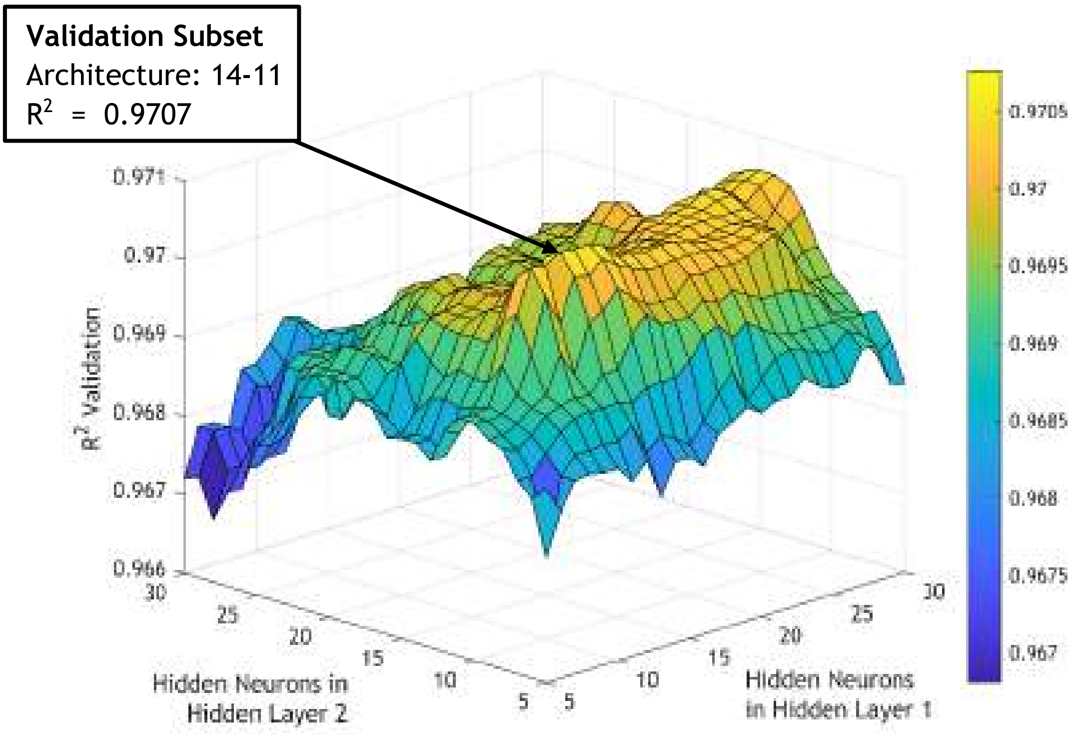

Figure 3: R^2 performance of the validation set for a two-hidden-layer network trained using the Levenberg-Marquardt (LM) algorithm

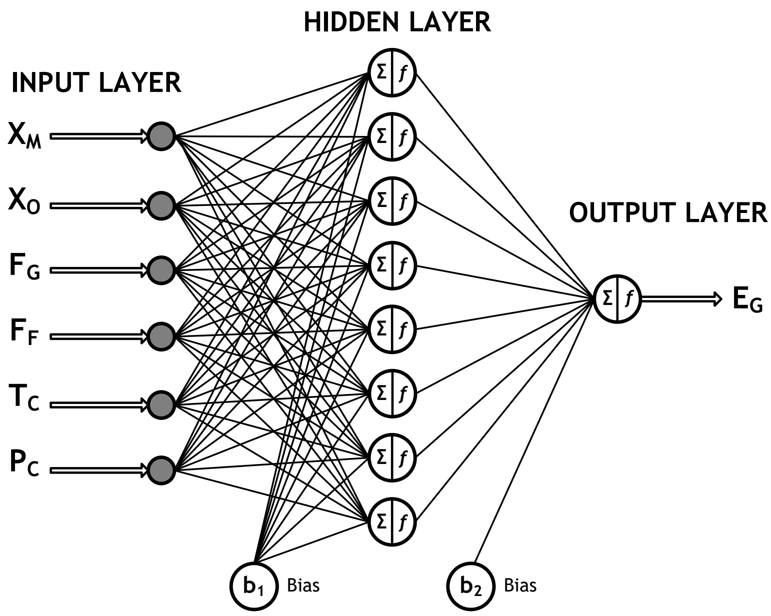

Figure 4: Schematic diagram of the developed ANN model

The relationships between the feed flow rate, methane content and power generated was investigated using the model. Taking the variability of the methane source into account, the best operating conditions that result in the highest power generated was determined. The purpose was to determine the maximum power and energy cost savings the engine can supply compared to the current average operation. To quantify the improvement, the MATLAB function *trapz* was implemented to perform the integration between the normal baseline and improved operation. Energy generated was converted to energy cost using the structured Eskom time-of-use (TOU) tariff system [39].

5 RESULTS & DISCUSSION

The performance of the ANN model was determined by plotting the R^2 prediction results for each subset. The plots are given by Figure 5 (a) – (d) for the training, validation, testing and combined data sets, respectively. From the training and test subsets' results, it can be observed that a high prediction performance and therefore generalisation capability was achieved by the model.

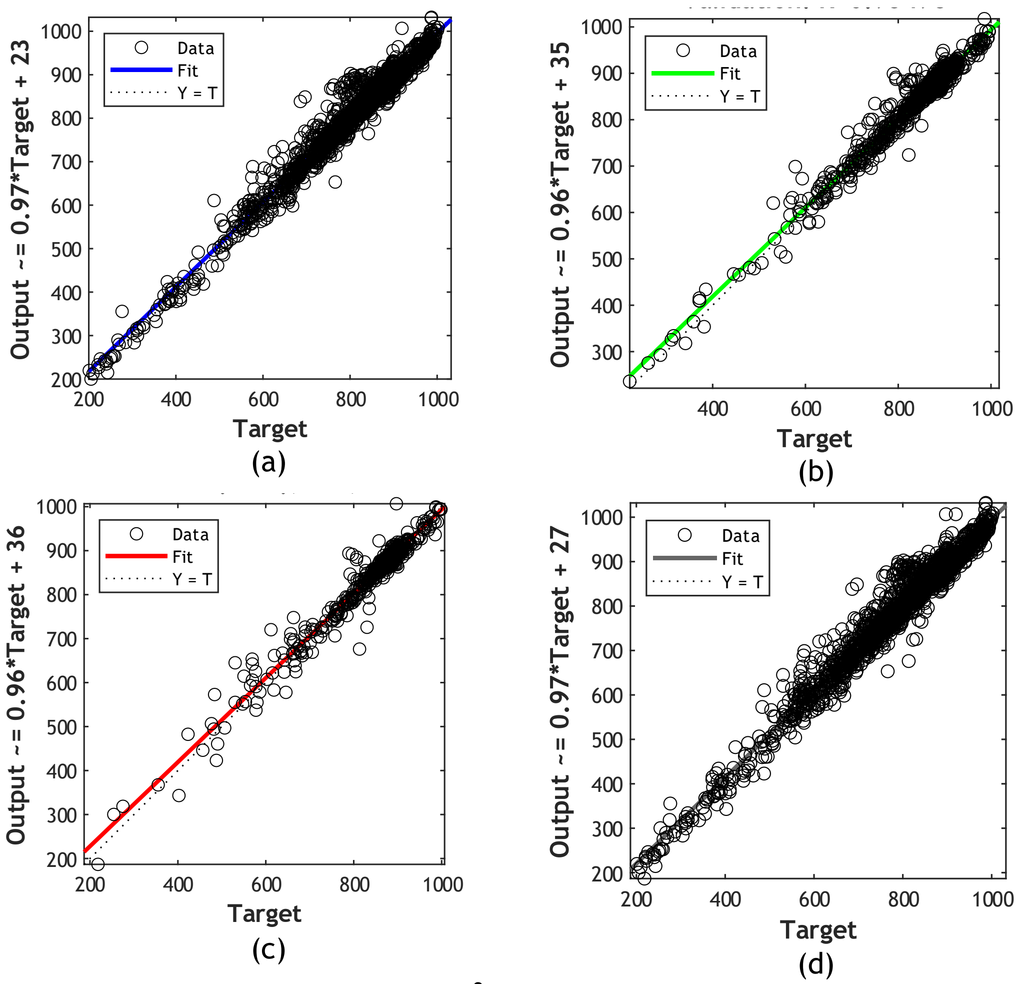

Figure 5: Coefficient of determination (R^2) plots for the model's outputs versus targets on the (a) training subset, (b) validation subset, (c) test subset, and (d) full data set

The statistical evaluation parameters for the prediction performance of power are given by Table 2. For the training set, the R^2 value and MAPE was 0.9865 and 1.2520, respectively. The R^2 and MAPE values for the testing set were 0.9803 and 1.6122, respectively. As seen from Table 2, acceptably high R^2 and low MAPE values were obtained. This indicates that the model was able to successfully learn the relationships between the input and output variables, resulting in accurate and robust predictions.

Table 2: Statistical parameter results for the prediction performance of power

Statistical Parameter	Training Subset	Testing Subset
MAPE	1.2167	1.2310
Coefficient of determination (R^2)	0.9874	0.9868

The relationship between the input variables and power generated was determined using the trained ANN model within the boundaries of the input and output data sets. The resultant relationships between feed stream methane content, feed flow rate and power are given by Figure 6. Feed flow rate has a significant impact on the power generated by the engine, contributing to an additional 520 kW (58%) generated by increasing the flow rate from 200 - 425 m^3/h. For the methane content in the feed stream, it was found that a fuel content of greater that 60% can contribute to approximately an additional 180 kW (17%) engine power. As expected, both the feed methane content (between 70% and 100%) and the feed flow rate exhibit direct proportional relationships to the power generated by the engine.

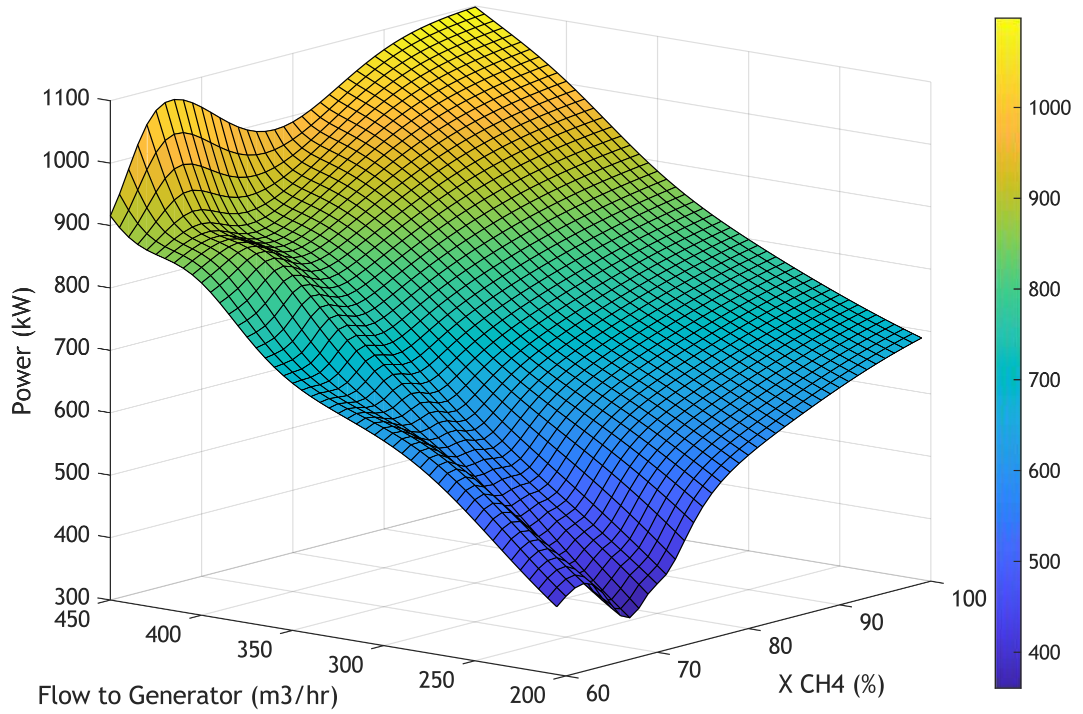

Figure 6: Relationship between the feed flow rate to the engine, methane concentration in the feed stream, and power generated by the engine

The feed temperature was found to have a less significant impact on the engine performance than flow rate and methane content, as a lower feed coolant temperature resulted in an increase in the power generated. An increase in coolant temperature from 20 - 40 °C results in a 6% decrease in power. A higher coolant pressure resulted in improved performance. It is important to note that the fuel feed temperature is not dependent on only the two coolant variables focused on in this study, namely coolant temperature and pressure, and that these two variables only serve to approximate the impact of the fuel feed temperature on the power generated by the engine. The range over which the feed oxygen composition data was trained was insufficient to evaluate its impact on the engine's power output. No relationship was found between the feed flow rate to the flare and engine power, as expected, due to the location of the flow meter.

The results from the evaluation of the ANN model were used to determine the best operating conditions and impact thereof to maximise energy cost savings. The best operating conditions included higher methane feed flow rates and composition, whilst maintaining lower feed coolant temperatures and high feed coolant pressures. With the improved operation, the engine generated 15 200 kWh per day in comparison to the baseline energy generation of 9 300 kWh per day. Therefore, an improvement of 5 900 kWh is possible for the engine if it operates at the best operating input variable conditions. The improvement in power between the baseline and improved engine operation is given by Figure 7. The improvement equates to an energy cost saving of R 11 000 per day and R 2 860 000 per annum for the specific deep-level mine when taking time-of-use into account.

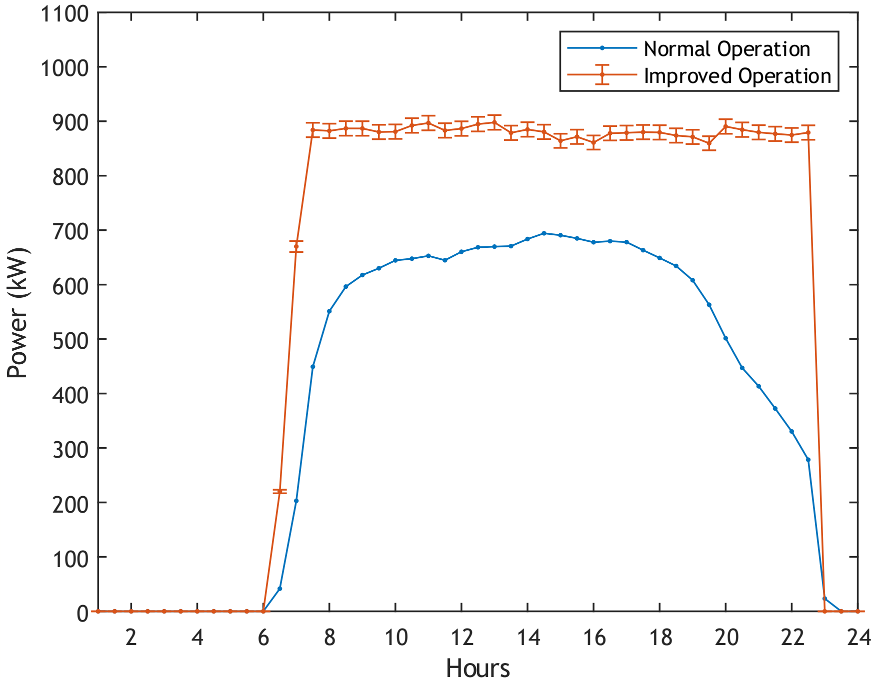

Figure 7: Average baseline operation and improved operation for the power generated by the engine for a day

6 CONCLUSION

The development and implementation of an ANN model is presented, aiming to predict the power generated by a SI engine and exploring the relationships between the system's operational and performance variables to determine the best performing operating conditions. A case study SI engine at a deep-level mine was selected that operates using methane-rich emissions from underground as fuel. A total of 23 856 data points during which the engine was operational and at steady state, were used to train the ANN.

The model demonstrates the ability to predict the SI engine's power output accurately and robustly. It was found, using the model, that an additional energy cost saving of R 2 860 000 per annum is possible by operating the engine at the best input operating conditions, depending on the variability of the methane supply.

This study shows that ANN models can be used as tools to effectively predict the performance of methane-fuelled SI engines at deep-level mines. The study further demonstrates that the methodology followed is successful in developing an ANN model to predict the output power for the case study engine. The model can therefore be applied to perform operational and economic optimisation using an optimisation algorithm to improve engine performance, energy savings and attain additional carbon credits, while decreasing the negative impact of greenhouse gases on the environment.

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EVALUATING THE CANNABIS VALUE CHAIN IN SOUTH AFRICA

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ABSTRACT

The South African government recently announced its intention to promote the growth of the cannabis and hemp industry, particularly among small-scale farmers where it sees opportunities opening. It has expressed the need to regulate the products for commercial use and align the industry with global trends. This paper evaluates the status of the cannabis value chain in South Africa in its four segments, cultivation, distribution, processing, and consumer products which all include a degree of diversity and specialization. The available opportunities are explored. It finds that the crop is underrated and there are missed opportunities economically, commercially, and pharmaceutically. While it recognises the industry's potential for investment and contribution to the country's GDP, the South African government is not exploiting the economic opportunities and potential of cannabis in comparison to other countries that have capitalized on cannabis across its value chain. Instead, the opportunity for economic exploitation is wasted.

Keywords: Value chain, Cannabis economy, Emerging products

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1 INTRODUCTION

Cannabis "is a multipurpose plant from which various parts (roots, stem, fibres, flowers, and seeds) can be used to produce various products" [1]. According to research, Cannabis Sativa suggests "cultivated cannabis" which was classified scientifically in the year 1735 with its first use dating back to 2737 BC when it is believed that the Chinese population consumed it for its medical properties [2]. All products resulting from the "Cannabis Sativa" plant are termed as "Cannabis". The "cannabis plant contains over 70 unique compounds, collectively known as phytocannabinoids, of which two are tetrahydrocannabinol (THC) and cannabidiol (CBD)" [3]. The cannabinoid that can produce a "psychoactive effect" is called THC which has also been reported to have medicinal properties whereas CBD is a cannabinoid with mostly medical properties [3]. Throughout history, "the cannabis plant has been used as a medicine, food additive, construction material, and a psychoactive drug" [2]. The way cannabis is consumed is dependent on individual preferences which vary from, "adding it as an ingredient in food products and inhaling it as smoke or vapor". According to [4], the cannabis sector "shares clear similarities with agriculture, food, tobacco, and pharmaceuticals". It has been reported that cannabis was among "the world's most commonly used drugs, consumed at least once by an estimated four percent (4%) of the world's population in 2019" [5].

The cultivation and use of the plant faced legislative condemnation for centuries; during the twentieth (20th) century, Cannabis Sativa saw an upward trajectory. The plant's multifarious potential became widely recognized, with several countries intent on building thriving economies and exploiting the plant's full potential across its value chain. Notable changes have been witnessed over the years relating to cannabis regulations, by illustration, 48 countries had somewhat moved towards the legalisation of medical cannabis in 2021 [6]. There was an increase in the number of countries that "decriminalised or legalised adult-use (recreational) cannabis; where others legalised or significantly liberalised the cultivation of industrial cannabis (hemp)" [6]. Cannabis is considered an "illegal drug in terms of the Drugs and Drug Trafficking Act" [7]. Several regulations were listed and published by the "South African Health Products Regulatory Authority (SAHPRA)" aimed at prohibiting the "cultivation, possession, and use of cannabis". The "Medical, Dental, and Pharmacy Act criminalised cannabis activities in 1928 however the "Medicine and Related Substances Act as well as the Drugs and Drugs Trafficking Act now govern the regulations which "permit the cultivation of Cannabis solely for medicinal and research purposes" [7].

Following the 2019 decision of the Cabinet to develop a "National Cannabis Commercialization Strategy" aimed at "increasing economic growth, creating jobs, and alleviating poverty", a "Draft National Cannabis Masterplan for South Africa (NCMP) (2021)" was released. The plan in its infancy challenges the current cannabis regulations arguing that "appropriate policy framework and new legislation to regulate the commercialization and industrialization of cannabis should be developed and be able to adapt to new developments regarding specific cannabis products" [8]. The premise of the NCMP is to "finalize the Drugs and Drugs Trafficking Act and, lift the limitations that are currently prohibiting commercialization throughout the cannabis value chain" [8]. The complexity of the legal cannabis industry with various product opportunities can be segmented into three broad areas namely "medical cannabis", "adult-use cannabis (occasionally referred to as 'recreational')", and "industrial cannabis (hemp)". They all present varying "supply and demand dynamics, regulatory systems, and value chain structures", each with unique forms of opportunities and challenges for the producers [9]. Each category encompasses various types of cultivation, processing models, and cannabis strains. The shift in the legal status of cannabis over the years has been significant whereby "adult-use /recreational cannabis" was decriminalised following the 'Constitutional Court ruling of 2018' and legal licenses were issued for the cultivation of "medical and industrial cannabis" by license-holding producers.

The "Draft Cannabis for Private Purposes Bill (CPPB)" presently being debated by Cabinet, maintains "the prohibition of commercial adult-use cannabis, but commits the government to ratify future legislation to legalize it [9]". The "multi-stakeholder National Cannabis Masterplan (NCMP) seeks to coordinate the private sector, government, and labour to support the growth of the industry [10]". President Cyril Ramaphosa mentioned in his 2022 State of the Nation Address (SONA 2022) that government is intent on exploring and "capitalising on cannabis as a development opportunity" as well as a driver for the creation of viable employment.

The main objective of this paper is to evaluate the status of the cannabis value chain in South Africa in its four segments, cultivation, distribution, processing, and consumer products with an interest in the available economic and related opportunities. It focuses on the key areas of Medical (Pharmaceutical), Industrial (Hemp), and Adult-Use (Recreational) Cannabis. To achieve the objective, a wide range of secondary sources are reviewed including the "international and domestic trends" of the cannabis market and its regulations, drawing data from industry stakeholders, leaders, investors, and policymakers. The report in its nature is exploratory and may be impeded by data that is publicly inadequate and limited.

2 LITERATURE

The cannabis market, although characterised by high uncertainty has significant potential to contribute to the economic, social, and environmental objectives of the country. Through its broad value chain streams and various value-added services (marketing, logistics, retail, etc.) the historically marginalised population can gain access to the market and create opportunities to earn an income whilst being financially emancipated. The unemployment rate in South Africa is on a rapid decline, reaching over 16 million in 2023 with the youth accounting for approximately 61%. The emerging cannabis industry will reduce this affliction and offer alternatives to traditional agricultural activities by creating jobs, uplifting communities, and granting access to local and international markets. The National Cannabis Master Plan mentions that "an estimated 900 000 small-scale farmers are growing dagga in the country [9]" which is an indication that many families rely on cannabis for their livelihood. According to industry experts, "South Africa's competitive advantage could be built on the back of a clear and predictable regulatory framework; an open investment regime; strong research and development support; knowledge networks that bring together university researchers, centres of excellence, and other industry players; product quality and standards authority; and low-cost licensing regime [8],[10]".

The National Cannabis Master Plan, published in 2021 "aims to create an inclusive medicinal, recreational, and industrial cannabis sector [9]". Published journals [12], [13] argue that "realising the developmental potential of cannabis means adopting principles of 'decent work' and ecological sustainability and pursuing social and environmental upgrading within the South African cannabis industry". Illustratively, the Cannabis market (legal and illicit) has shown potential for rapid expansion where analytical data [14] estimated that "the global market value of combined legal and illicit cannabis markets was $344.4 billion in 2018 and Africa accounted for 11% of the world's market value, at $37.3 billion". By 2019, the global cannabis market (legal and illegal combined) was estimated at $415 billion with "adult use" accounting for over 90% of this estimate [6].

The plants in the cannabis genus, include an array of species, the dominant ones being "Cannabis Sativa, Cannabis Indica, and Cannabis Ruderalis [15]". The strains are "bred according to their various qualities, some species are bred to contain larger concentrations or particular 'cannabinoids', and others for their fibre content used for industrial applications [9]". Cannabinoids are "chemical compounds found in the cannabis plant that affect the human body, the notably important cannabinoids are tetrahydrocannabinol (THC) and cannabidiol (CBD) which can be extracted from the cannabis plant through various forms of post-harvest processing [15]". "THC" is the "main psychoactive cannabinoid that produces the 'high' in adult-use (or, 'recreational') cannabis" and also has medical applications. The "cannabis produced for adult-use" and medical applications often has a high THC concentration [9]" and is a central focus of the prohibition debate. "CBD", on the other hand, is regarded as an "important non-psychoactive cannabinoid, with a range of health and wellness applications [16]". Hemp, which typically contains 'higher concentrations of CBD' is a "commonly used term for cannabis varieties used in industrial applications. It is bred for low-THC concentrations, longer and stronger fibrous stems, or higher oil concentrations [17]". The cannabis plant is "cultivated to contain various concentrations of cannabinoids, such as THC and CBD", depending on the final application (see Figure 1 below). The high THC-containing cannabis plant, "generally used for recreational purposes, is commonly referred to as 'marijuana, weed, ganja, or insangu' while the low-THC-containing cannabis plant, cultivated for the production of fibre (included in such products as bricks, ceiling boards, and textiles) or seeds and the products produced from the seed (such as cosmetics, oils, paint), is commonly referred to as hemp [7]".

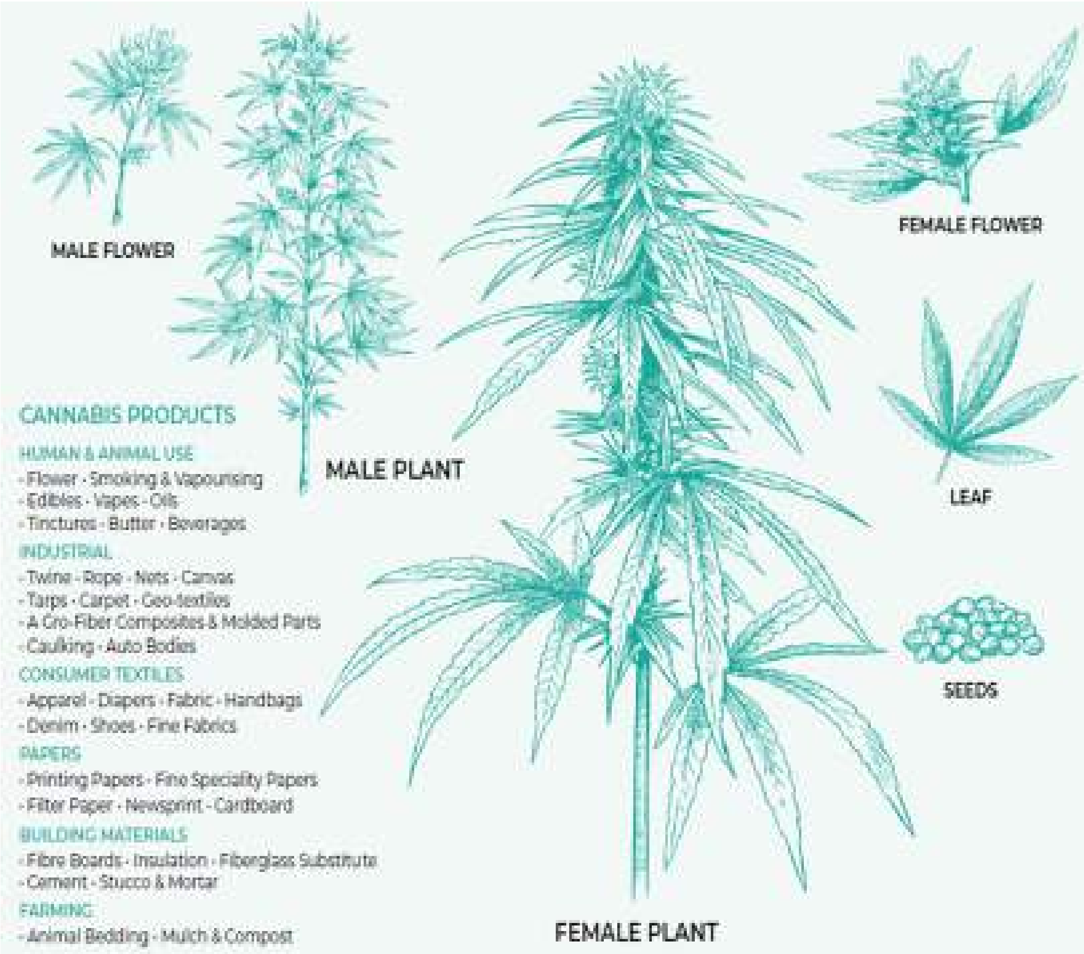

Figure 1: Botany of the Cannabis Plant [15]

2.1 Cannabis Pathways

The regulations governing the cannabis market can be simplified into pathways, each encompassing the various 'sectors with a specific set of characteristics' to which distinct regulations apply [18].

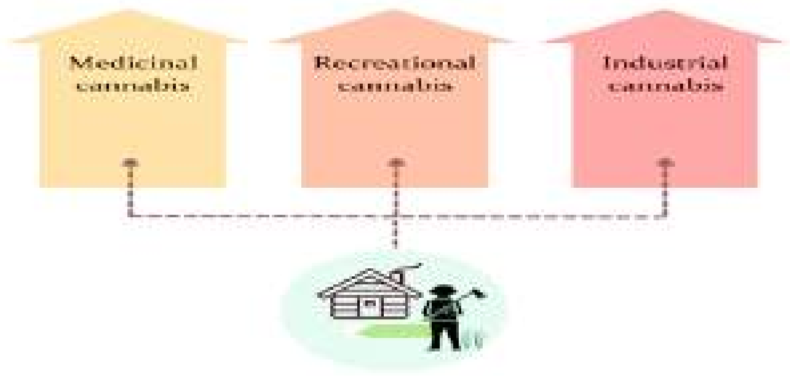

Figure 2: Schematic representation of the cannabis pathways [18]

2.1.1 Hemp

Hemp has been a historical agricultural crop for thousands of years, as an "important and widespread industrial fibre [19]". However, "cannabis prohibition policies also suppressed hemp production in many countries [19]". According to journals [19], [20] "its recent rejuvenation stems from the broader shift away from prohibition. The division between hemp and cannabis used for adult-use/medical markets is somewhat artificial as hemp plants are also varieties of Cannabis Sativa except that they are bred for different purposes". "Hemp varieties are legally differentiated by a THC threshold, commonly in the range of 0.2-1%" [20] and vary according to the regulatory jurisdiction.

Hemp has a diverse "range of potential applications, with as many as 5,000 hemp-based products by some estimates [19]", including "consumer goods and industrial products, seeds and their oils that are used in food and animal feeds (hemp seeds are highly nutritious), and cosmetics [21], [22]". "Fibrous stalks and hurds are processed into products including textiles, paper/card, composites, plastics, and building materials [21], [23]". Figure 3 below illustrates the various applications of hemp. Hemp oil and seeds can be used for food and feed, while its fibre for clothing items, cement, plastic, paper, and more.

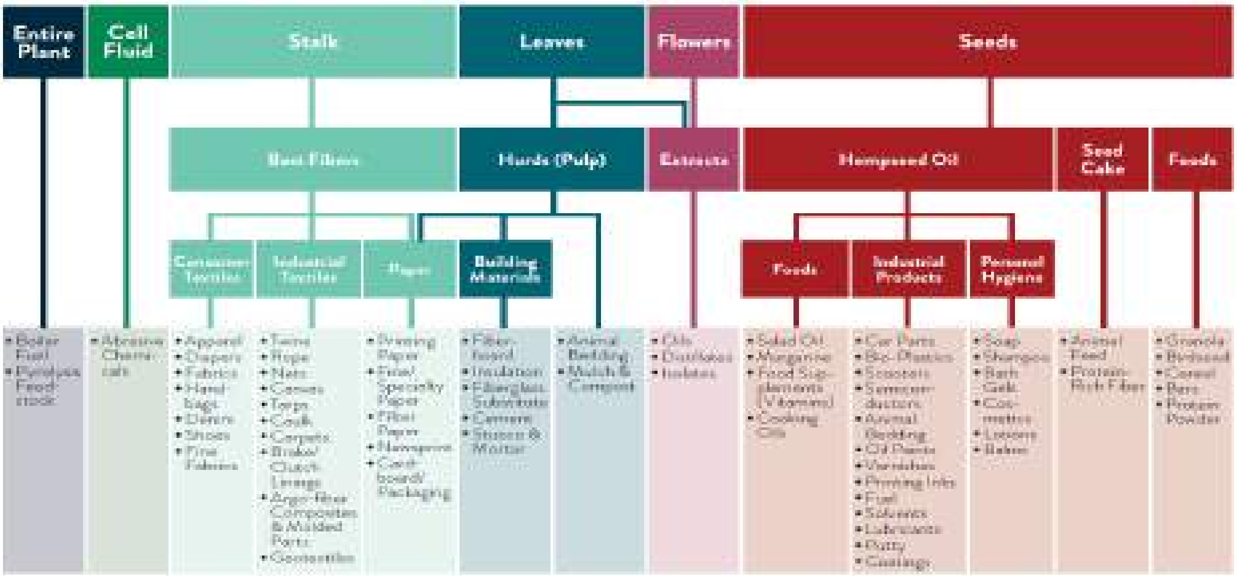

Figure 3: Uses of Hemp [6]

2.1.2 Recreational Cannabis (Adult-Use)

Data reports [9] show that by value, "adult-use cannabis accounts for a large percentage of the global cannabis industry" and "appears to provide the best opportunities for participation by small businesses [9]". It has been estimated that "South Africa has between 3.5 and 4 million recreational users, which is approximately 10% of the adult population [26]". This variant of cannabis containing high THC concentrations produces a psychoactive effect achieved by smoking the bud (dried flowers), inhaling the oil concentrates (dabbing), and edibles. The recreational users "account for over 90% of the estimated $415 billion global cannabis market (legal and illegal combined) [6]".

The legalization of cannabis provides significant opportunities for economic growth, but these are limited to the domestic market because of international conventions that do not allow activities of export and trade. The Government released the "fifth draft of the National Cannabis Master Plan" in 2021, this mandate was initiated by the "2018 verdict of the South African Constitutional Court [9],[24] stating that a coherent policy framework for cannabis commercialisation was required in response to the legality of adult cannabis consumption in private spaces". The primary factors of these documents [24], [25] focus on the "cannabis multi-variate potentials of economic growth, product development, medical applications, and harm reduction". In contrast to the "medical and industrial sectors", where no "legal framework for the commercialisation of recreational cannabis" exists. There is however reported progress on a draft regulatory framework, but the lack of a legal directive remains a pressing legislative gap that prevents the "legal recreational market" from developing [18].

2.1.3 Medical/ Pharmaceutical Cannabis

Cannabis as a medicine is highly regulated and requires a legislative framework. Licenses are issued by the "South African Health Products Regulatory Authority (SAPHRA)" as well as the "registration and regulation of cannabis-containing medicines [7]". Tied to "The International Narcotics Control Board (INCB)", SAHPRA follows "the guiding principles of the 1961 United Nations Single Convention on Narcotic Drugs [27]". Cannabis activities related to "cultivation, extraction, possession, research, and development, patenting, exporting, and importing" are highly regulated and require that a permit or license be issued as defined by "Section 22C of the Medicines and Related Substances Amendment Act [7],[18]". Given that, "South Africa does not have a national framework of quality standards for cannabis medicines" [17]; the "European Union Standards of Good Manufacturing Practices (EU GMP)" is integrated into the "Medicines and Related Substances Act of 1965 (Act 101)" which is mandated by the Department of Health [7]. According to [6], "more than 50 countries around the world have legalised some form of cannabis for medical use, whilst Canada, Georgia, Guam, Mexico, the Northern Mariana Islands, South Africa, and Uruguay—have legalized it for personal or recreational use".

Cannabis has been medically consumed for many years [28], but scientific research remains relatively limited due to its prohibition. According to [29], "there is a growing body of research on the efficiency of cannabis in treating medical conditions relating to epilepsy, multiple sclerosis, and Parkinson's disease; as well as pain-related conditions estimated to affect a fifth of the world's population at some point [6]". Even though "clinical research on cannabis as medicine" is limited, there is evidence [9] that supports its medicinal use worldwide. According to reports [26], [30], the American and European health systems have "integrated the plant into chemotherapy treatments as nausea and vomiting remitters". Additionally, the plant is used to "improve the appetite of HIV/AIDS patients, reduce chronic pain, and control severe forms of epilepsy [18]".

Lastly, there is "increasing research on the therapeutic effects of cannabis for an array of diseases, such as multiple sclerosis and Huntington's disease" according to reports [31], [32]. A published report on medical cannabis consumption [6] shows that "as of 2020, medical cannabis was legally available to some degree in 48 countries with an estimated 4.4 million 'active medical cannabis patients' accessing high-THC products worldwide", 84% of the users accounted for the United States. According to [33], "there has been considerable investment in export-oriented medical cannabis production in South Africa, with over 70 cultivation licences granted and a growing number of cultivators succeeding in producing dry flowers for export."

3 VALUE CHAIN ANALYSIS

Value chain analysis "is a part of the larger 'family' of chain-based approaches" [34], [35], essentially examining the "sequence of activities involved in the production of a product or commodity, from the transformation of inputs and raw materials to the final distribution and marketing of the product or commodity [36]."

The legalisation of cannabis has the potential to "create important economic opportunities" [9]. Illustratively, "Global markets for high-THC cannabis were estimated to be worth $415 billion in 2020, with only 6% of this value being legally traded, almost all within Canada and the United States [6]". According to a report [6], "the legal market demand is projected to grow at a compound annual growth rate (CAGR) of 16.6% between 2020-2025, increasing legal market value from $23.7 billion to $51 billion". The growth grants an opportunity to establish employment options within "cannabis cultivation, processing, and manufacturing of complex value-added industrial products, and the supply of specialised inputs and equipment in the value chain [6]".

Despite several efforts by policymakers, South Africa continuously faces the "triple challenges of unemployment, poverty, and inequality" and remains trapped in a low-growth–low-investment economic environment. These challenges have further been exacerbated by the Covid-19 pandemic. Therefore, South Africa is at a crossroads where radical change is urgently needed if the current trajectory is to be reversed.

The cannabis segments, cultivation, distribution, processing, and consumer products which all include a degree of diversity and specialization are illustrated in Figure 4 below.

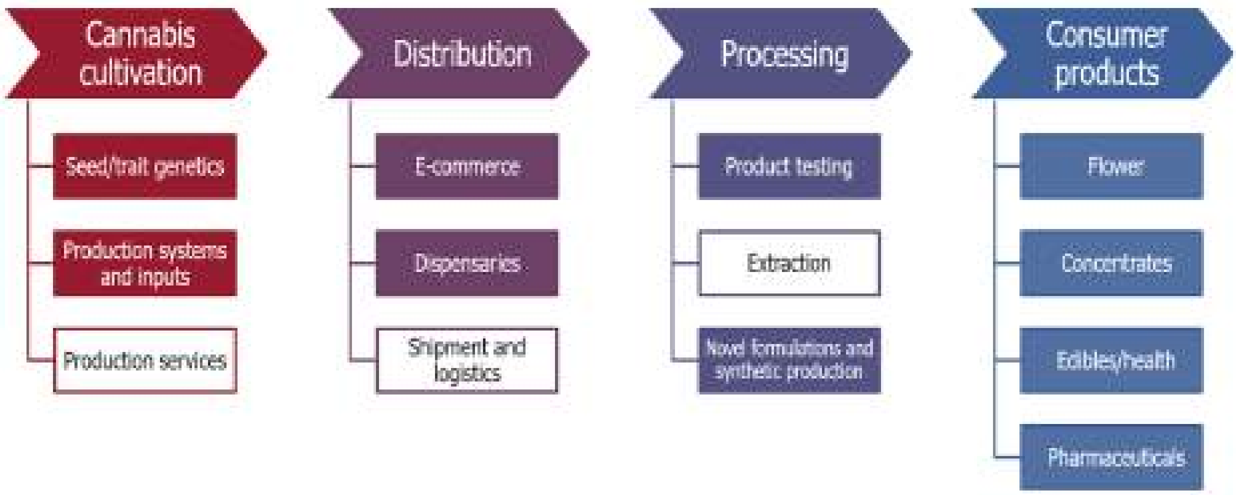

Figure 4: Cannabis Value Chain [37]

3.1 Medical Cannabis

Similar to agricultural products, the starting point of cannabis farming, also known as “growing or cultivating”. Cultivation consists of six (6) distinct phases: “germination, seeding, vegetative, pre-flowering, flowering, and harvesting [6], [18]”. According to industry experts, “medical cannabis cultivation is a form of precision agriculture, carried out either in controlled-environment greenhouses, mesh covers, or indoors under LED lights [9]”. The regulations [33] state that “a controlled environment is a licensing requirement” and a necessity to ensure that the product is ‘contaminant-free and chemically consistent’. Growing facilities require “specialised equipment, computer systems, and skilled staff, to control key production variables: including light, temperature, humidity, CO2 levels, and access to water and specialised nutrients [38]”. The plants are “sensitive and any changes in the variables can cause significant differences in crop production” [9]. Cannabis plants are “vulnerable to pests/fungi and absorptive of pollutants, requiring regular inspections and lab testing” [9], rendering the production of medical cannabis specialised as it requires knowledge, and skills, and is to be deemed “labour-intensive” [9]. A published journal [22], refers that “consistency imperatives mean that rather than growing from seeds, cultivators produce from clones or tissue cultures with some producing these seeds in-house and some purchasing from specialised suppliers.”

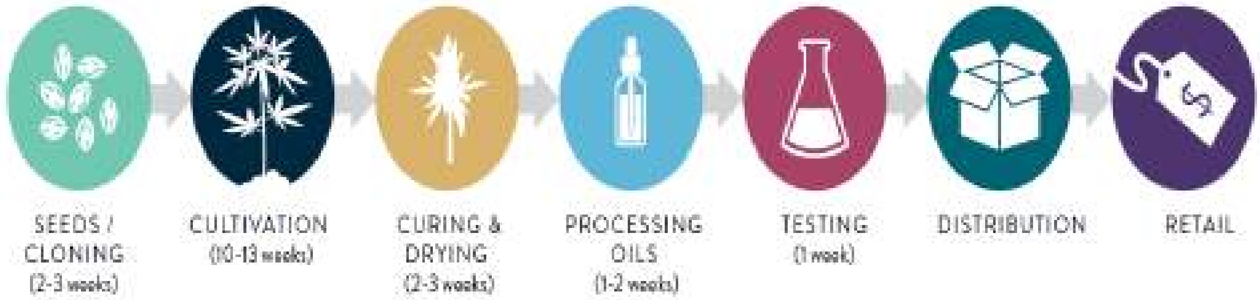

Figure 5 Cannabis production life cycle [6]

Following harvest, “plants move into facilities regulated under GMP standards [33] for drying, cutting, and then trimming to remove buds from stalks and leaves”. The processing can be “automated using specialised machinery, which is reportedly widespread in Europe and North America and being adopted in South Africa [9]”. The buds that are to be cured then vacuum-packed require an “ultra-sterile and controlled environment with specialist security and ventilation/decontamination systems” according to GMP standards [33]”. Specialised laboratory testing by SAHPRA-licensed labs is required before dispatch [16]. Flowers then enter several value-adding channels such as “processing to make extracts/concentrates of varying refinements, isolates for pharmaceutical manufacturing, or re-packaging for end-users” depending on the applicable regulatory system [39]. According to [39], “export market access requires multiple permits and licences, domestically and internationally.” Domestically, “producers must obtain SAHPRA licences and export permits” and internationally, the importing country’s regulatory requirements must be met and adhered to.

3.2 Industrial Hemp

Hemp processing is a “specialised activity requiring specific equipment,” and the “processing techniques, as well as equipment, likewise differ according to the end market [43]”. Industrial hemp has numerous potential applications, including as “an environmental substitute for fossil fuel-based plastics, cotton, and some cement-based building materials [40]”. The farming of Hemp [44], “can produce positive environmental externalities through carbon sequestration and phytoremediation and may be used to generate additional income streams through carbon offset credits” which is particularly important in South Africa due to excessive mining activities that have contributed to land contamination. According to [42], "while South Africa has key gaps in its fibrous plant economy – of which hemp is a key component – relative to the overall level of economic complexity, there are sufficient adjacent capabilities to enable diversification into these activities". Despite reports [10, 19, 23 41] of processing capacity limitations being a "critical constraint for hemp farmers in most parts of the world"; [40], suggests that "the most easily achievable opportunities are in consumer goods such as food products, where existing manufacturers possess significantly advanced capabilities, and could incorporate hemp into existing production processes".

4 DISCUSSION

The global cannabis cultivation market size was valued at USD 392.1 billion in 2022 and is expected to expand at a compound annual growth rate (CAGR) of 21.3% from 2023 to 2030 [44]. Growing legalization and the adoption of cannabis for the treatment of chronic diseases are the key factors driving the growth according to [44]. A "licensing framework for the domestic cultivation of cannabis and manufacture of cannabis-related pharmaceutical products for medicinal and research purposes" was introduced in 2017 by SAHPRA along with the Department of Health [7]; to "ensure the availability of standardised quality-assured medicinal cannabis grown locally for the manufacture of suitable pharmaceutical products". However, South Africa's participation in the value chain remains stagnant in comparison to neighbouring countries.

Lesotho is one of the first countries to legalise the cultivation and use of medical cannabis. The Ministry of Health began approving cannabis cultivation licenses in 2017, and in May 2018 the industry regulations were finalized. The market was established to attract foreign direct investment and stimulate economic growth. The estimated cannabis spent in 2019 was $4.57 million [6].

Zimbabwe became the second African country to legalize medical cannabis in 2018. Legal reform was one among many policy changes effected by the newly elected administration of President Emmerson Mnangagwa as intended "to modernize the Zimbabwean economy, expand agricultural infrastructure, address health-care spending, reduce dependence on food imports, and increase agricultural export opportunities [45]". The estimated cannabis spent in 2019 was $200.1 million [6]. The program was however suspended pending further development of regulations.

The Kingdom of eSwatini (formerly Swaziland), is a small country, and one of the world's few remaining absolute monarchies. The country's economy is heavily reliant on South Africa, which is the destination for 94% of the Kingdom's exports by value, estimated at $1.83 billion in 2017. The estimated cannabis spent in 2019 was $7.4 million [6].

Malawi is one of the world's least-developed economies. It is heavily reliant on agriculture, but rapid population growth combined with the worsening effects of climate change has increased its food insecurity. Agriculture is central to the economy, with the sector accounting for 29% of the GDP and employing 77% of the workforce, mostly as subsistence farmers. The estimated cannabis spent in 2019 was $34.4 million [6].

Ghana has been recognized as a relatively stable West African economy, though falling oil prices since 2015 have reintroduced some instability. Ghana's policies are also relatively friendly to investment and trade compared to other countries in the region. Ghana's exports were valued at $13.8 billion in 2017, driven largely by oil, gold, and cocoa. The estimated cannabis spent in 2019 was $277.4 billion [6].

In 2018, South Africa was expected to be the first African country to formally legalize adult-use cannabis, following a landmark ruling from the Constitutional Court [24]. The Court decided that the "criminalization of private cultivation and use of cannabis was inconsistent with the right to privacy entrenched in the Constitution," and therefore instructed the government to “revise the Drugs and Drug Trafficking Act and the Medicines and Related Substances Act within 24 months to be in accordance with the ruling [24], [45]”. Even though the estimated cannabis spent in 2019 was $1.18 billion [6], the regulations governing the development of the industry are still blurred.

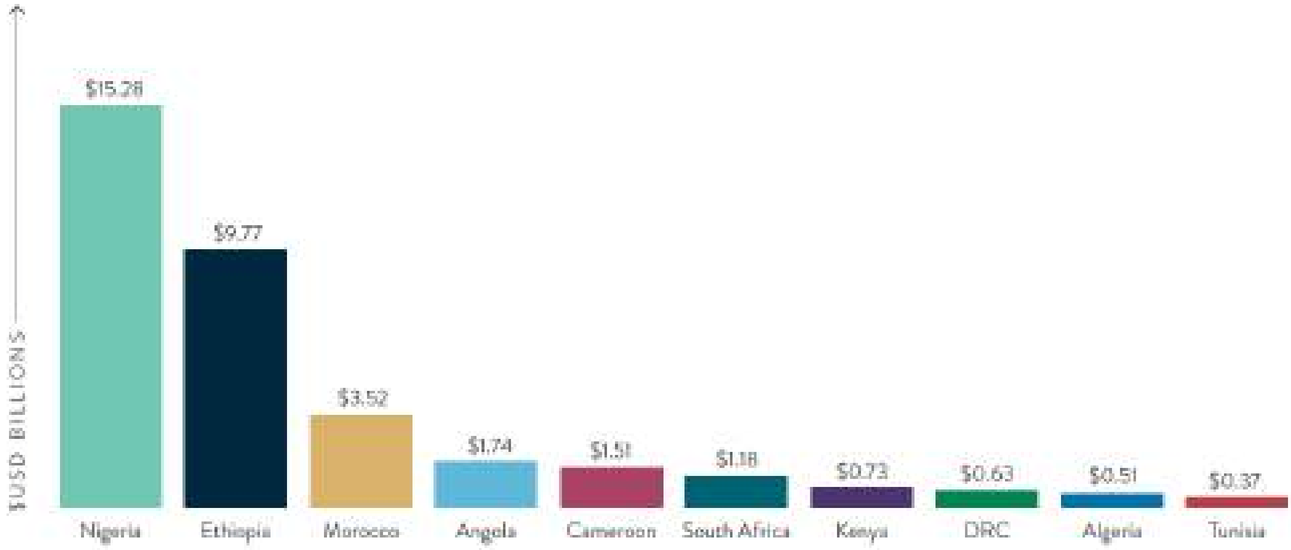

Figure 6: African Cannabis Markets Value Estimates [14]

5 CONCLUSION

Throughout the world, governments have modified or considered the role and state of cannabis. There is a notable growth in demand for cannabis and its products. [6], estimated “the value of the combined legal and illicit African market for cannabis in 2019 at $37.30 billion, with an average annual cannabis use rate of 11.4% (nearly double the global average of 6.0%)”. The high consumption rate, given that Africa’s population of approximately “1.26 billion people translates to 83 million consumers on the continent” which accounts for one-third of cannabis consumers globally [6].

According to [39], “the African medical cannabis and industrial hemp industries have experienced significant growth and development over the course of 2021 and 2022 where countries such as South Africa, Lesotho, Zimbabwe, Uganda, and Malawi have seen an increase in licence issuance, exports, and investments in the industry”. They [39], further state that “South Africa has been the headline driver of growth in Africa, with President Cyril Ramaphosa again highlighting cannabis and hemp as being priority growth sectors for the South African economy”. The President of South Africa made mention of this potential during his State of the Nation Address (SONA) over the last three years. In the last SONA (February 2022), he reiterated his vision of “creating over 130,000 sustainable cannabis and industrial hemp jobs in South Africa.”

The cannabis industry is regarded as a potential economic driver in South Africa and beyond, setting aside the legal framework, globally, the industry is growing rapidly. There are vast avenues to explore within the value chain which give rise to ample prospects, wherein ‘small enterprises’ and ‘traditional growers’ will be able to participate and benefit.

While hemp and cannabis have the potential to transform markets and economies, “the success of any legal medical program is contingent on the creation of thoughtful, realistic regulations and continued appraisal and refinement of their implementation” [9].

The Cannabis and hemp value chain can play a significant role in contributing to the economic, social, and environmental objectives of the country. However, according to [9], "the current licensing requirements for hemp and medical cannabis will largely exclude traditional growers and under-capitalised small enterprises from participation in these value chains". [9] further argues that "the creation of a legal, regulated adult-use cannabis market offers the most accessible opportunities for traditional growers and small enterprises alongside several other benefits and that regulation would need to ensure commercial, equity, and public health imperatives are balanced."

The barriers to entry into the cannabis market are seemingly high, considering the cost of obtaining a license and meeting the prerequisites for establishing a cultivation facility, the current systems and framework are proving to be a hindrance that limits access to the formal industry.

Africa's slow progress in developing its industrial hemp capabilities is a missed opportunity for job creation, rural development, and sustainability solutions. According to [18], "over the next five years, it is likely that a market for decriminalized cannabis will grow in South Africa, with a need for supplies such as grow equipment and seeds for cultivation".

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REVIEW OF SENSING TECHNOLOGIES AND AUTOMATION PLATFORMS TO OPTIMIZE THE PERFORMANCE OF CONSTRUCTION PROJECTS

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ABSTRACT

The study reviewed the application of sensing and automation technologies used in construction projects. A semi-systematic methodology was used to analyse the literature reviewed between 2019 and 2022. Based on the characteristics of relevant material, stratified sampling was used to draw literature on different sensing technologies. Meta-analysis was used to analyse and detect patterns in the usage of the technologies. The analysis established that the common sensing technologies used in this field are location-based sensing, vision-based sensing, and wireless sensor networks. It was also found that sensors can be linked to external systems through robotic process automation or application programming interface. The benefit of the linkage is that on-site performance data can be captured, analysed, and reported in real-time. However, there is room to improve the performance of sensing technologies in the construction industry through the adoption of artificial intelligence. This will increase the success rate of construction projects.

Keywords: sensing technologies, performance optimization, construction projects

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1 INTRODUCTION

Construction projects are essential to the development of infrastructure, housing, and urbanization, as well as in the maintenance and repair of existing structures and infrastructure [1]. Despite their complexity and challenges, construction projects are crucial to society. Some of the benefits of construction projects include the creation of jobs, a boost in the economy, and increased quality of life [1]. Construction projects often require significant investment, but the return on investment can be significant [2]. The average return on investment for construction projects is 70% [2]. Additionally, construction projects can negatively affect the environment, so protection measures are imperative [1].

Sensing technologies are used to monitor and measure the conditions of construction projects. These include temperature, vibration, pressure, and other environmental factors. Using this data, construction progress can be monitored, potential hazards can be identified, and workflows can be optimized [3]. Automated platforms use sensing technologies to control machines, automate tasks, and make decisions [4]. This technology can increase safety and productivity by reducing the amount of manual labour needed in hazardous areas, as well as reducing the amount of time spent on tasks [4]. Increasing the efficiency of construction projects requires reliable sensing technology and automation platforms. This review examines the various sensing technologies and automation platforms available.

2 EVOLUTION OF CONSTRUCTION PROJECTS

Construction projects are essential to the development of infrastructure, housing, and urbanization, as well as to maintaining and repairing existing structures [1]. They generate jobs and stimulate the local economy, allow for the development of new businesses, and provide public services, such as roads, bridges, and sewers [1]. In addition, they help to maintain existing structures, which are essential for safety and efficiency [1]. A wide range of stakeholders are involved in construction projects, including architects, engineers, contractors, and suppliers [5]. It is also important to factor in environmental and social considerations to ensure the project is completed in a sustainable and ethical manner.

Recent years have seen significant changes in the evolution of construction projects. Introducing new technologies and materials has increased the scope of what a construction projects can accomplish exponentially. Among the first steps in the evolution of construction projects is the introduction of building information modelling (BIM). Using this technology, a more comprehensive view of a building's structure and the use of three dimensional (3D) models to visualize the project is possible [6]. It reduces the amount of time and resources needed to complete the project by allowing the design and engineering phases to be completed more quickly and with fewer errors [6].

The evolution of construction projects also involves the use of prefabricated materials. In contrast to traditional building methods, prefabricated materials are prefabricated in factories [7]. Construction can be completed faster and more efficiently, optimizing project costs [8]. Prefabrication can speed up construction by up to 50% and reduce costs by 20% [8]. Construction projects have increasingly incorporated robotics in recent years. It is anticipated that the construction robot market will grow by 17.5% annually by 2030, from USD 1,028.6 million in 2022 [9]. An array of robotic tasks can be performed by robots, from carrying materials to performing inspections, increasing the efficiency and accuracy of the process [10]. Additionally, robots can reduce construction site injuries and improve accuracy and speed.

The use of sensor technology in the construction industry is also becoming increasingly important since it enables better monitoring of projects and enhances the safety of construction workers. This technology also helps to reduce the risk of errors and delays, allowing projects to be completed more quickly and cost-effectively [3]. It is expected that the global sensor market will grow by 8.4% from 2023 to 2032 to reach USD 508.64 billion [3].

3 SENSING TECHNOLOGY

Sensor technology involves using sensors to collect data from the environment, detect events, and monitor physical or environmental conditions. Data collected can then be used to make decisions or take action, depending on the situation [3]. The most common types of sensors used in construction include pressure, temperature, flow, position, level, and contamination sensors [3]. By using sensors, a project's progress can be monitored in real-time to make sure that it is completed according to schedule and according to budget [11]. They can also be used to detect areas that may present a risk to the construction process, and if necessary, adjust the construction process as a result [11].

2.1. Categories of sensing technologies used in construction projects.

Sensor technology is available in a variety of forms and can be used in a variety of construction projects. Generally, these technologies can be divided into three categories, namely location-based sensors, vision-based sensors, and wireless sensor networks. The next section presents a detailed summary of the three categories as summarized by several scholars.

2.1.1. Location-based sensing technology

The technology of location-based sensing is sometimes referred to as real-time location systems (RTLS) or real-time positioning technologies. RTLS is a wireless technology including Bluetooth, Wi-Fi, Radio Frequency Identification (RFID), Global Positioning Systems (GPS), and Ultra-wideband (UWB), that can automatically identify and track the locations of people and objects in real-time and after the event has occurred[12]. RTLS helps improve activities' visibility and enables key decisions to be taken to reduce costs and boost Return on Investment (ROI) by identifying where and when assets are located within a facility [13]. Table 1 provides a brief overview of the various types of Radio Frequency (RF) technologies that provide real-time location services. It may be possible to combine a variety of RF types and methodologies to achieve the best results for organizations.

Table 1 Summary of location-based sensing technologies and their applications.

Technology	Brief Description	Advantages	Disadvantages	Source
Bluetooth	Wireless short-range connectivity solution for portable electronic devices such as computers and phones.	• It is possible to transmit files wirelessly without the use of cables. • A universally accessible service.	• Low transmission speed. • The transmission range is limited. • Security level is quite low.	[14] [15]
Wi-Fi	Radio wave systems facilitate the exchange of data between nearby digital devices by providing Local Area Networks (LAN) and internet access.	• Convenient, multiple users can be connected at the same time. • Flexibility, allowing multiple users to be connected by one device and scalable. • Easily deployable, does not require extensive infrastructure.	• The transmission range is limited. • The system is susceptible to hacking, posing a security risk. • Walls and other physical obstacles may cause signal interference. • Slower than wired networks, such as Ethernet, because it uses radio waves to transmit data.	[16] [15]

Technology	Brief Description	Advantages	Disadvantages	Source
Radio Frequency Identification (RFID)	Using electromagnetic fields, identify and track tags attached to objects automatically. The system consists of three components: radio transponder, receiver, and transmitter. Upon detection of electromagnetic pulses from nearby RFID readers, the tag transmits digital data.	• A variety of RFID devices are available in various sizes, making RFID technology very versatile. • Gives the reader a sense of location. • The system is safer and cannot be easily replicated. • Stores more information than barcodes.	• Compared to other tracking methods, it is relatively expensive. • It is difficult to read tags installed in metals and liquids. • There is the possibility of interference from two-way radios (walkie-talkies) in proximity.	[17]
Global Positioning System (GPS)	As part of the GPS reference system, it uses a network of looping satellites to transmit the precise coordinates of an element or object in a specific space.	• Achieves high levels of precision. • Provides real-time coordinates for objects located anywhere on the planet. • It is cost-effective to implement.	• A minimum of four satellites must be visible to receive signals.	[18]
Ultra-wideband (UWB)	UWB is a wireless communication protocol that uses radio waves to transmit data over short distances. UWB transmits pulses over a broad range of frequencies, and the receiver generates pulses or information based on the transmitter's pulse sequence.	• It is possible to achieve very high data rates or speeds. • Various materials are easily penetrated by UWB signals. • Secure with a low probability of interception and detection. • Signals are reliable even in bad weather.	• Cost of implementation is very high. • There is a slow adoption rate of the technology. • There may be challenges in coexisting with other radio-based technologies.	[12]

2.1.2. Vision-based sensing technology

Vision-based sensors examine images or video recordings to determine if things are present or absent, precise, oriented correctly, and moving [19]. Videos and photographs are included, as well as contemporary technology such as laser scanning. There is a wide range of applications for this technology, from enhancing public security to enabling autonomous robots to map their surroundings efficiently and perform tasks independently [19]. Table 2 summarizes the different vision-based sensing technologies used in construction environments. There is a brief description of each vision-based technology, as well as a discussion of its advantages and disadvantages, depending on the specific objective to be achieved.

Table 2 Summary of vision-based sensing technologies used in construction projects.

Technology	Brief Description	Advantages	Disadvantages	Source
Computer Vision	Motion detection, object identification, and distance measurement are among the techniques used to help machines interpret their environment. Self-driving cars and facial recognition use this technology.	• Improve safety and enhance accuracy. • Offers real-time data for predictive analysis. • Data can be collected remotely using remote monitoring.	• Intrusive and may invade the privacy of individuals. • False alarms can occur, making it unreliable. • Cost of deployment and maintenance is high.	[19] [11]

Photographic (i.e., infrared, visual range, and ultraviolet light)	Objects and people can be identified and classified automatically by cameras and computer vision algorithms, and their movements can be considered in an image.	• Provide good resolution and sensitivity. • Broad dynamic range, thus capturing all light levels. • Require less processing and storage than film.	• Easily distorted and interfered with by the environment. • Expensive and maintenance intensive.	[19] [11]
Laser Scanning	Laser light captures the geometry of an object or surface. Technology creates a 3D representation of any object without contact or destruction. In this process, a laser beam is projected onto the object and its reflection is measured. A 3D model of the object is then created using the data collected.	• Enhances situational awareness on construction sites. • First-time' comprehensive record eliminates future visits. • Having a well-designed fieldwork plan reduces delays. • Can be used to monitor construction activities on-site.	• Not suitable for scanning moving objects since it requires a clear line of sight. • High temperatures can cause the laser scanner to overheat and cause scanning errors. Low temperatures can reduce battery life and performance.	[20] [11]

2.1.3. Wireless Sensor Networks Technologies

A Wireless Sensor Network (WSN) consists of several devices that sense their surroundings and transmit the information links collected from the environment in which they are installed via wireless [21]. The data is then processed and analysed, either by the nodes themselves or by some other device, like a computer [21]. The data gathered from the installation site or environment is transmitted via multiple hops to a sink (also called a monitor) [21]. This sink can process the information locally or connect to other networks. WSNs can be used for a variety of applications, from monitoring temperature and humidity to providing security and surveillance [22]. WSNs are often used in remote and hazardous locations, or places where it is difficult to install a wired network [22]. They are also used in distributed systems, where they provide a low-cost alternative to wired networks.

4 AUTOMATION PLATFORMS

Automation platforms automate tasks and processes that would otherwise need to be performed manually [4]. System automation can be as simple as automating a single process or as complex as integrating multiple processes and tasks [4]. The use of automation platforms can provide many benefits to businesses, including increased efficiency, better accuracy, and cost reduction [4]. Using automation platforms allows businesses to save time and money by giving their employees the opportunity to concentrate on higher-level tasks [23]. Further, they reduce errors caused by human error. Robotic Process Automation (RPA) and Application Programming Interfaces (APIs) are two of the most popular automation platforms today.

4.1. Robotic Process Automation

A Robotic Process Automation (RPA) system automates back-office procedures by imitating human actions using technology [23]. Automation of repetitive tasks, such as data entry, document processing, and customer service, can reduce human error and increase efficiency [23]. In this way, response times can be shortened, accuracy can be improved, and cost savings can be realized. RPA combines User Interface (UI) and Application Programming Interface (API) interactions to automate repetitive tasks within enterprises and applications [23]. It is possible to automate transactions and activities across unrelated software systems with RPA tools [4].

4.1.1. Types of Robotic Process Automation

RPA platforms are usually web-based, providing users easy access to all features and tools, with intuitive user interfaces, making it easy to set up and configure processes [24]. Using powerful analytics and monitoring tools, users can identify and resolve issues quickly. [24].

The cloud-based platform is another popular type of RPA platform [25]. Business applications can be accessed anywhere with an internet connection with cloud-based RPA platforms. This type of platform is great for managing processes across multiple locations and devices. Scalability and flexibility of cloud platforms enable businesses to adapt quickly to change [25].

Finally, organizations can choose to implement RPA on-premises. Companies install this type of platform on their own servers, giving them complete control over the system. On-premises platforms are more secure and reliable, ensuring the safety of processes [25].

4.1.2. Robotic Process Automation Platforms

There are several industries where RPA platforms are used to automate processes, including banking, retail, healthcare, insurance, telecommunications, and manufacturing.

- *Banking:* The process of opening new accounts can also be automated with RPA, as can fraud detection and prevention [26].
- *Retail:* Retail industry uses RPA to process orders, notify customers of shipments, ship products, and track shipments [27].
- *Healthcare:* In the healthcare industry, it is used to schedule appointments, enter patient data, process claims, and process bills [28].
- *Insurance:* Using RPA, claims processing can be automated. Insurance companies can use RPA for underwriting to make more accurate and timely decisions [29].
- *Telecommunication*: RPA can automate manual processes such as customer service, billing, and data entry. Faster response times can also improve customer service [29].
- *Manufacturing:* RPA can be used to automate the process of inventory management, quality control, order processing, and quality control [29]

Table 3 is a comparison of the widely used RPA platforms by businesses. These platforms allow businesses to automate tasks quickly and easily, improving efficiency and reducing costs.

Table 3 Comparison of various RPA Platforms.

Platform	Description	Advantages	License Cost	Footprint	Source
Automation Anywhere	An innovative tool that automates processes using Machine Learning (ML) and Robotic Process Automation.	• User-friendly interface for creating automation scripts. • Easily customizable for any organization.	• Free trial period of 30 days. • Monthly subscriptions starting at $2,500. • Pricing plans for large enterprises.	Deployed over 2.8 million bots by end 2022 worldwide.	[26] [27]
UI Path	Utilizing the latest artificial intelligence and machine learning technologies, UI Path simplifies the process of automating complex processes.	• Workflows, prebuilt bots, and advanced analytics make automation easy. • Powerful visual designer for complex workflows. • Identifies process issues quickly.	• The basic plan provides access to platform features for free. • Entry-level plans start at $399 per month, mid-level plans at $999, and enterprise plans at $4,999.	More than 500,000 bots have been created by UiPath since its launch in 2018.	[28] [27]
Blue Prism	Streamlines manual processes by customizing systems, resulting in greater	• Automation workflows can be created using intuitive user interface.	• A single application license costs $30,000 yearly.	More than 200,000 bots have been created by Blue Prism	[26] [27]

	automation by enabling repetitive automation using RPA.	• Easy to scale, allowing organizations to expand automation. • Ideal for businesses of all sizes.	• Additional applications cost $10,000 to $25,000 yearly, based on complexity. • A monthly subscription model starts at $4,000.	since its launch in 2001.	
Microsoft Power Automate	Automates business processes and saves time by creating workflows between apps and services. Power Automate bots can enter, analyse, and report data.	• Custom bots and applications can be created. • Respond to events, such as email receipts, emails sent, or database updates. • Using automated workflows, alerts can be sent.	• Flows used per month determine pricing. • Pricing starts at $15 per month for a single flow and goes up to $500 per month for unlimited flows. • Free plans available for personal use.	Over 5 million bots have been created by Power Automate as of June 2020.	[30] [31]

4.2. APPLICATION PROGRAMMING INTERFACE

Increasingly, businesses are utilizing application programming interface (API) platforms as a means of streamlining processes and gaining a competitive advantage [38]. The API is a collection of protocols, routines, and tools used to create software applications [38]. Various software components and systems can communicate with each other, allowing data to be exchanged between them. Several types of API platforms exist, each with its own distinctive capabilities and features.

4.3. Classification of API Platforms

There are several classifications that APIs can be categorized under. APIs can be classified in many ways, and the classification that is most appropriate depends on the specific application. For example, APIs can be classified based on the type of data they provide access to, the level of security they offer, or the type of interaction they enable [39]. APIs can also be classified according to the programming language they use [39].

4.3.1. Open APIs

Open APIs, also called public APIs, allow developers to access software components without having to write any code [39]. The creation of new applications and tools becomes easier and faster as a result. Through open APIs, companies can monetize their data by allowing others to access and use it [39]. Since these APIs are public, they can be accessed freely.

4.3.2. Partner APIs

Partner API allows businesses to integrate their existing systems with the API platform [39]. These APIs are not available to the public and require specific rights or licenses to access them [39]. By leveraging the latest technology, businesses can streamline processes. Small, medium, and large businesses can easily use the Partner API due to its secure and easy-to-use nature [40].

4.3.3. Private APIs

Private APIs, also known as internal APIs, allow teams within an organization to access one another's data and services [40]. APIs of this type are typically exposed only by internal systems, and they are typically designed for internal use within a company [39]. In this way, development cycles can be shortened, and collaboration can be more effective. Using internal

APIs allows organizations to create a single source of truth for data and services, improving consistency across the organization [39].

4.3.4. Composite APIs

Composite APIs integrate multiple APIs into a single API, allowing users to access multiple services from a single API call [39]. As an example, a composite API might combine an API that creates customer records in a CRM system with an API that sends an email notification when customer records are created. It is a powerful tool for developers as it eliminates the need to make multiple API calls to accomplish the same task [39].

4.4. Types of API Platforms

The use of API platforms has become increasingly popular in recent years as a means of accessing data, creating user experiences, and connecting web and mobile applications. Developers can develop, deploy, and manage applications more quickly and easily with the right API platform. A comparative analysis of some of the most popular API platforms is provided in Table 4.

Table 4 Comparison of various API Platforms.

API Platform	Description	Advantages	Pricing	Source
Amazon API Gateway	Developers can easily create, publish, maintain, monitor, and secure APIs using Amazon API Gateway's fully managed service.	• Create APIs that can be integrated with existing applications. • Allows developers to create APIs that can be used to create new applications.	• Pricing is based on API calls and data transfers. • Offer free 400,000 GB data transfer and 1 million API calls monthly.	[41]
Azure API Management	Azure API Management provides developers with a set of tools for creating, securing, publishing, and managing APIs.	• Provides web, mobile, and Internet of Things (IoT) devices with secure API access. • Access to APIs can be controlled by monitoring usage and analysing performance.	• Price depends on the number of requests and data transferred. • Provides free tier with up to 10 million API calls per month.	[42]
Google Cloud Endpoints	Developers can securely expose APIs written in any language using Google Cloud Endpoints, a fully managed service.	• A minimum of configuration is needed to authenticate and authorize users, protect against malicious attacks, and monitor usage. • APIs can be authenticated, authorized, and monitored.	• Pricing is based on usage and additional authentication and analytics fees. • Provides free tier with up to 8 million API calls per month.	[43]
IBM API Connect	API Connect is IBM's API management platform designed for enterprises.	• Besides enabling secure and reliable access to data and services, it facilitates rapid and easy scaling of APIs. • Businesses can easily manage APIs while developers can quickly develop, manage, and deploy APIs.	• Pricing is based on the number of users and API calls made and starts at $50 per month. • Flexible pricing plan available for larger companies.	[44]
Oracle API Platform	The Oracle API Platform offers developers a comprehensive solution for developing, publishing, managing, and securing APIs.	• Supports both Representational State Transfer (REST) and GraphQL APIs, as well as API analytics and monitoring tools for developers. • APIs are authenticated, authorized, and monitored with the help of this service.	• The pricing plan is based on API calls and API gateways. • Subscriptions can cost more at higher tiers due to more powerful analytics and security.	[45]

5. CONCLUSION

Although the use of sensor technologies and automated platforms is still at its infancy in the construction industry, it has the potential to revolutionize the process of delivering projects. As sensor technologies develop, they are likely to become more widely adopted, leading to significant improvements in safety, productivity, and quality. In construction, sensing technologies and automation platforms can provide the following benefits:

- In addition to improving safety, sensing technologies can assist in the identification and prevention of hazards, such as collisions, falls, and exposure to hazardous materials. Furthermore, automation platforms can help to reduce the amount of manual labour required in hazardous environments.
- Sensing technology can assist in monitoring construction progress, identifying potential bottlenecks, and optimizing workflows. Additionally, automation platforms can assist in automating tasks, thereby freeing up workers for more complex tasks.
- Enhancement of quality: The use of sensing technology can assist in ensuring that the materials are used correctly, and that the construction is completed to the required standard. The use of automation platforms can also increase the quality of construction by reducing the number of errors.

Construction projects can be made safer, more productive, and more productive using sensors and automation platforms. With the continued development of these technologies, they are likely to become more widely adopted, resulting in a more efficient and safe construction industry.

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THE IMPLEMENTATION OF AN ANDON PRODUCTION MANAGEMENT SYSTEM TO IMPROVE THE EFFICENCY OF TRACKING OF OUTPUT SCORES

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ABSTRACT

With the rapid ever changing technological advances, simple processes are easily changed from manual to automated. An automotive company struggled to keep track of their hourly target as well as the shift production scores. This was crucial to the production line management as this posed as a difficulty to determine the line overall efficiency as well as the possible factors of downtime. This paper is aimed to improve the tracking of hourly scores on a moving conveyor using an automated production management Andon system. Using the PDSA cycle, this automated system was implemented which made capturing of scores easier and more efficient. Once implemented, the daily downtime analysis report could be analyzed and factors affecting the production score were further investigated by the production line management. These contributors were then addressed with implemented countermeasures resulting in a high efficiency line as well as correctly tracked hourly scores.

Keywords: Automated, Andon, PDSA

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1 INTRODUCTION

Continuous improvement forms an integral part of a company which chooses to improve continuously. The world and methods of technology are rapidly improving as new systems are being integrated. Once what needed manual labor in a process can be easily made automated and robotic. There is vast knowledge and literature on improving man and machine related processes as well as methodologies to enhance manufacturing processes. These methodologies focus greatly on standardized work and kaizen. Many companies opt for this method and this is greatly carried out by Industrial engineers, process and production engineers. However, many of the companies do not investigate other technological improvements that can assist a process in increasing productivity. A perfect example of a methodology that consists of improving and adding technological processes is the Toyota Production systems and its 14 principles.

A production assembly line was selected for this investigation and improvement. This production process struggled to keep up with recording their hourly target. Their line management which consists of a senior group leader as well as a team leader was in charge of this process and the hourly tracking of production scores. A sewing line was selected for this improvement. The main struggle was having two separate sewing assembly lines, with one group leader and one team leader whom also have other functions to do during a day of shift. This was a problem as management of the line could not understand why hourly scores were made or not achieved. They were also unable to understand exactly what was the reason for scores not being met. The aim of this paper is to develop a system that records the hourly target as well as to investigate characteristics of other factors that could assist production in reducing their downtime. This paper will also focus on the use of the PDSA cycle of implementation of the Andon system as well as the root-cause analysis to assist the line in reducing the amount of downtime.

2 LITERATURE REVIEW

Technology can be integrated into a lean manufacturing system as long as it supports lean principles and adds value to the manufacturing process. According to Hirvonen [14] Lean manufacturing originates from Toyota Production Systems (TPS). This production system was developed for the need to manufacture more with less. Digitalization of production can be defined as using technology to automate data handling and to optimize processes. It is more especially related to autonomous data collection and analysis as well as interconnectivity between products, processes and people. With the use of advanced enterprise software, this can enable a real time view of the production process and has a positive association with operational performance [13].

According to Dekier [5], The TPS systems can date back to the twentieth century in Toyota. The father of the system was Sakichi Toyoda, a manufacturing engineer. Sakichi Toyoda [8] first invented a motor driven loom which he incorporated a specialized mechanism that stopped in the case of the thread breaking off. This mechanism later became one of the pillars of the TPS house, known as Jidoka (automatization with human manufacturing). The TPS principle is shown below in Figure 1 which is also broken up into the 14 principles.

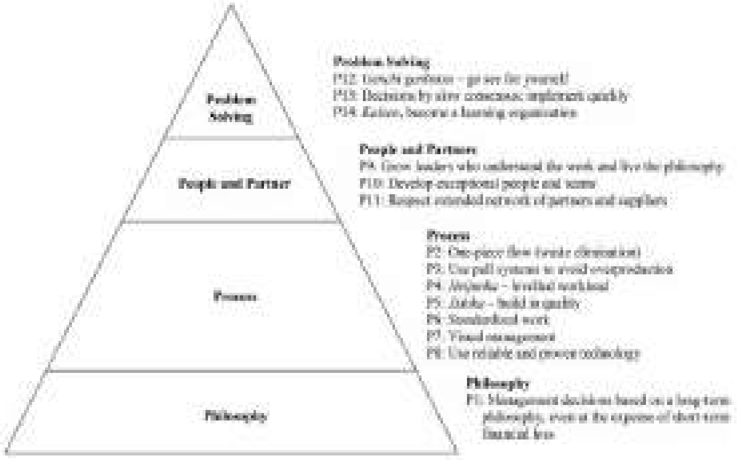

Figure 1: The Toyota way model [5]

Part of the 14 principles there are 2 principles that support the use of production processes to be visual as well as technological. Principle 7 and 8, describes and contributes to the use of technological use in TPS and processes. Principle 7 which is known for visual management has been effectively employed in some manufacturing and service industries. It is not considered an essential element of the lean production system [2]. This tool is unique to a manufacturing process as it incorporates the entirety of the manufacturing process to promote transparency throughout the company [10]. Visual controls tools and communication goes beyond production management in shop floors as it can be successfully adopted by commercial educational, healthcare, government and other fields as stated in literature [2]. Visual tools need to be integrated and openly exposed in the work environment for being easy to reach and easy to see.

Principle 8 refers to using reliable and proven technology in processes. Technological innovations and changes in business environments affect both firms' short-term performance and long-term sustainability. When future directions and options in technology are obscure and uncertain, firms need to formulate an appropriate technology strategy to support their planning for interacting with upcoming future technological developments such as Industry 4.0 [11].

According to Merino [13], there are currently few industries and companies that is aware of the andon systems and their benefits of implementation. Overall Equipment Effectiveness (OEE) is a powerful lean manufacturing tool to measure the effectiveness of a machine or a process line by integrating factors related to availability, quality, and performance [9]. An OEE is also described as an andon system. An Andon systems allow you to visualize the status of different workstations simultaneously. This creates awareness based on visual information to improve efficiency of the manufacturing processes and business as a whole [15]. Visual systems also reduce the waste by saving the supervisors time by directing the attention to where it is required. Importantly visual systems add additional transparency to production as this is one of the visual tools of lean [12].

Although there are multiple models offering frameworks for change, this article focuses on the PDSA cycle. PDSA is a process of Plan, Do, Study and Act, similar to the PDCA cycle. The use of the word 'study' in the third phase of the cycle emphasizes that the purpose of this phase is to build new knowledge. The PDSA model can be applied to the improvement of processes, products and services in any organization. The PDSA model attempts to carefully study a process or activity being implemented before taking further action [3]. The benefits of using the PDSA cycle is that this process enables one to test changes on a small scale. This allows individuals implementing an activity to test cycles in a structured way before doing any further implementation. This basically guarantees success and if a project fails, one can always go back and restudy and re-implement the changes. Through this, the process of change and implementation is safer and less disruptive for patients and staff [14].

The fishbone diagram, also known as the Ishikawa diagram, has become a key diagnostic tool for analyzing and illustrating problems through root cause analysis. This is also a useful diagnostic tool for improvement [6]. Fishbone analysis begins with a problem. This diagram provides a template to separate and categorize the causes of the major problems in a process [11]. The article [9] further goes on to state that because this method allows problems to be analyzed, if it is used with colleagues, it gives everybody an insight into the problem so that solutions can be developed collaboratively. This tool can also assist groups or individuals to identify the root causes of problems to understand the reasons behind the failures, and to determine a progression of actions and consequences to prevent another failure from occurring [1].

3 RESEARCH APPROACH

For this activity the PDSA cycle was adapted to follow through the implementation of a proposed andon system to improve the tracking of score keeping of the production assembly line. The PDSA cycle is a four step model with the first step being the plan or the planning stage. During this stage it is vital to develop a plan in which predictions of outcomes are clearly stated. This is the step where the who, what, when and where is decided. The planning stage of any improvement plays a vital part as this decides the direction of the project. If much emphasis is done during the planning stage, the remaining stages of the PDSA cycle becomes easier to accomplish and plan out. Here the requirements needed for easy visibility of line control are brainstormed collectively with production management and other relevant departments before carrying out any implementation. The second step which is the do stage, consists of the changes or activities identified to be implemented or roll out preferably with a timing plan or schedule (depending on environment). Here the andon is implemented and trialed at production. The study stage known as the third stage, requires the leader in charge of the activity to study the implementation. This was trialed for a week and the data was presented to be analysed. From these findings, additional requirements for the andon were discussed to improve the project as a whole. In this aspect, this refers to the andon and to monitor the workability of the Andon with production. In this stage if any further changes are required, it is further investigated and implemented. The final stage of the process is the act phase. This step incorporates any modifications that are deemed necessary from the study stage that may lead to an improvement. Here, full implementation is also carried out to ensure the end users (the quality and production) fully understand how the system works to enable an easier working environment. The PDSA cycle is shown below in figure 2.

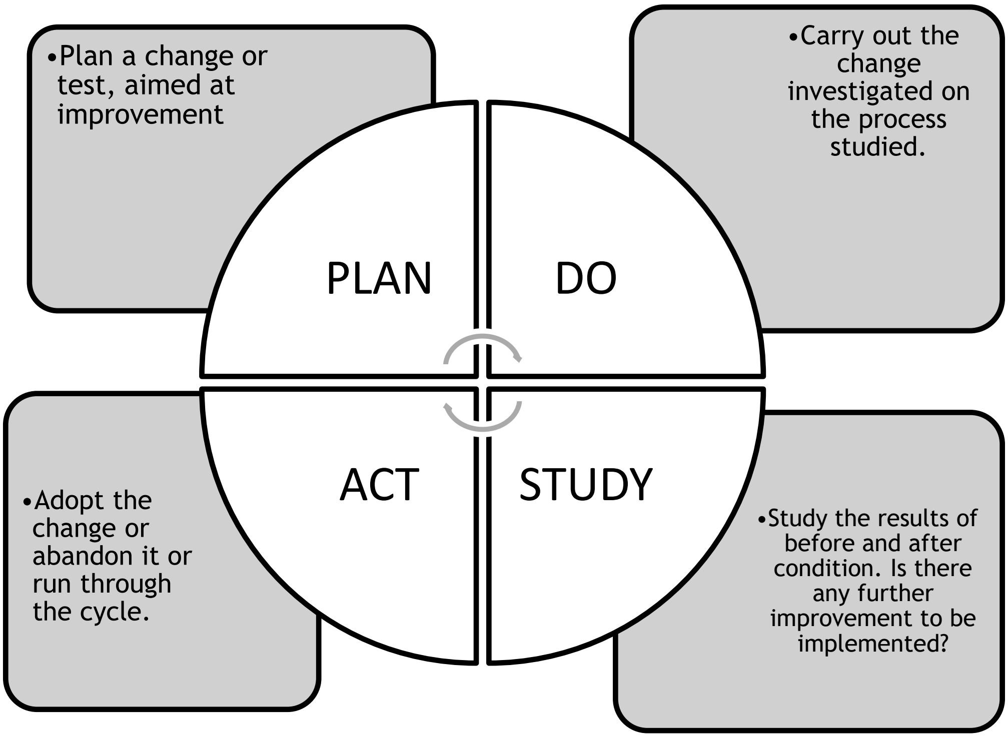

Figure 2: The PDSA Cycle (Authors own)

4 DEFINITION OF PROBLEM AND IMPLEMENTATION OF SOLUTIONS

4.1 Problem identification

An automotive assembly supplier based in South Africa, manufacturers components for one of the market leading car manufacturers in the country. At the sewing production assembly line, it was found that the production output of scores were not be recorded hourly or correctly by the line management. This showed a struggle in analysing the hourly scores as line management. Line management could not determine the struggles being faced hourly by the production line. Production scores was not being met and this posed a difficulty in determining the factors in determining what was wrong.

4.2 Process description

There are two assembly conveyor processes known as the cushion cover assembly and the back cover assembly. Both processes are run by conveyors at a speed of the volume requested by the customer. Each conveyor has eight work stations on the conveyor. Each workstation has one person stationed at it. Once each line completes the assembly of a cover, this cover then goes to the final point on the cover which is the quality inspection. At the quality inspection process (QCI), the cover is checked before going to the finished goods storage. At the finished goods storage, the goods are then taken by the next process when needed. Figure 3 below shows the process flow of the line.

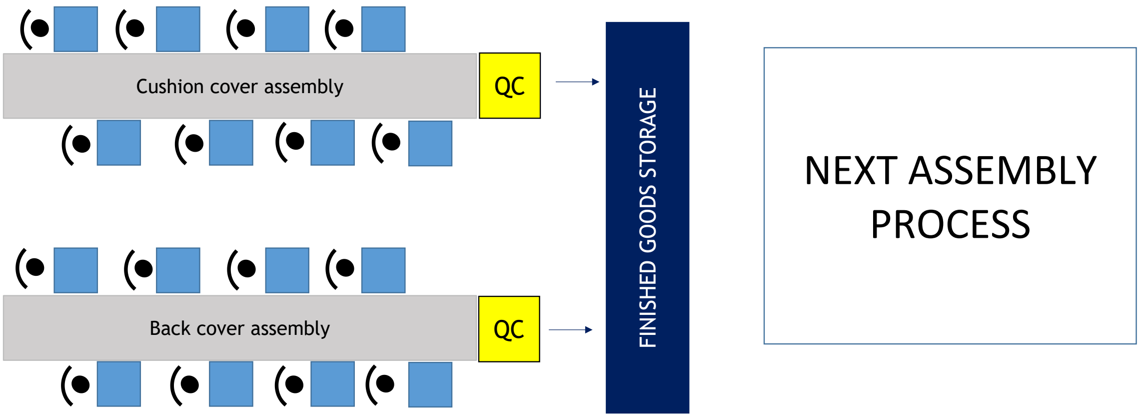

Figure 3: Production line shown diagrammatically

4.3 Potential cause of scores unable to be recorded

Each line has production sheets which hourly information needs to be recorded. This assists management to determine if the production requirement is being met at any part of the day. Unfortunately, this was found as a difficulty by the line team leader and group leader as there was many other tasks required of them. This was difficult to prioritize hourly due to line performance and abnormality on certain days.

The requirement and production standard of the company is that production records scores of output hourly as well as the quality inspection department. Quality inspection records how may covers have been checked for a day. Production requirement a day is of 240 pieces. Data was requested from the quality department of the number of scores recorded daily for the month of November 2022. These scores were then compared to the recorded production scores by production. The compared scores per department is shown below in Figure 4. The blue scores indicate the scores recorded by production, the orange bars indicate the scores recorded by quality and the red line graph indicates the target required by the line to produce.

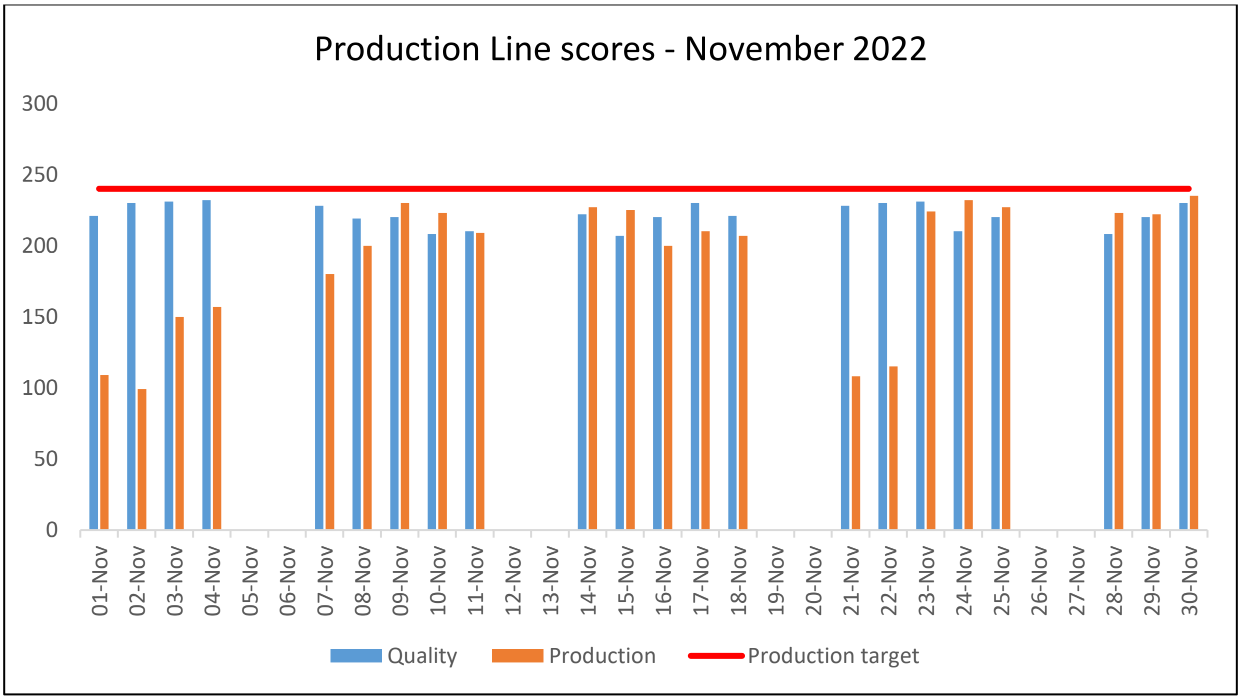

Figure 4: Bar graph showing the different scores captured by the quality and production department against the line requirement

As visible, scores were not aligned and not a true reflection of production pieces being produced. There were days were production scores are higher and days were the scores captured by quality was higher. Actual scores could not be presented to management as true reflection of scores could not be recorded. Downtime analysis was difficult to do as real data of what prevented the hourly score from not being achieved could not be determined.

A fishbone diagram assists in determining root causes of issues of line constraints and finding possible solutions to the problem areas. A fishbone diagram is broken up into six categories, man, method, material, machine, measurement and environment. The Fishbone or Ishikawa diagram in figure 5 shows factors that affected the production line in not being able to record and track the hourly scores

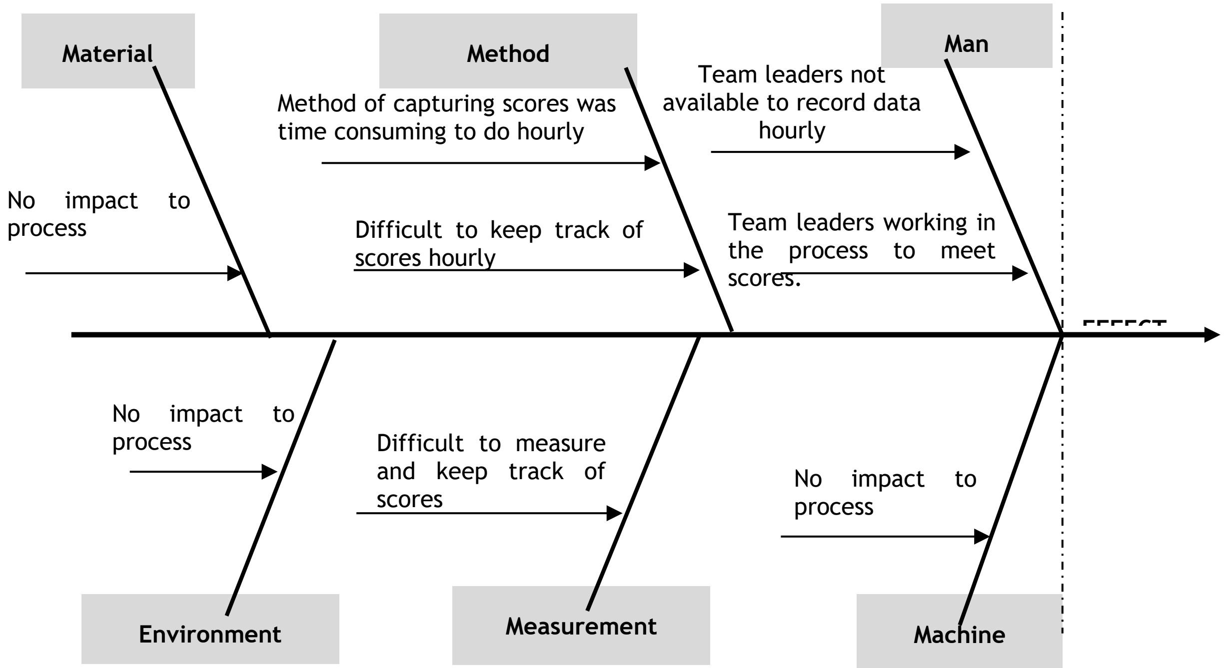

Figure 5: Fishbone diagram of what prevented team leaders and group leaders in capturing scores.

From the fishbone diagram we can see that are factors under the method, man and measurement category in which scores could not be captured. Under man, we determined that the team leaders who are in charge of capturing the scores found it difficult to do as there are other tasks required of them. When there is high absenteeism of the line, they have to work at different work stations. This prevents them from capturing the scores. Under measurement, we found that there is no easy way of capturing scores, this took time and was difficult to do. This was also time consuming to keep track of.

4.4 Implementation of possible solutions

Plan – Brainstorming with relevant departments

When consolidated with manufacturing and the quality department, it was agreed that an easier and technological approach should be used as this would be an efficient and creative way of capturing scores as well as developing a system. With this research, this activity began with a draft of the system and what should be displayed. This was completed and the proposal was then discussed with the relevant departments. The approach used was installing an automatic production management andon system.

Do – Installation of Andon.

Once the requirements were verified and completed, this was shared with an external supplier to implement, install and program the andon system to the manufacturing line requirements. This is described below in detail of how implementation went about in Table 1. This activity was implemented in December 2022.

Table 1: PDSA cycle used to install an andon system

Step	Description	Responsibility	Status
Plan	• Create a schedule of implementation • Source a contractor to understand the activity	Industrial Engineer	Completed
Do	• Implement the Andon system at the sewing assembly line	Industrial Engineer	Completed
Study	• Study and observe that the push buttons are working	Industrial Engineer	Completed
Act	• Train production members on how to use process push buttons • Monitor condition and screen display.	Production management and Industrial engineer	Completed

4.5 Process set up of andon system

Act – Workability of Andon at each workstation

An andon cord or button is used to generate alerts to the line management. Here at each workstation, a push button for "CALL TEAM LEADER" and "WORK COMPLETE" was installed. The call team leader button is for the member to call the team leader without moving from their station if there is any abnormalities or breakdowns. The WORK COMPLETE button is pressed after each cycle done by a member. So every cycle of the calculated takt, ideally it should be pressed to confirm each member at each process has completed their work cycle. If this not the case, the work complete starts flashing to indicate to the member at the process that she is running behind. This is also displayed on the screen showing which process is now delaying the overall line. This screen is displayed at the end of the line or at any point that is visible to line management or management walking by. While this is being shown, a melody is also played for the line management to draw attention to the screen to visually see which processes are behind the schedule and takt time. Using the PDSA Cycle, this was followed through.

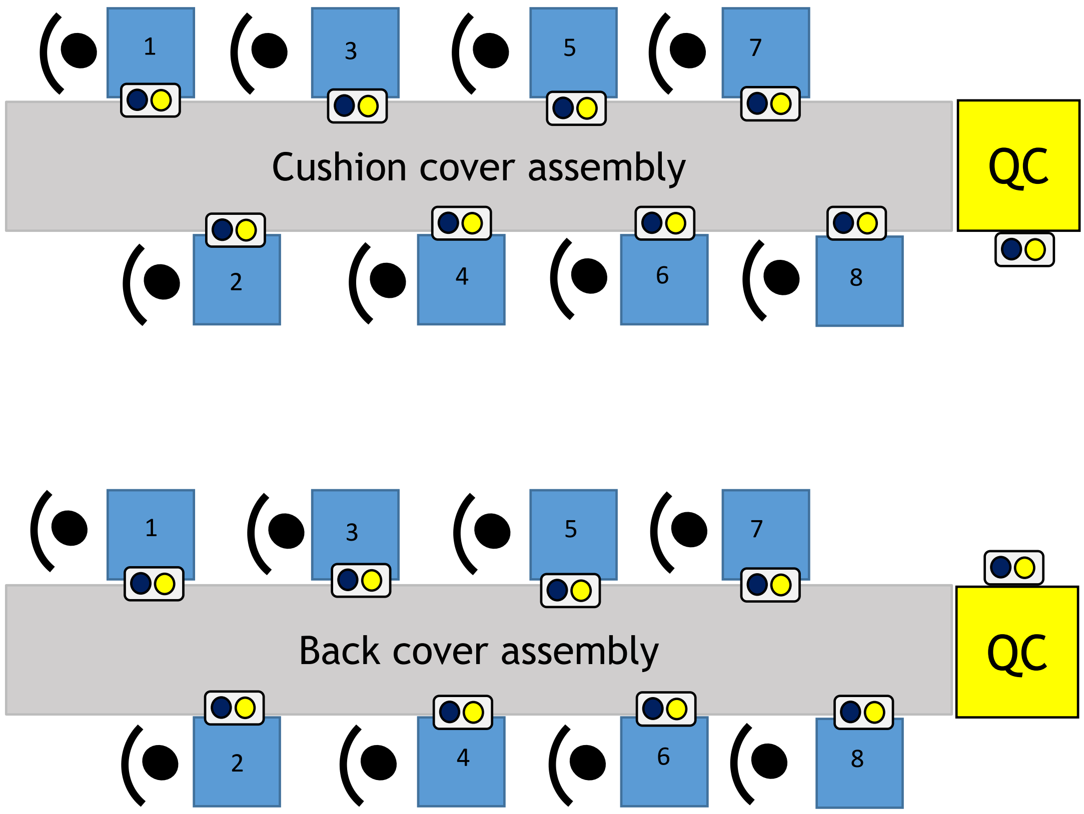

Figure 6: Line set up with andon buttons at each process

Each work station /process was set up with a set of andon buttons at each process. If there was an issue, the member at each process would press the yellow button – the call button. This was displayed on two LED screens situated at line side. There was one screen dedicated for the cushion cover assembly line and another screen dedicated for the back cover assembly process. After each member at each process was completed with each piece of sewing at their process, there were required to press the blue button to indicate a piece was complete. A set of andon buttons was also installed at the quality station as it also records each day's data and could easily be retrieved on any day as the system records the information automatically. This was required as manufacturing confirms how many units they produced and so does quality. The reason as to why this is separated and quality final counts are displayed on the andon is specifically because quality does the final count and are the last to touch the product before final shipment to the finished goods storage. For example, manufacturing can state that they manufactured 20 products and hour and quality only counts 18 units. The variance of the 2 components can either be rework or units scrap.

If there was an issue, any process would press the call button and it would display as shown below.

Cushion	Process 1	Process 2	Process 3	Process 4	Process 5	Process 6	Process 7	Process 8
	-	TL CALL	-	TL CALL	-	-	-	-

Back	Process 1	Process 2	Process 3	Process 4	Process 5	Process 6	Process 7	Process 8
	-	-	-	TL CALL	TL CALL	-	TL CALL	-

Figure 7: Display for Call button

The display of each process assembling a piece is also shown below in figure 8:

OVERALL LINE PRODUCTION SCORES

	PROCESS	1	2	3	4	5	6	7	8
Cushion	TARGET	240	240	240	240	240	240	240	240
	ACTUAL	233	222	220	219	230	222	224	219

	PROCESS	1	2	3	4	5	6	7	8
Back	TARGET	240	240	240	240	240	240	240	240
	ACTUAL	234	236	230	222	231	217	220	222

Figure 8: Production score tracking per process

Study – Study of the results

The overall line andon display is shown below in figure 9. This made it extremely easy to track scores and improve line efficiency. This was easy to view by ay line management walking past.

CUSHION ASSEMBLY COVER DISPLAY SCREEN

	Cushion Assembly	Back Assembly
Plan	240	240
Actual	222	232
Calculated OA	93%	97%
Takt time of the line	1,89min	

BACK ASSEMBLY COVER DISPLAY SCREEN

	Cushion Assembly	Back Assembly
Plan	240	240
Actual	222	232
Calculated OA	93%	97%
Takt time of the line	1,89min	

Figure 9: Andon display screens at the process

5 RESULTS

Installing an automated andon system posed may benefits for the line management. Many of which are listed below:

- Assisted the managers in knowing real time data at any point in time.
- Data from the line is recorded on the system which is linked to the company drives. Each shifts data and downtime were recorded so at any point in time, it could be back tracked.
- Assisted management in determining the reasons for inefficiencies. With the downtime analysis reports, many of the work station delays were due to line stoppages of no parts or maintenance issues. This was resolved internally and addressed.
- Data and piece count was corrected and were now easy to keep track of.
- Each workstation was also evaluated to see which process was a bottleneck or which work station did not meet the scores required for the shift. With this process improvements were done to reduce the effects of bottleneck processes on the line.
- If a process did not press the work complete button, the conveyor would then stop to indicate work delay at that process.
- If there was a maintenance issue, the member at the process would then press the work call button and indicate on the andon that it was a maintenance breakdown that occurred and how much of downtime occurred.

Three months of data was captured and this gave a more realistic view of the actual production scores being captured. This shows the real time target and production scores being captured. The production scores captured by the Andon system were verified and compared with the quality department. This showed us that the record of production scores was correct.

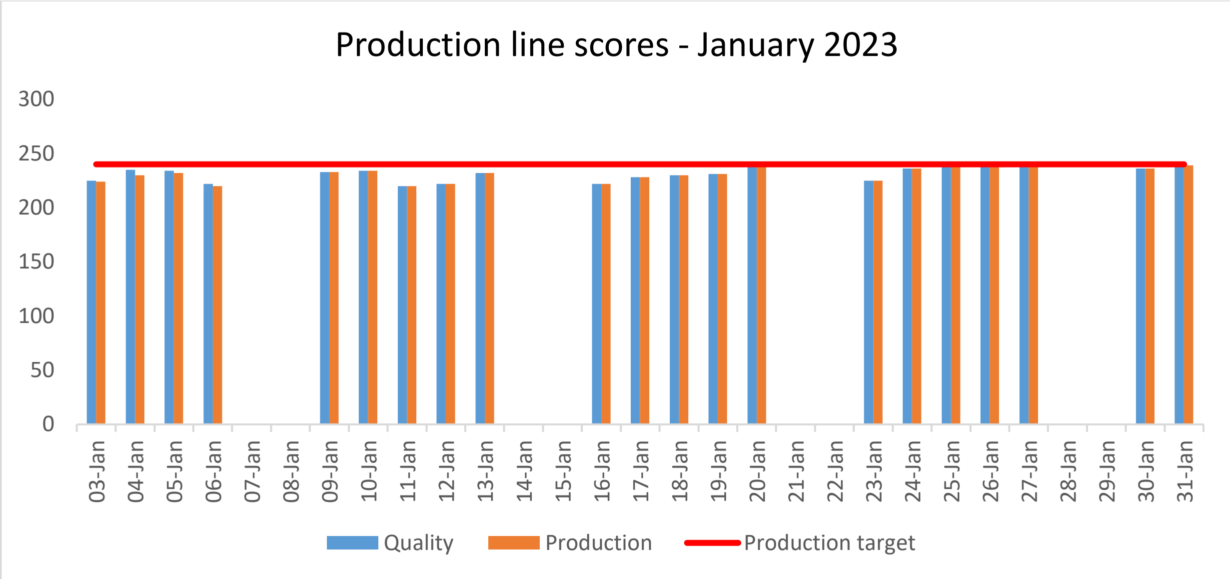

Figure 10: Production scores captured by the Andon in the month of January 2023

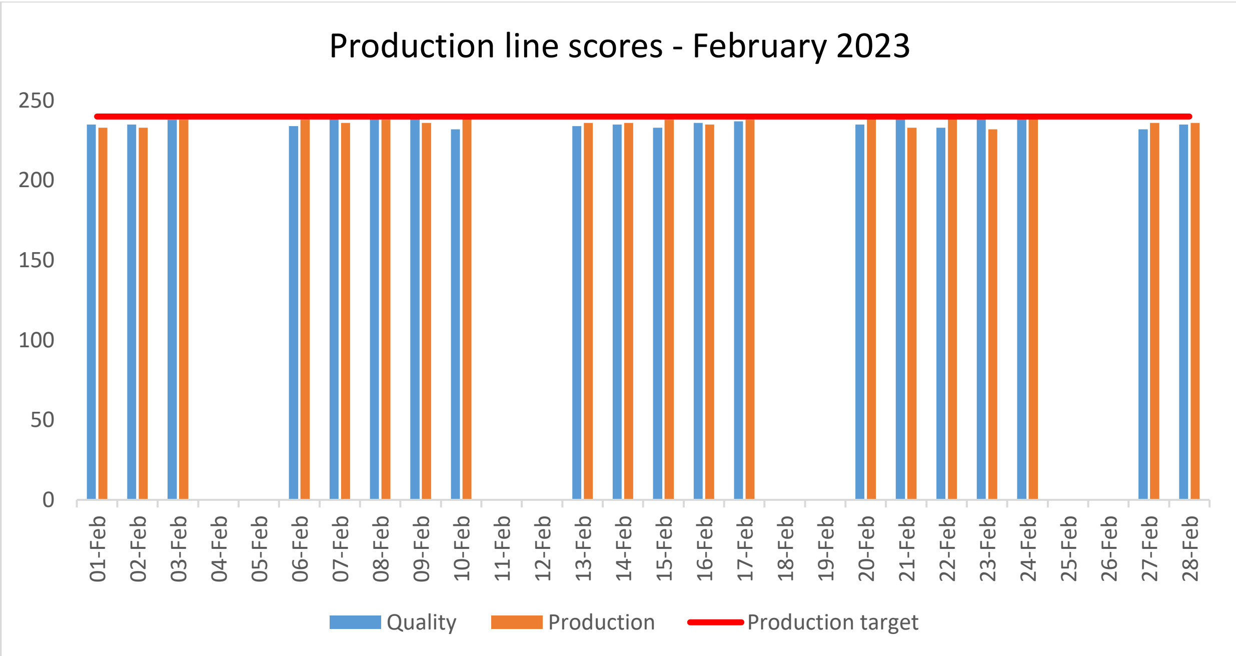

Figure 11: Production scores captured by the Andon in the month of February 2023

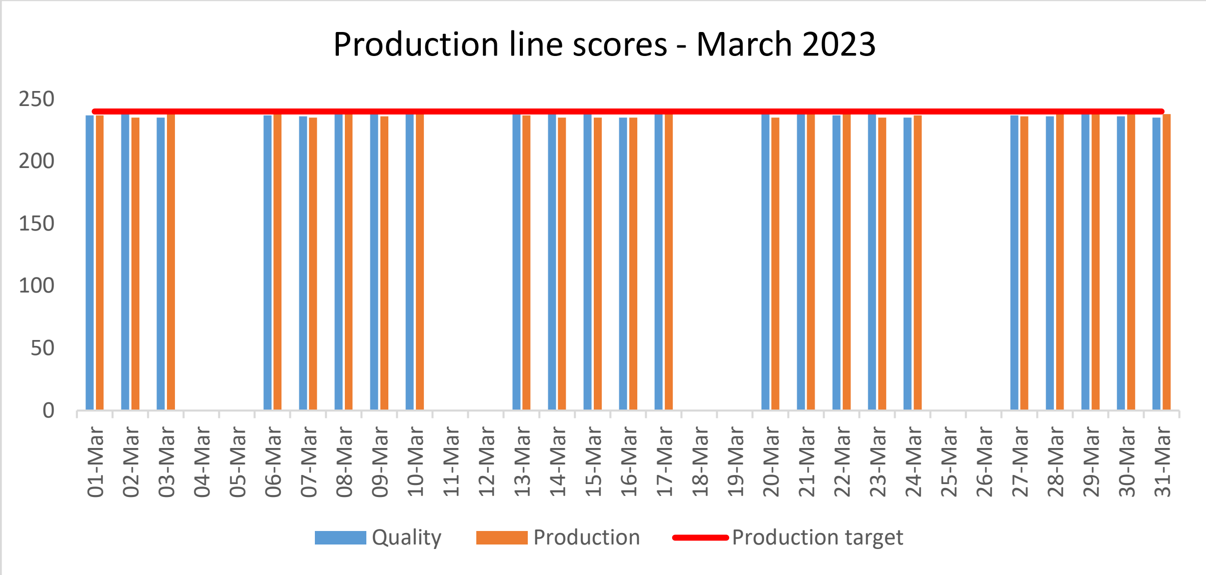

Figure 12: Production scores captured by the Andon in the month of March 2023

We could also see over that over a week of production, there were issues that prevented the production line from meeting their scores. The implementation of the andon assisted the manufacturing department in analyzing the data and putting in respective countermeasures in place. The data for a week is shown below in the pie chart figure 13 below. These issues were addressed and is shown in Table 2.

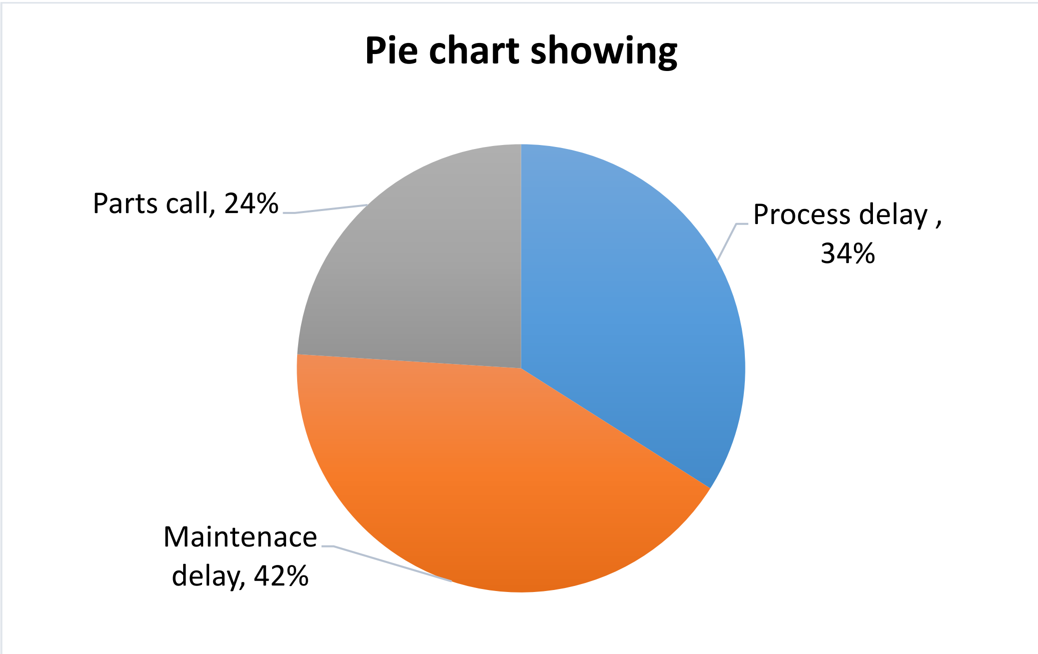

Figure 13: Pie chart showing issues at workstations for 1 week.

From the analysis reports, we could see that there were many issues affecting the line productivity. Each issues are listed below and the countermeasure of each item was also addressed. This is shown in table 2 below.

Table 2: Downtime analysis and countermeasures

Downtime	Description	Countermeasure	Status
Maintenance	Poor lead time to break downs. No dedicated technician for the area	Hire a dedicated maintenance technician for this process to be dedicated to. This will enable a fast response to any breakdown of the line	Completed
Process delay	It was found that there were two process on each line (Cushion and back assembly) that were bottlenecks	Restudy and balance process to ensure there are no stoppages or processes falling behind.	Completed

The reports from the andon were helpful in addressing issues that occurred and putting countermeasures to ensure an efficient process.

6 CONCLUSION AND RECOMMENDATIONS

Many companies are still very traditional when it comes to process planning as well as process improvements. Installing an Andon system at the end of the process as well as simple buttons to control the process at each stage makes it easier to control as well as to track and monitor hourly production efficiently. With this, this enables the production line management to easily deal with other tasks needed on a daily basis. Even though an andon system was implemented there are still many improvements that can be done. Some are listed below:

- Add on logistics call button at each process.
- Add on delay button at each process.
- Add on maintenance call button at each process.

By breaking it down further, we are even more able to distinguish the issues affecting productivity. The production visualization system or the Andon system was successfully implemented at the line side. This assisted greatly at responding to issues at each process to ensure the line runs efficiently.

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SMART MANUFACTURING FOR MODELING OF FOUNDRY PROCESSES IN THE ERA OF INDUSTRY 4.0: A SOUTH AFRICAN PERSPECTIVE

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ABSTRACT

Foundry manufacturing industries plays a vital role in the economy as all other manufacturing industries were dependent on it for the tools, castings, components and systems used to operate in mining, rail, electricity generation and other industries. The purpose of the research was to analyse the factors affecting the implementation of smart manufacturing processes by foundries through digitalisation of Industry 4.0. A quantitative research approach was adopted using the survey method in a which a questionnaire was administered to 143 randomly selected foundry employees of a South African manufacturing organisations. The empirical findings established that three foundry process factors affect the digitalisation of Industry 4.0 technologies in foundries. These factors comprise management and training; smart manufacturing Industry 4.0 technologies; and control strategies, procedures and Industry 4.0 readiness and will help the foundry managers to improve cost efficiencies and gain competitive edge for foundry industry in South Africa.

Keywords: smart manufacturing; artificial intelligence; foundries; industry 4.0 technologies

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1 INTRODUCTION AND BACKGROUND

The Fourth Industrial Revolution (4IR) is described as being a technology and digitalisation revolution in which technologies such as artificial intelligence (AI), the internet of things (IoT), and robotics are merging with our lives and ultimately leading to a societal transformation [1]. The foundry industry has experienced closing down of several foundries, the unavailability of training capacities, expensive technologies, and damaging perceptions such as distress of job loss by industry professional. In today's fast-changing marketplace, steady improvements in foundry manufacturing organisations do not guarantee sustained profitability or survival of the organisation (Nyembwe, 2010). One of the segments of smart manufacturing for modeling of foundry processes do apply AI techniques to overtake the work of human being. The production of metal parts by a casting process is a very old manufacturing process, the basic principles of which have remained unchanged up until now [2]. Metal casting products are present in all spheres of human life, from small bolts to components with various dimensions and complexity for foundry systems. As a result, the value of metal castings exports declined in 2022 and employment in industry has decreased [3]. Hence the integration of smart manufacturing industry 4.0 places an emphasis on automation, machine learning and real-time data.

Manufacturing technology can be understood as the introduction of new technologies that further digitalisation of Industry 4.0. For the purposes of this research, technology will be defined as the application of scientific knowledge for practical purposes, especially in manufacturing industry [2]. This definition follows the slow technological advancement trend facing foundry manufacturing organisations. The lack of knowledge, contradictory manufacturing processes, responsibility concerns and the reluctance of the foundry industry to adopt new technologies of manufacturing have led to the slow implementation of smart manufacturing within foundries in South Africa. This emphasises the need to invest in skills and infrastructure by enhancing operational efficiency and switch to smart manufacturing Industry 4.0 technologies [1].

The South African foundry industry, comprising of ferrous castings (steel and iron), non-ferrous castings (brass, aluminium and zinc), investment castings, and high pressure die castings, is expected to benefit immensely from the Fourth Industrial Revolution (4IR) through engineering design, process control, smart manufacturing, and product and service innovation. This industry contributes 12% of the country's gross domestic product (GDP) [4]. Many researchers have found that manufacturing organisations including foundries encounter challenges in the process of implementing industry 4.0 technologies [5]; [6]; [7]. Industry 4.0 assist foundries improve product quality cope, improve cost efficiencies and flexibility requirements of the future. Industry 4.0 technologies also assist in minimising human exposure to hazards such vibrations, toxic fumes, extreme heat and dust. Adopting Industry 4.0 technologies can be significant investment decision for a foundry organisation, therefore a great deal of attention should be given to the selection of the state-of-art technologies such as additive manufacturing, robot-molding, and robotics. In order to maintain an effective implementation of Industry 4.0 technologies require a different skills and training to operationalise. Foundry manufacturing organisations need to invest in the training of the relevant skills and work towards implementation of industry 4.0 technologies.

The paper examines smart manufacturing process factors by foundries through digitalisation of Industry 4.0. The study focus is on smart manufacturing process implementation that helps foundries gain a competitive advantage. The main question to be investigated in this study is "what are the key factors influencing the modeling of smart manufacturing for foundry organisations?

2 LITERATURE REVIEW

2.1 The smart manufacturing concept in a foundry industry

Over the last two decades, smart manufacturing plays a significant role in South Africa in dealing with the challenges of economic deprecation. Particularly, the vision of Industry 4.0 technologies carrying significant for the integrated development of a country. In recent years, increasing emphasis on the casting process stands out as a specific manufacturing process due to its complexity and diversity. The application of AI in the improvement of the casting process represents a new wave of automation development in foundry manufacturing industry. A study conducted by Lewis [7] finds that smart manufacturing concept involves debt, and requires a workforce that values its importance and can accept the monitoring of the technological process.

smart manufacturing is a discipline in which manufacturing engineers analyse machine and sensor data to improve operational efficiency and downtime [8]. The literature states that the metal casting foundries in South Africa are closing because of circumstances on micro-macro-economic levels [9]. In addition, the foundry industry has been contracting over the last two year due to poor economic growth, high input costs, high levels of imports and inconsistent supply of raw material (casting) in South Africa [5]. There are many factors that have a potential impact on high quality and proper manufacturing process. Smart manufacturing and Industry 4.0 are empowering each other, both often described in foundry industries [10]. Similar to Industry 4.0 proposed by Germany, “Made in China 2025 Strategy” also focuses on smart manufacturing [11]. Oztemel and Gursev [12] also suggest that the adoption of the well-acclaimed smart manufacturing concept, can enable sustainable manufacturing and increased need of customised or personalised products. Smart manufacturing provides employees with real time information to improve work procedures and decision-making processes. Based on extensive literature review and foundry experience, smart manufacturing and Industry 4.0 technologies are critically necessary for a foundry organisation to sustain in current foundry market which is highly challenging and competitive [13]; [14]. Smart manufacturing foundries can apply additive manufacturing such as 3D printing to prototype and manufacture components in small batches. By implementing smart manufacturing, foundry organisations could reduce production costs, reduction of design errors and shorter product development.

2.2 Artificial Intelligence

Artificial intelligence needs to be applied by all foundry employees and used for modeling and optimisation of processes, to find new solution for digital monitoring and control [13]. Studies such as Schwab [1] identified the artificial neutral network (ANN) as the basic AI technique capable of modeling non-linear process by establishing relationships between input and output process parameters based on the appropriate amount of data. This is mostly true for smart manufacturing and Industry 4.0 technologies due to the fact that most important characteristics of ANN are the network architecture, which includes the number of the neuron in them, training algorithm and the number of hidden layers [15]; [16]; [17]; [18].

ANN had been applied in the foundry industry and in some cases in services and achieves good results, increasing proficiency of processes. This, in turn, will assist foundry manufacturing organisations in achieving their objective of promoting sustainable use of metal casting processes and for economic growth to benefit the community. Writing about South African foundry manufacturing organisations, Mpanza, Nyembwe and Nel [19] states that to enable growth and production costs, they need to have strong interconnected management and also utilise the various foundry management techniques available. This study concentrates on the smart foundry processes and Industry 4.0 technologies that can be utilised to substitute for human thinking and increase tasks.

2.3 Implementing smart manufacturing and Industry 4.0 technologies in foundry industry

Industry 4.0 applied to metal casting would enable rapid manufacture of small intricate metal parts with high quality even for single and at much lower cost than conventional casting [5]. Having specific procedures, clear policies, standards, training and guidelines systems is positively correlated with smart manufacturing and industry 4.0 technologies would bring added value to manufacturing performance. Researchers in the literature quoted the significance of investment casting mainly due to the fact that the new competitive challenge for foundry organisations is the successful combination of the quality of the casting process and casting technology characterised by nonlinear and complex relationships between the process parameters [20]; [21]. In a similar vein, Oztemel and Gursey [13] emphasises the effective implementation of smart manufacturing could lead to improved performance and competitive edge amongst other competitors. This implies that the implementation processes of smart manufacturing and Industry 4.0 technologies involve understanding the starting position before moving forward into Industry 4.0 adoption; create a strategy; start with small casting process; create a friendly ecosystem and focus on improving processes [22].

3 RESEARCH METHODOLOGY

This study adopted a positivist research philosophy and utilised a quantitative research approach. The research design employed was a primary data, and survey was gathered through a well-structured and self -administered questionnaire. A pre-test of the questionnaire was performed at Foundry organisations located in Gauteng, South Africa to assess its validity and correct comprehension of the research questions. The research instrument was put through a discriminant validity using Field [23] criterion. This was accomplished by comparing the correlations among the latent constructs with square roots of average variance extracted [24].

A review of literature on smart manufacturing, the adoption of Industry 4.0 technologies, artificial intelligence, Internet of Things, metal casting process and implementation processes related to foundry manufacturing organisations was undertaken. A quantitative survey study using a random sampling strategy was then adopted for the empirical portion of the study [25]. The survey method was considered applicable for this study because it definitely facilitates data generation procedure from large populations, making it easier to develop and administer the study questionnaire while generalising the study findings [26].

3.1 Population and sample size

The sample for the current study comprised of 143 employees of foundry employees in Gauteng Province of South Africa. Rule of thumb prescribes that no less than 50 participants are appropriate for a regression or correlation with the number increasing with larger numbers of independent variables was employed as the nominal anchor in determining the sample size [22]. The study also adopted an exploratory and descriptive research designs to investigate a multiple regression model in order to improve productivity in foundry manufacturing industry.

3.2 Instrumentation

The analysis of the information collected during the distributing of questionnaire and the data collected from the respondents were loaded into the Statistical Package for the Social Sciences (SPSS) version 26.0 software programmes for descriptive statistics. The influence of variables such as smart manufacturing Industry 4.0 technologies, skills development & training, IoTs, Robotics, Artificial Intelligence and management support on the smart manufacturing organisations were tested to determine whether there were significant differences between these variables. Sensitivity to outliers was checked and deleted in order to produce meaningful results in the study. The statistical technique used to analyse the data were multiple regression, correlation and analysis of variance.

Pallant [26] referred to multiple regression as a major statistical technique used to explore relationships in the form of correlations and analyses of variances. Further to this, multiple regression explores the predictive ability of a set of independent variables. It permits evaluation of the importance of independent variables in the model and tests the overall fit of the model based on the data. Multiple regression provides the relationship between variables, and thereafter indicate the most important variables in the model and in this case, it formed part of attempt to address the research objective and develop a smart manufacturing of foundry processes in the era of Industry 4.0.

4 RESULTS AND DISCUSSION

4.1 Respondents' profile

The demographics of the sample are described, followed by the presentation of results based on the research questions. The purpose of the research was to develop a smart manufacturing model of a foundry processes in the era of Industry 4.0 using multiple regression. The research analysed data through the application of the SPSS version 26 to the collected information. The initial step was to establish metal casting process and factors influencing smart manufacturing Industry 4.0 to improve production in Gauteng foundry manufacturing organisations. The following Table 1 shows the research study focus, sample size, the response rate and valid response rate.

Table 1: Response and valid response rate

Description	Data detail
Research Study focus	Foundry manufacturing organisations
Study area	Gauteng Province, South Africa,
Distributed questionnaire	190
Respondents	147
Response rate	77%
Response profile	Foundry manufacturing employees

The associated field worker dedication of being dropped at the area for administering and collection at agreed periods assisted this response rate. Questionnaires were rejected based on empty spaces or missing information. The following analysis shows the summary of respondents' statistics. According to Table 2 covering modeling of foundry processes in the era of Industry 4.0, on a 5-point Likert scale, the respondents mean is above 2.5 on average, signifying that the eight input resource factors are measuring components relevant for improving metal casting process in foundry manufacturing organisations in Gauteng.

4.2 Validity and reliability

Feedback obtained from pilot study facilitated further refinement of the questionnaire items [25]. The scale's internal consistencies in the instrument showed Cronbach alpha coefficients (refer 2) ranging from 0.725 to 0.876, while the alpha score for the entire scale was 0.776. Field [23] recommended that since these alpha values were all above the minimum acceptable level of 0.70, it was concluded that the measurement scales used in the study were internally reliable and consistent.

Table 2: Mean scores and internal consistencies

Factor name	Number of items	Cronbach Alpha	Mean score	Position in mean score rank
Management & Training	5	0.776	4.535	2
Smart manufacturing Industry 4.0 technologies	10	0.876	3.902	1
Control strategies, procedures & Industry 4.0 readiness	4	0.725	4.129	3
Total	19			

Table 2 indicates the mean scores of the factor scales considered in the study. These ranged between 3.902 and 4.535, representing clear inclinations towards either the agree/strongly agree or the satisfied positions on the Likert scales. Respondents were, therefore, satisfied with the existing levels of these factors in the modeling of foundry processes in the era of Industry 4.0. As depicted in Table 2, the respondents perceived that lack of digital use and unavailability of training capacities of many foundries in South Africa could partially be ascribed to the inadequate management support and commitment. Correlation of foundry processes and importance variables using factor analysis identified as factor 1 as "smart manufacturing Industry 4.0 technologies'; factor 2 as 'management and training'; and 'factor 3 'control strategies, procedures and Industry 4.0 readiness'.

Investing in Smart manufacturing, Internet of Things, skills development and training, Industry 4.0 technologies and robotics are reported to enhance productivity within foundries. The adoption and use of latest technology are believed to improve casting quality in foundries and this is supported by the research of Liska, Klimkiewicz and Malinowski [10] Industry 4.0 and related technologies assists foundry manufacturing organisations to increase their competences and productivity growth. Reducing costs, and eradicating surplus and imperfections ensures investments and that quality products get to the customer. It is through new technologies such as smart manufacturing, advanced simulations and smart sensors that manufacturers compete to intensify their productivity, while at the same time ensuring that targets are met and rewards are given to employees based on their efforts. The accessibility and availability of smart manufacturing Industry 4.0 reduces the cycle time and ensures a swift response to customer requirements. Foundry manufacturing organisations agree that frequent quality housework, on-time delivery and efficient service levels promote efficiency and manufacturing processes. Application of artificial intelligence in the improvement of casting process, integration of smart manufacturing technology and the Internet of Things ease of access to the manufacturing process play a significant role in increasing productivity within foundry manufacturing industry [1]; [3].

4.3 Regression analysis

A multiple regression model method was used to identify the effects of selected independent variables on dependent variables. Field [23] defines multiple regression as a descriptive tool used for developing a self-weighting estimation equation used to predict affinity or coefficient values of independent variables of the dependent variable. Thus, multiple regression was used to develop a mathematical model which establish the significant factors or themes influencing smart manufacturing for foundries. The hypotheses formulated to guide the study's direction were tested using linear regression analysis. This inferential statistical technique is performed to identify the variables predicting the best explanation of the total variance in the scores of a set of dependent variables [24]. Modeling of foundry process was entered into the regression model as the dependent variable. The three factors; namely, management and training; smart manufacturing Industry 4.0 technologies; and control strategies, procedures & Industry 4.0 readiness, were entered as the independent variables. The results are reported in Table 3.

Table 3: Regression analysis

Independent variables: Extrinsic motivation factors	**Dependent variable: Modeling of foundry process**			
	Standard Coefficients *Beta*	**T**	**Sig.** *Tolerance*	**Collinearity Statistics** *VIF*
Management & training	0.292	4.268	0.000	0.579
Smart manufacturing Industry 4.0 technologies	0.250	5.846	0.001	0.685
Control strategies, procedures & Industry 4.0 readiness.	0.278	2.140	0.002	0.708

Model summary: R=0.479 Adjusted R2=0.440 F=16.730 Std. error of the estimate =0.84387

A comparison of the mean scores shows that modeling of foundry process (mean=4.085) scored the highest mean, meaning that respondents were most satisfied with this factor compared to the other three. The three independent factors accounted for approximately 44% (R2=0.440) of the variance explained in modeling of foundry process. Collinearity statistics for the three independent variables were satisfactory, indicating that the problem of multicollinearity was insignificant in this study since there were no high correlations between the independent variables. All tolerance values fell above 0,5, as prescribed by Field [23]. Variance factor (VIF) values fell between 1.0 and 4.0, as recommended by Gorsuch [28].

5 CONCLUSIONS AND RECOMMENDATIONS

Based on the results, the research concludes that Industry 4.0 technologies plays an important role in ensuring metal casting progress of foundry manufacturing organisations. By using regression analysis to test the results, Industry 4.0 technologies focusing on employee involvement and environment, user-friendliness; cleanliness by foundry manufacturing organisations improves to a larger extent metal casting process of their industries as compared to other variables that were part of the study. Centred on the results, the research concludes that virtual reality strongly plays an important role in ensuring casting process progress in foundry manufacturing organisations. By using regression analysis to test the results, management commitment and support through control strategies, manufacturing technology, procedures, artificial intelligence techniques, substructures such as metal casting process and machine learning algorithms as well as training strongly improve casting processes of foundry manufacturing organisations improves to a larger extent productivity of their industries as compared to other variables that were part of the study.

There is great potential for smart manufacturing and Industry 4.0 technologies in the foundry industry. Modeling and optimisation of the design of casting process are considered in addressing the creating job opportunities and assist increase economic growth of South Africa. This study aimed at analyse and developing a smart manufacturing of foundry processes in the era of Industry 4.0. The application of artificial intelligence techniques has a diverse nature, depending on the specificity of the casting knowledge. The Gauteng foundry industry managers and leaders should increase their efforts in supporting foundry employees implementing smart manufacturing processes and Industry 4.0 technologies, which encourages development of Foundry metal casting process. Firstly, smart manufacturing training programmes need to be arranged by top management for foundry employees, information technology and communication (ICT) experts or practitioners as well as other industry role players. It is imperative to note that most of these smart manufacturing programmes, particularly in the foundry industry are mostly concerned with modeling and optimising, establish the relationship between the process restrictions and the characteristics of the casting process, in order to obtain a high-quality process. Secondly, it was also noted that the more issues of lack of artificial intelligence techniques arise, the less improvement relating to quality of metal casting processes and smart manufacturing process is seen. Overall, the findings show that there is a need for foundry authorities to ensure that smart manufacturing and Industry 4.0 technologies are well-implemented related to the improvement of the investment casting process are taken into consideration through modeling and optimisation of the casting process.

The issues of lack of adequate artificial intelligence techniques should be addressed by ensuring that there is commitment and support from top management, adequate implementation training, smart manufacturing awareness and improvement activities should be place. Advanced smart manufacturing and Industry 4.0 technologies training programmes should be introduced for foundry manufacturing organisations and its employees, and a wide-range of artificial intelligence techniques should be applied that are rooted in the perspectives of foundry industry. Therefore, artificial neutral network (ANN), Internet of Things and robotics are recommended. When quality of metal casting process is implemented in these foundry manufacturing organisations, domestic product (GDP) improves for the nation and growth of the economic in the country is ensured.

The results of this study can assist foundry industry authorities and manufacturing organisations as well as metal communities at large in implementing the processes of smart manufacturing and Industry 4.0 technologies properly; thus, ensuring that casting process inefficiencies are identified and resolved during the planning phase. If this is not done, smart manufacturing and Industry 4.0 technologies experts or consultants could train foundry managers and societies on how to apply this method in order to implement and control inadequacies occurring on their foundry processes. More importantly, Gauteng Foundry manufacturing authorities and managers will be enabled to better establish and implement digitized smart foundries.

5.1 Limitations of the Study

There were limitations associated with the sampling of the population and analysis of data. Because the study was not across South Africa, the findings cannot be generalised to manufacturing industries in South Africa.

5.2 Further research

Based on these issues addressed with negatively reflect on Gauteng foundry industries, future research should focus on designing and applying artificial intelligence techniques as an integral part of the Industry 4.0, the quality of metal casting process used and linked cost of digitized smart foundries.

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AN APPLIED MECHANICS' APPROACH TO SOLVING THE PRODUCTIVITY DILEMMA
[A General Mechanics of Machines Theory and Practice]

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ABSTRACT

According to productivity improvement technical theory, and as per the technical principles of enhancing productivity, a scenario of productivity predicament arises when traditional tools and methods aimed at boosting productivity are employed within a production process yet fail to yield the desired productivity enhancement. This occurrence becomes evident when the outcome demonstrate a reduction in the production cycle time, however, there is no corresponding increase in the production output. Although the application of conventional productivity enhancement techniques leads to a shorter production cycle time, the time saved is not substantial enough to result in amplified production output. The deficiency in output augmentation is a subject currently examined within this scholarly investigation. This qualitative research article presents a comprehensive illustrative instance that underscores the consequences of a design engineering approach in resolving the challenges surrounding productivity improvement. Through a comparative analysis of outcomes attained with and without the integration of supplementary equipment, supporting proof is presented to emphasize the influence of design engineering on augmenting productivity, when deployed within production processes.

Keywords: Productivity; Engineering; Process improvement; Production; Mechanization.

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1 INTRODUCTION

When productivity enhancement tools and techniques are employed to address the production challenges stemming from constrained and scarce resources, the outcome is a notable rise in the efficient utilization of existing resources. Consequently, this leads to a substantial increase boost in overall productivity. According to Shanker et al. [1], the main purpose of a productivity study and analysis is the improvement of productivity. The authors identify the three main components of productivity improvement process as, first the external component, internal soft component, and the internal hard component [2]. Figure1 below illustrates the main components of the productivity improvement process. Adendorff and de Wit [2] explains that the external components is the factors beyond man's control, the internal soft components are the intangible factors that predispose the whole organisation's flexibility and capability to endure change, and the internal hard components are the tangible quantitative measurable factors of productivity [2].

Assessment of productivity involves the examination of internal hard components within the realm of productivity. Findings and insight derived from this evaluation are the utilized as input data for making informed decisions aimed at enhancing the internal soft components of productivity [2]. The expansion of production or the increase of productivity that arises from augmenting the volume of factor-inputs within a production process is deliberately restricted and modest in nature [3], as illustrated in figure 1. In the scenario where production input volume shifts from P1 to P2, the subsequent growth in output advances from T1 to T3. However, it is important to note that while T3 does not represent the maximum production system capacity, it does signify the upper most level achievable through the augmentation of input-factor volume. Opting for growth achieved through productivity improvement proves more effective for augmenting production output [4], as demonstrated in fig 1. When this enhancement is driven by improvements in productivity, the resultant expansion in production is achieved while using the same input-factors and increasing the volume from P1 to P2, results in T2 (fig.1).

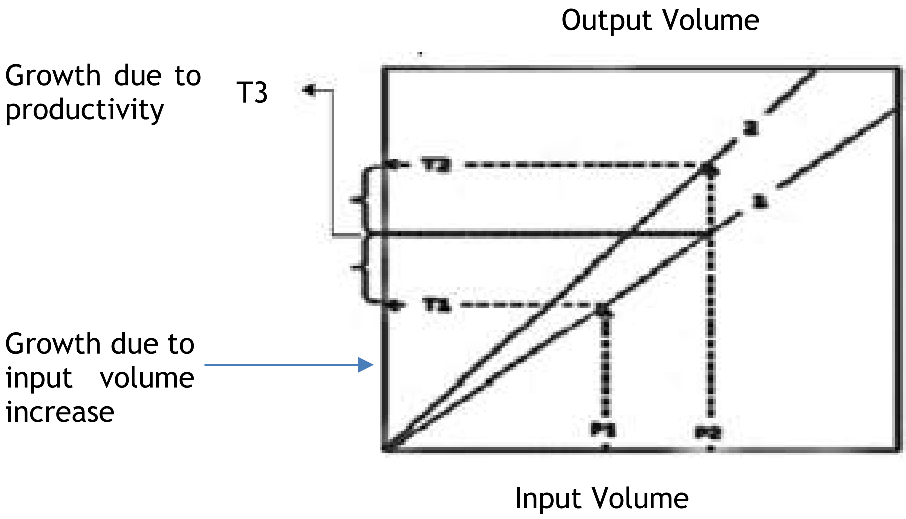

Figure 1: Components of Production Growth (Adapted from Saari, 2006)

The underlying cause for the absence of output growth stems from the discrepancy between time saved in production and the time required to facilitate an increase in output (e.g., Servicing an additional locomotive). Consequently, even though there is an enhancement in cycle time, the overall production output remains unaltered, leading to an absence of measurable productivity advancement [5]. The challenge in achieving productivity improvement lies in the fact that productivity typically signifies the quantity of tasks completed within a specific time-frame, utilizing the same quantity of input-factors. This holds true without an expansion of input-factors within the production process. It also worth noting that productivity enhancement can materialize when the volume of work completed within a set time-frame remains unchanged, despite a reduction in input-factors [6]. The productivity dilemma is apparent when cycle time improvement (i.e., reduction in process cycle time) is attained but there is no output increase. Since the reduction in cycle time means an increase in output per process cycle.

2 LITERATURE REVIEW

The examination of existing literature underscores the widespread recognition of inherent constraints within the productivity theory [2]. Additionally, it substantiates the proposition that the delay in the progression of productivity enhancing technological solutions is a direct result of the productivity gap [7]. Furthermore, this review reaffirms the presence of the productivity measurement and enhancement quandary. While the theory pertaining to productivity improvement in product development is primarily centred around design productivity, its applications reverberate through the measurement and enhancement of the production process productivity.

Furthermore, the discourse extends to emphasize that prospects for productivity enhancement are consistently available. Consequently, strategies and avenues remain pivotal in the realm of production engineering research. This is the reason why the design and fabrication of attachments or jigs and fixtures, are constantly explored by engineers, to enable the manifestation of productivity improvement [8]. Therefore, Kahng's theory is plausible and material, that it takes longer to transfer leading edge publications into production flows and therefore, the lag experienced forces industry to battle today's problems with yesterday's technology solutions [7]. Thus, proclamations of [8], that to further improve productivity, a constant exploration of ways and means is critical.

Applying productivity enhancement methods solely to the internal soft components of productivity has been explored [2]. However, achieving maximum productivity necessitates a comprehensive approach that integrates both the internal hard and soft components of productivity across various industrial contexts [2]. One such comprehensive approach is the utilization of design engineering methods for enhancing productivity. This approach leads to the refinement of work methods, optimisation of process output, and overall productivity improvement. Successful implementation of this productivity enhancement approach has the potential to bridge the gaps and overcome the limitations inherent in productivity improvement theory, thereby effectively addressing the productivity enhancement challenge.

3 RESEARCH METHOD

This study employs a qualitative research methodology, which offers the advantage of comprehending the phenomenon from viewpoint of individuals directly engaged in it ([9];[10]). The congruence in the objectives of qualitative research, as outlined by [9], strengthens the rationale for opting for this method. Therefore, this research is orientated towards embracing a qualitative research approach, specifically employing the action research methodology (AR) in conjunction with a case study methodology.

The distinctive feature of the case study approach involves leveraging diverse data origins ([11]; [12]), which contributes to bolstering the reliability of data gathered and employed ([12]; [11]). In this case study, a multi-pronged approach to data collection will be implemented, especially encompassing the following: i) Scrutiny of documents and archived records; ii) analysis of journal publications and field notes; iii) observation and evaluation of the production process through a work method technique known as SREDIM (Select, Record, Examine, Develop, Install and Mauntaun). This comprehensive integration of data sources and collection methods within the framework of examining a single phenomenon empowers researchers to harness a multitude of evidence origins. As a result, this approach facilitates the pursuit of convergence and validation, exploiting the distinct credibility of different data sources ([12]; [11]. The culmination of this triangulated data acquisition strategy is in a panoramic comprehension of the subject of the study.

In this case study research, data gathering involves a triangulation of distinct qualitative research data collection methods. The methods utilised encompass the following data collection tools and techniques: i) examination of archived records and documents related to design engineering and DFMA (Design for Manufacturing and Assembly); ii) analysis of field notes authored by other researchers, in tandem with an exhaustive review of journal publications. Thus, the research approach adopts qualitative action research techniques, academic and applied mechanics literature iii) and the application of design thinking paradigm to uncover research data pertinent to developing an appropriate and suitable solution.

The rail locomotive industry is one of the oldest engineering enterprises. The technology employed has been evolving over the years, although not as fast as other industries. A thinking paradigm that was deemed suitable for the task of productivity improvement, is that which is executed through an application of technology, as established and embedded in the complex sphere of engineering design ([13]; [14]). Therefore, for the development of a method that can leverage efforts to increase production output, the eponymous applied mechanics practice has been selected as a method for design thinking in productivity improvement.

4 DISCUSSION

Various productivity improvement methods were applied to improve productivity and as can be seen in table.1 the results are below the required target for all interventions.

Table 1: Comparison of Productivity Improvement Techniques (Adapted from Nave, 2002)

Improvement Programme	Six Sigma	Lean	Theory of Constraints [TOC]	Time and Method Improvement
Theory	Reduce variation	Eliminate waste	Manage constraint	Reduce cycle time
Application Guidelines	1. Define 2. Measure 3. Analyse 4. Improve 5. Control	1. Identify value 2. Identify value stream 3. Improve flow 4. Pull 5. Perfection	1. Identify 2. Exploit 3. Subordinate process 4. Elevate 5. Repeat cycle	1. Select 2. Record 3. Examine 4. Develop 5. Install 6. Maintain
Focus	Problem	Flow	Constraint	Process
Assumptions	Process output increase when variation is reduced	Waste elimination improves process performance	Any systems have constraints that prevent it from producing target results	Process improvement yield improved process performance
Primary effect	Uniform process output	Reduced flow time	Improved throughput	Shorter cycle time
Secondary Effect	Reduced fluctuation and fast throughput	Improved flow and less variation	Improved throughput and less waste	Reduced cycle time and improved throughput
General Criticism	System interaction not considered	Statistical analysis not valued	Data analysis not valued and minimal worker input	Process productivity dilemma apparent
Ease of Application	Require specialist knowledge of statistics	Appreciated by workers in operations	Developed into a system methodology	Applicable at all levels of the organisation
Results	Fast throughput and output	Flow time reduction	Improved throughput and a 20% increase in output	Reduced cycle time and a 20% increase in output

The outcomes depicted in Table 1 showcase the resemblances across various productivity enhancement techniques, indicating a shared objective among all the initiatives. However, instances where these programs yield unsatisfactory outcomes may emerge, particularly in environments characterized by pronounced rigidity and complexity. In such scenarios, identifying constraints can prove challenging, and devising a definitive solution to address the issue might not be straightforward [15]. To address this, the thinking process grounded in

Theory of Constraints (TOC) is employed, aiming to facilitate the identification of a viable solution. TOC based BPR (Business Process Re-engineering) thinking is applied to remedy the dilemma of productivity improvement as follows:

i) The identified necessity for change: Disappointing productivity improvement results lead to the need to re-engineer the production process; results of the TOC thinking process led to the identification of 'what to change' and 'what to change it to'.

ii) Ensure leadership commitment and support: Management is behind the request to increase output and therefore productivity. Process and organisation leaders agree with the vision process.

iii) Communicate the necessity for change with employees: The human side of BPR is thoroughly engaged using principles of [16], [17], [18]. Assertions of Oreg [19] and Wanous [20], that change disturbs employees until the new process is fully normalised [21], are given special attention and a change management programme is instituted.

iv) Develop process objective: The goal and objective of the new process is derived from the need to improve productivity to meet the production target, and more so, to circumvent the limitation of the productivity improvement tools and techniques applied in the rail industry.

v) Form a reengineering team: The team consists of knowledgeable employees who are directly involved in the bogie production process and the line managers.

vi) Develop the scope and scale of the project and develop a project plan: The application of BPR is limited to the bogie production process, in particular the components replacement process. A project plan is developed for the new production process implementation.

vii) vii) Designate the process to be reengineered: This step has been covered in the TOC thinking process through the application of the CRT and EC.

viii) Analysis and understanding of current processes: The TOC thinking process enables this process.

ix) Design the new process: Cooper's stage-gates facilitate the process of redesign and the TOC thinking process completed it.

x) Take advantage of IT: The use of IT is limited to simulation and interpretation of data during the TOC thinking process.

xi) Include collaborators such as suppliers and freight forwarders in the reengineering initiative: The bogie replacement process is reliant on the demand and supply of stock; thus, inventory management plays a crucial role. Suppliers and customers of the bogie production process were involved.

xii) Pilot the new process: The CRT stage of the TOC thinking process is used to pilot and test the new process.

xiii) Train employees who are affected by the redesigned process: The new process requires new skill sets and a new safety process. Therefore, training is organised accordingly.

xiv) Implement and monitor the new process and implement Kaizen: This stage is executed in the TOC thinking process, first by the application of FRTs and then the PRT and last with TTs.

The TOC based BPR technique applied converts and transform the current production process from a locomotive lifting process to a component removal process without lifting a locomotive see fig.2 to fig.3.

Figure 2: Locomotive Lifting process

Figure 3: Component removal process

The new component replacement process removes components from a locomotive from underneath the bogie frame as seen in fig.3 (without lifting the locomotive, as in fig.2). The novel procedure involves the utilization of a lever to incline the component, such as a Traction Motor (TM), at an angle, facilitating the removal of the TM nose bracket assembly. The precise angle of inclination is necessary for detaching the bracket depends on the locomotive engine's model series, hence, this angle calculation is imperative for each individual series. Subsequent to the extraction of the nose assembly, the mechanism capitalises on the force of gravity, causing the TM to descend into the bracket holder (as illustrated in fig. 4), which is affixed to a pneumatic jack 9depicted in fig. 4). Utilizing the pneumatic jack, the TM is gradually lowered from within the bogie frame. Thereafter, it is moved out from beneath the locomotive via wheeling. Upon its successful clearance from the locomotive, the motor is conveyed to a storage location for components through the utilization of an overhead crane. The process of component replacement is then carried out.

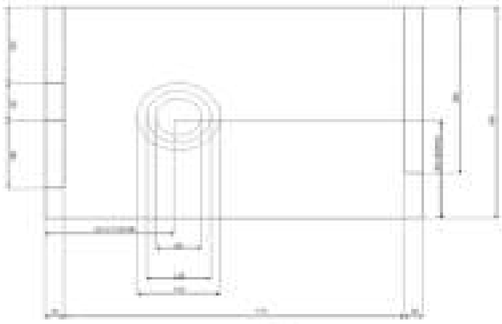

Figure 4: Bracket holder drawing

Figure 5: pneumatic Jack in the pit

A comparison of the production statistics for current production operations and the statistics when productivity improvement is applied are viewed in Table.2. As can be depicted from Table.2, for the variable 'overtime' there is no significant growth in output, even though there is a 20% overall production improvement in this case. Therefore, in this case process improvement does not yield the process capacity required to increase productivity. Applying the 'horizontal' logic in case study analyses, it is evident that, for the variable over time, not all instances of productivity enhancement will yield an increase in production output, particularly when the time saved is not adequate to cause an increase in production output.

Table.2: Production statistics for 'As Is' and Improved operations

Analysis Theme	'As Is' production process			Productivity Improvement		
	HRS	Output		HRS	Output	
Normal shift	9	4		9	5	
Overtime	3	1		3	1	
Night shift	12	5		12	6	
Total	24	10		24	12	
Increase in productivity	%	0		%	20	

Since a 20% increase in production output is very insignificant and as depicted in Table.2 it is not cost effective. Design thinking is applied to establish a productivity improvement approach that will assist in eliminating the productivity dilemma experienced. The component replacement process is established by applying Mechanics of machines theory to design, develop and use production support tool and equipment in production execution. The tools and equipment improves productivity and increase production output when applied in the production process.

4.1 Applications of mechanics of machines theory to develop Production support tools

The application of mechanics of machines theory in the design and development of production auxiliary tools is paramount to achieving efficient and precise manufacturing processes. Understanding of principles of dynamics and mechanical behaviour, enabled the creation of specialized tools that seamlessly integrate into the production workflow. Tools and equipment designed and developed to be used with production process equipment available in the inventory is the bracket holder and a lever. These tools are meticulously designed to optimize tasks such as components assembly and quality control. Leveraging mechanics of machines theory ensures that these auxiliary tools are not only capable of performing their designated functions reliably, but also operate safely within the maintenance production environment.

Through a comprehension of mechanical forces, motion patterns, and structural integrity, these tools are created to contribute to the overall efficiency and productivity. Existing equipment in the production process equipment inventory is used to manufacture the production support equipment required. The equipment available consists of a removable track in the maintenance pit, a four wheeled trolley jack, placed on a rail track that runs transversally to the locomotive track. As a result, the TM when removed will fall into the bracket holder and hauled out into the components store. Calculation for the design of the bracket holder is computed to establish the centre of balance for the bracket holder mounting on the lever. Moments of a force concepts are applied to complete the calculation of the bracket and the lever design. The weight of the TM is used to establish force and distance to position the mounting plug of bracket holder (annexure 1). The results of the computation are used to develop a mechanical drawing of a bracket holder (fig 4) and then a bracket holder is produced.

5 RESULTS

When the bracket holder and the lifting rod have been designed and manufactured, they are then used in the production operations. The lifting rod is used to tilt a traction motor to an angle that will enable it to drop into the bracket using the force of gravity. The results achieved are presented in table.3.

Table 3: Productivity Improvement Statistics

Analysis Theme	**'As Is' production process**		**Productivity Improvement**		**Application of Production Support equipment**	
	HRS	**Output**	**HRS**	**Output**	**HRS**	**Output**
Normal shift	9	4	9	5	9	8
Overtime	3	1	3	1	3	3
Night shift	12	5	12	6	12	11
Total	24	10	24	12	24	22
Increase in productivit y						
	%	0	%	20	%	120

It is thus apparent in Table.3 that the productivity dilemma is solved, since the cycle time improvement results in an increased output.

6 CONCLUSION AND RECOMMENDATIONS

A comparison of the results in Table.3 is proof that the application of production support equipment, designed using mechanics of machines techniques, has resulted in an improvement in production yield. Production output increases because of the improvement in production cycle time is significant enough to impact production operations positively. The "As Is" production output is 10 in 24hrs (double shift), when productivity improvement techniques are applied 12 outputs are achieved. This is an insignificant increase in production out because the production cycle time is not significant enough to impact production maximally. Application of production support tools (a bracket holder and a tilting rod), designed and produced using mechanics of machines techniques, results in a maximum productivity improvement.

Production statistics presented clearly indicates that when engineering design methods are applied to calculate dimension of production support equipment required in productivity improvement, maximum productivity enhancement is achieved. The dilemma of productivity improvement, in which attained cycle time optimization is insignificant to enhance production yield, is solved with the use of auxiliary production support equipment. The tools and equipment is designed and produced with the application of engineering design techniques and mechanics of machines in production operations. This approach to solving the productivity improvement dilemma proves to be a working engineering innovation method for applying mechanics of machines theory and practice in the production process for productivity improvement.

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PRODUCTIVITY IMPROVEMENT DILEMMA IN A HEAVY INDUSTRIAL SETTING
[A case for the debate about what constitutes productivity improvement]

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ABSTRACT

The The dilemma of productivity improvement in a heavy industry setting, such as in the rail locomotive maintenance, is that it manifests when productivity improvement techniques are applied in production and the resultant is an improvement in production activity cycle time that is less than that of a production activity cycle-time. In this case the cycle time improvement will not result in an increase in production output. Therefore, this improvement in production activity cycle time cannot be regarded as productivity improvement because production output is not increased. This paper adopts a qualitative case study method and contributes to the debate on what constitutes productivity improvement. The research applies the concept of production cycle time to reinforce the fact that productivity improvement manifests with the increase in production output. Thus, the research exemplifies the dilemma driven debate that not all production cycle-time increase will result in productivity improvement.

Keywords: Productivity; Production; Dilemma

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1 INTRODUCTION

Productivity improvement is a critical aspect of enhancing economic growth, organisational efficiency, and individual performance across various sectors. It is an ongoing pursuit for businesses and policymakers alike, as they strive to optimize resources, reduce costs, and maximize output. However, the definition and understanding of productivity improvement can vary depending on the context and industry, leading to a need for comprehensive research and analysis. The aim of this research paper is to provide an in-depth exploration of what constitutes a productivity improvement and to identify key factors and strategies that contribute to its achievement. By examining the existing literature, empirical studies, and real-world case examples, we seek to shed light on the multifaceted nature of productivity improvement and its implications for different stakeholders.

Defining productivity improvement requires a comprehensive understanding of the term "productivity" itself. Productivity is commonly defined as the ratio of outputs to inputs, reflecting the efficiency with which resources are utilized to generate desired outcomes. To anchor our research, we refer to the work of notable economists and management scholars who have extensively contributed to the field of productivity improvement. One influential framework in this domain is the Total Factor Productivity (TFP) approach, which measures the efficiency of production inputs and technological advancements. Notably, Mankiw et al. [1], provided a foundational framework by incorporating technological progress as a crucial determinant of productivity growth. Their research highlighted the importance of innovation, research and development, and knowledge accumulation in driving productivity improvements across economies.

In addition, this paper draws upon the research of scholars like Brynjolfsson & McAfee [2], who emphasize the role of digital technologies in productivity enhancement. Their work highlights the impact of automation, big data analytics, and artificial intelligence in transforming industries and driving efficiency gains. Such advancements have reshaped the traditional understanding of productivity improvement, necessitating a contemporary analysis of the subject. By conducting this research, we seek to contribute to the existing body of knowledge on productivity improvement and provide actionable insights for businesses, policymakers, and researchers. Understanding the factors and strategies that drive productivity improvements can enable organisations to make informed decisions, allocate resources efficiently, and remain competitive in a rapidly evolving global landscape.

Production cycle time reduction plays a vital role in driving productivity improvement by streamlining the manufacturing process and eliminating bottlenecks. Shortening the cycle time allows organisations to produce more within a given time frame, leading to an increase in production output. When organisations can deliver products faster without compromising quality, they can fulfil customer orders promptly and gain a competitive advantage in the market. One key benefit of reducing production cycle time is the improved efficiency of resource utilization. By minimizing idle time and eliminating unnecessary steps in the production process, organisations can optimize the use of their labor, equipment, and raw materials. This optimisation leads to higher throughput and a more efficient allocation of resources, ultimately resulting in increased production output. Furthermore, a shorter production cycle time enables organisations to respond more effectively to changes in customer demands and market dynamics.

By emphasizing the significance of production cycle time reduction and its correlation with increased production output, this analysis aims to provide organisations with valuable guidance and insights for implementing strategies and initiatives to enhance their productivity levels. Productivity improvement is a key objective for organisations seeking to optimize their operations and achieve higher output levels. One critical factor that significantly influences productivity is the reduction of production cycle time. Production cycle time refers to the total duration required to transform inputs into finished products or services. As organisations strive to meet customer demands in a timely manner, reducing cycle time becomes imperative for enhancing productivity. This in-depth analysis aims to explore the relationship between production cycle time improvement and the resultant increase in production output, reinforcing the notion that productivity improvement manifests through efficient time management in production processes.

1.1 Understanding Production Cycle Time Improvement

Production cycle time improvement involves streamlining and optimizing the various stages involved in the production process, including manufacturing, assembly, testing, and delivery. By identifying and eliminating bottlenecks, minimizing non-value-added activities, and enhancing workflow efficiency, organisations can significantly reduce cycle time, resulting in increased productivity. The Impact of reduced cycle time on productivity improvement and the concomitant increase in production output is characterised by the manifestation of the following scenarios in the production process.

- Accelerated Throughput: Reducing production cycle time allows organisations to complete more production cycles within a given time frame. This increased throughput enables organisations to produce a higher volume of goods or services, thereby driving productivity improvement. Research by Black et al. [3] found that organisations that achieved notable reductions in cycle time experienced substantial increases in production output.
- Improved Responsiveness to Market Demands: Shorter production cycle times enable organisations to respond swiftly to market demands and customer requirements. By delivering products or services faster, organisations can capitalize on emerging opportunities and gain a competitive edge. This responsiveness not only boosts customer satisfaction but also contributes to increased production output, as highlighted by the study conducted by Kim et al. [4].
- Enhanced Resource Utilization: By reducing cycle time, organisations can optimize the utilization of resources such as labour, machinery, and raw materials. With faster production cycles, these resources can be reallocated efficiently, allowing organisations to produce more output within the same resource constraints. As a result, productivity levels increase due to the improved utilization of available resources [5].
- Cost Savings: Shorter cycle times often lead to cost savings, which can be reinvested to further enhance production capabilities. Reduced cycle time minimizes holding costs, inventory obsolescence, and other associated expenses, enabling organisations to allocate resources more effectively. Consequently, the cost savings derived from cycle time improvement contribute to increased production output, reinforcing the notion of productivity improvement [6].

This in-depth analysis has underscored the significance of production cycle time improvement to enhance productivity.

2 LITERATURE REVIEW

Productivity improvement is a central concern for organisations across various sectors, as it directly impacts operational efficiency, profitability, and competitiveness. In order to comprehend the key factors that contribute to productivity improvement, it is essential to review and synthesize relevant literature from multiple disciplines. Research by Becker [7] emphasizes the significance of education, training, and continuous learning in enhancing productivity. Investments in employee development programs, performance management systems, and knowledge-sharing platforms have been found to positively impact productivity levels ([8]; [9]). Moreover, studies highlight the importance of employee motivation, engagement, and job satisfaction as influential factors in productivity improvement ([10]; 11).

The adoption and integration of innovative technologies are recognized as catalysts for productivity improvement. Automation, digitalization, artificial intelligence, and data analytics contribute to process optimization, increased accuracy, and reduced cycle times ([2]; [12]). Research indicates that organisations that effectively leverage technology achieve higher productivity gains compared to their counterparts ([13]; [14]). However, the successful implementation of technology requires careful consideration of factors such as compatibility, employee skills, and organisational change management ([2]; [15]).

Efficient and streamlined processes are vital for productivity improvement. Lean management principles, Six Sigma methodologies, and other process improvement techniques aim to eliminate waste, enhance flow, and optimize resource utilization ([16]; [17]). Studies emphasize the benefits of process redesign, workflow analysis, and continuous improvement initiatives in achieving significant productivity gains ([18]; [19]). Additionally, effective supply chain management practices and collaboration with suppliers and partners contribute to productivity improvement by minimizing disruptions and improving overall process efficiency ([20]; [21]).

The Just-In-Time (JIT) philosophy, developed by Ohno [22], emphasizes the importance of reducing cycle time as a means to eliminate waste and enhance efficiency. JIT principles advocate for synchronized production processes, where each activity is performed at the right time, in the right quantity, and without delays or interruptions. This approach not only minimizes inventory levels but also streamlines production flows, leading to improved productivity ([23]; [24]). Research studies have provided empirical evidence supporting the link between production cycle time improvement and increased production output. For instance, a study by Kumar and Chandrasekharan (2006) conducted in a manufacturing setting found that reducing cycle time led to a significant increase in daily production output. Similarly, research by Basso et al. [25] in the semiconductor industry demonstrated that shorter cycle times resulted in higher production volume and improved productivity.

Shorter production cycle times enable organisations to achieve accelerated throughput, which directly influences production output. Research by Roy & Cherrett [26] in the automotive manufacturing industry revealed that reducing cycle time led to increased production capacity, allowing organisations to produce more within the same time frame. This increased throughput positively impacts productivity by meeting customer demands, reducing backlogs, and optimizing resource utilization ([27]; [26]). Reducing production cycle time enhances an organisation's ability to respond quickly to market demands and changing customer requirements. By shortening lead times, organisations can adapt to dynamic market conditions, seize opportunities, and maintain a competitive edge. Research by Swafford et al. [28] in the context of supply chain management highlighted the positive relationship between cycle time reduction and customer responsiveness, which ultimately contributes to improved productivity.

While the existing literature provides valuable insights into the relationship between production cycle time improvement and productivity, there is a notable gap in terms of the comprehensive examination of the contextual factors that influence this relationship. Specifically, there is a need to explore the moderating effects of industry-specific characteristics on the impact of production cycle time improvement on productivity outcomes. Different industries have unique characteristics, production processes, and supply chain dynamics that may influence the impact of production cycle time improvement and productivity. However, there is a lack of research that systematically examines how industry-specific factors shape this relationship.

Thus, complex product configurations, or stringent regulatory requirements face distinct challenges and opportunities in achieving productivity gains through cycle time reduction ([29]; [22]). Understanding the interplay between industry-specific factors and cycle time improvement efforts can provide valuable insights for practitioners seeking to optimize productivity in diverse sectors. Another significant gap in the literature is the limited exploration of the long-term effects of production cycle time improvement on productivity. While many studies focus on immediate productivity gains resulting from cycle time reduction, there is a need to investigate the sustainability and durability of these improvements over time. Longitudinal studies that track productivity outcomes beyond the initial implementation phase can provide insights into the long-term impact of cycle time improvement initiatives and identify any potential decay or diminishing returns over time ([30]; [31]).

Analysis of the gap in the literature, gives a more comprehensive understanding of the complex dynamics between production cycle time improvement, organisational contexts, and productivity outcomes. This knowledge can inform the development of more effective strategies and interventions tailored to specific organisational and industry contexts, ultimately leading to enhanced productivity and competitive advantage. It is, therefore, the aim of this research to contribute to the productivity improvement body of knowledge and specifically to contributes to the debate on what constitutes productivity improvement by increasing comprehension of the complex dynamics between production cycle time improvement, organisational contexts, and productivity outcomes, in a rail industry setting.

3 RESEARCH METHOD

To achieve the aim and objectives of the research and satisfy the requirements of the primary research question and the hypothesis, a research paradigm is developed. This paradigm is used to explain the nature of the scientific truth, the theoretical framework, methodology and the data collection tools applied in the research. This will enable the researcher to explore the definition of reality of the research and deliberate on the following questions: what and how is the knowledge acquired. The procedure, tools and techniques used to acquire this knowledge, and the data collection process used is explained. Thus, this research requires a methodology that takes a broader perspective than a single primary research study focused on a particular direction.

The goal of the research is to explore and explain how digital competencies can enable students and instructors to navigate the technology in the T&L environment? and how they support the new normal? The outcome of the research and analysis is the data collected through the application of a qualitative research method, tools, and data collection techniques. The data will serve as a validation of the propositions that led to the development of a conceptual framework of the study and therefore, rival and/or contesting hypothesis will be accepted or rejected. This research adopts a qualitative case study research approach because it enables researchers to establish an understanding of the phenomenon from the perspective of those experiencing it [32].

In this AR intervention, a case study method is applied. Case study method applies the science of singular, which aims to understand what is distinctive of a particular case, defined as a complex functioning system [33]. Qualitative case study method enables researchers an opportunity to explore and explain a case within its context using a variety of data sources [33]. The hallmark of this case study is the use of multiple data sources [34], which is a strategy that enhances data credibility [35]. This case study will employ the following triangulation of data sources: i) document analysis and archival records analysis; ii) Journal publications and field notes analyses; iii) production process SREDIMM.

A combination of data sources and data collection methods in a study of a single phenomenon enables researchers to draw upon multiple sources of evidence [36] and therefore, enables them to seek convergence and corroboration. Using different data sources data credibility is achieved [35] and the culmination of a triangulated data capturing method is a holistic picture of the case under study. A qualitative case study is argumentative by nature and therefore, there is a fair amount of competing hypothesis and evidence that is to be disconfirmed. Thus, the research follows the theoretical propositions leading to the original objectives, the design of the case, the research question, and the literature reviews, to define and assess rival explanations and theories.

The proposition that productivity improvement only manifests when there is an output increase, is assessed and rival and contesting hypothesis are analysed. Validation of the propositions that lead to the development of the conceptual framework of the study is engaged and then, the rival and contesting hypothesis is nullified or accepted. In this qualitative action research case study, data is collected through a triangulation of qualitative research data collection tools. The tools employed begin with the analysis of archival records and document. The aim of this data collection techniques is to uncover various perspectives of role players in this research niche and incorporate these ideas in the solution proposal. The second techniques applied is an analysis of field notes of other researchers and an extensive review of journal publications, data collected with this second techniques clarify the progress of work done in this area of research and provides the latest information that forms the body of knowledge. The last technique applied is the observation and analysis of the production process using the SREDIMM method.

3.1 Experiment

Various productivity improvement philosophies, tools and techniques are applied to the current production process in an endeavour to improve the productivity of the current production process and therefore increase output. Currently, the output of the production process per shift is four (4) locomotive liftings and the current demand for locomotive liftings is eight (8) per shift. Numerous conventional productivity improvement techniques are applied to increase production output and meet the current demand as stipulated in the maintenance plan. Output is increased when production cycle time is reduced, meaning more liftings occur in the same production shift. Thus, the production method is studied, production process analysis is engaged, method analysis is initiated, and the result is method improvement.

Method improvement leads to shorter cycle time that leads to an increase in output and ultimately, productivity improvement. Method analysis is a critical and technical investigation of all factors involved in an existing production process. These are factors that characterize the current working methods in the production operations. The objective of a method analysis is to develop an easier, simpler, more efficient, and cost-effective working method. Successful method analysis in the industry involves investigative thinking, analytic thinking and creative thinking processes combined. These three critical actions form the basis of the method study process technique, known by the acronym SREDIM.

A method improvement is employed to improve the production operations process by reducing non-value adding activities and removing waste. The improved process will operate with a shorter production cycle time. Application of a method improvement technique on the current production process resulted in a 10% reduction of wasteful operations activities, a 4% reduction in non-value adding movement, and an elimination of storage within the production process. These results were achieved through the improvement of the production setup and by performing some operations concurrently. Production setup is a set of activities performed in preparation for the value-adding production activity in the production process. Setup time reduction is the efficient reduction of time taken in preparing for the start of the value adding production process.

As can be depicted from Table.2, for a variable ‘overtime’ there is no significant growth in output, even though there is a 20% overall productivity improvement in this case (i.e., Lesser cycle time same output). The cycle time required for a production of one (1) locomotive maintenance production output is 2hrs, thus in a production shift of eight (8) hour 4 locomotives output is achieved. Therefore, in this case process improvement does not yield the process capacity required to increase productivity, since 20% of 8 HRS is 1.6 HRS. Applying the ‘horizontal’ logic in case study analyses, it is apparent that for the variable ‘overtime’, not all productivity improvement cases will result in an output increase. Since a 20% increase in productivity improvement is very insignificant and as depicted in Table.2 it is not cost effective and cannot increase output by at least one (1) locomotive maintenance. A 20% production process improvement result does not yield a production output increase and thus, the productivity improvement event does not result in production output increase. The dilemma manifests because the production cycle time improvement (reduction) does not yield a capacity improvement required to increase production output.

Table 1: Productivity Improvement Statistics

Analysis Theme	'As Is' production process		Productivity Improvement	
	HRS	Output	HRS	Output
Normal shift	9	4	9	5
Overtime	3	1	3	1
Night shift	12	5	12	6
Total	24	10	24	12
Increase in productivity	%	0	%	20

4 DISCUSSION

In addressing the gap in literature, this research focused on examining the moderating effects of organisational characteristics and industry-specific factors on the relationship between production cycle time improvement and productivity outcomes. The research has made it apparent that production cycle time, defined as the time it takes to complete a process or product cycle, is a vital determinant of operational efficiency and overall productivity. Organisations constantly seek to improve cycle time as a means to enhance productivity.

However, the effectiveness of such improvements is contingent upon the interplay of various contextual factors, including organisational characteristics and industry-specific dynamics. The structure and complexity of a production process setup can significantly influence the relationship between production cycle time improvement and productivity outcomes, as seen in this case. Factors such as engineering complexity hierarchical layers, infrastructure complexity, technology application dynamics, decision-making processes, and interdepartmental coordination mechanisms impact the speed and effectiveness of cycle time improvements and subsequent productivity gains.

The research has proved that the relationship between productivity improvement, production output increase and production cycle reduction and their impact on productivity outcomes is complex and can be influenced by various contextual factors. Therefore, the relationship between productivity increase, production output increase, and the impact of production cycle time improvement on productivity outcomes is generally expected to be positive, with higher productivity leading to increased production output. However, in certain scenarios, organisations may face a productivity improvement dilemma, where productivity improvements do not translate into a corresponding increase in production output. This dilemma manifests when, despite productivity gains, the expected increase in production output is not realized.

5 RESULTS

The relationship between productivity increase, production output increase, and the impact of production cycle time improvement on productivity outcomes is generally expected to be positive, with higher productivity leading to increased production output. However, in certain scenarios, organisations may face a productivity improvement dilemma, where productivity improvements do not translate into a corresponding increase in production output. This research discussion explores the factors contributing to this dilemma and examines the complex dynamics that can hinder the alignment between productivity gains and production output, highlighting the need for a nuanced understanding of these relationships.

Factors Contributing to the Productivity Improvement Dilemma:

- Bottlenecks and Constraints in the Production Process: The presence of bottlenecks, capacity constraints, or limitations in the production process can impede the translation of productivity gains into increased production output. Even if certain steps in the process become more efficient, other stages may be unable to keep pace, creating a misalignment between productivity improvement and overall output.
- Inadequate Resource Allocation: Insufficient allocation of resources, including raw materials, equipment, and labour, can limit the ability to scale up production despite productivity improvements. If the necessary resources are not available in sufficient quantities, productivity gains may not translate into a proportional increase in production output.
- Technological Limitations: Technological limitations or outdated infrastructure may hinder the full realization of productivity gains in terms of production output. If the existing technology or machinery is unable to handle higher productivity levels or process improvements, the expected increase in production output may not be achieved.

Mitigating the Productivity Improvement Dilemma:

- Process Redesign and Optimization: To address the productivity-production dilemma, organisations can conduct a thorough review and redesign of their processes to identify and alleviate bottlenecks or constraints. Optimization efforts should focus on streamlining the entire production cycle to ensure that productivity improvements are synchronized and effectively translate into increased production output.
- Capacity Planning and Resource Management: Proper capacity planning, including forecasting demand and aligning resources accordingly, is crucial to overcome the productivity-production dilemma. Organisations must ensure that resource allocation is sufficient to support increased productivity levels and meet the corresponding increase in production output.
- Technological Upgrades and Innovation: Investing in updated technologies, automation, and advanced equipment can help overcome technological limitations that hinder production output.

These findings highlight the importance of understanding the relationship between production cycle time improvement and productivity enhancement.

6 CONCLUSION

While productivity improvement is often expected to result in increased production output, organisations may face a productivity-production dilemma, where productivity gains do not translate into the anticipated increase in output. Understanding the factors contributing to this dilemma is essential for organisations to address the misalignment between productivity improvements and production output. By implementing process redesign, optimizing resource allocation, embracing technological upgrades, and establishing effective performance measurement systems, organisations can mitigate the productivity improvement dilemma and achieve optimal outcomes in terms of both productivity improvement and increased production output.

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TECHNOLOGY ENHANCED PRODUCTIVITY IMPROVEMENT
[a case of technical change in productivity improvement]

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ABSTRACT

Enhancing productivity is a concept examined from two primary perspectives: the industrial scale and the corporate level. On the corporate front, the drive to bolster productivity involves enhancing the effectiveness and efficiency of deploying limited resources within a production process, a phenomenon referred to as technical advancement. In this pursuit, the analysis relies on the utilisation of production frontier curves to assess and quantify productivity enhancements. A crucial point, in this theory, is that productivity experiences a decline (or a dip) whenever production occurs below the optimal technical scale mark of the production frontier. Consequently, the path to heighten hinges upon executing an efficient technical progression, which can be exclusively attained by capitalising on the benefits of economies of scale. Within this manuscript, a qualitative research method is embraced to delve into the influence of technology on the enhancement of productivity. This investigation aims to substantiate the viability of technical advancement through the evolution of production technology.

Keywords: Technology; Productivity; Profitability; Economy; Technical

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1 INTRODUCTION

Productivity is calculated as the ratio of output to the unit of all inputs used to produce this yield [1]. Productivity differs from production, for production is concerned with the increase of the yield over a period of time. Whereas productivity is concerned with the ratio of the yield over the input-effort [1]. In essence, productivity improvement has to do with an effective and efficient combination of resources in a manufacturing process to attain higher levels of output, while expending the same or less input resources [2]. The improvement in productivity manifest through the reduction in cycle time, setup reduction, standardised work, and waste elimination [3].

According to Hoffman& Mehra [2], analysing productivity improvement problems reveals factors that are potentially fatal to productivity improvement programmes. These include the following: a) inadequate awareness by engineering about the implications of product and process design and b) competency weakness in industrial and manufacturing engineering [2]. Considering a vast background of scholarly research output about productivity and a wide array of literature from numerous disciplines, it is easy to hypothesize about the severity of the productivity dilemma. Hoffman & Mehra [2] postulate that conventional productivity improvement programmes are susceptible to producing disappointing results.

The foundation for this hypothesis is the fact that each of the productivity improvement tools and techniques have a minimal or insignificant impact on productivity improvement, when singularly applied. Technically, this means when these tools and techniques are applied to the internal hard components of productivity alone, the resultant improvement is minimal, and the same manifestation is experienced when applied to the internal soft components of productivity exclusively. Maximisation of productivity requires an inclusive application approach that when applied (in any industrial setting), engages both the internal hard and soft components of productivity [4], [5]. Thus, to comprehend the possibilities available in productivity improvement, there must be a good understanding of attainable levels of efficiency and productivity improvement. This desire to understand the total possible picture speaks to the concept of productivity improvement through technical change.

2 LITERATURE REVIEW

Manufacturing methods became obsolete with the emergence of programmable machines; production operations have to adopt a more economical approach to operations in manufacturing. These new economical methods are developed and implemented through better designs of auxiliary production systems such as the fixturing systems that employ jigs, fixtures, and other auxiliary production tools [6]. Auxiliary production support equipment (APSE) such as jigs and fixtures are tools and devices used both in traditional manufacturing and in modern flexible manufacturing systems to improve machining quality, increase productivity and reduce cost of products. Auxiliary production equipment forms a system in which production improvement tools enable a faster and more profitable production process through a quick clamp or positioning of fixtures into a correct relationship with production process tools or machines [6].

Narasimha et al. [7] asserts that the pursuit to increase productivity is an ever-challenging mission and the capacity for further improvement of productivity always exists; hence engineers are constantly exploring ways and means for design and fabrication of attachments or jigs and fixtures (production support auxiliary equipment) [7]. Redesign suggestions which can increase the maximum possible output can be made in the design for production (DFP) [8]. This is a method used to evaluate product design by comparing its manufacturing requirements to available capacity [8].

A preliminary review of literature highlights the prevalence of the limitations inherent in the productivity measurement theory as well as the materialisation of the theory that the lag in productivity technology solutions is consequential of the productivity gap as stipulated by Khang [9]. Although the productivity gap theory is confined to design productivity, it has implications on the production process productivity measurement. Thus, the purpose of designing APSE such as attachments, spindles and jigs, and the application of APSE in productivity improvement projects is considered critical and indispensable in literature. This primary literature review brings forward the notion that enhancing productivity is a key concern for almost all industries and that further productivity improvement 14 opportunities always exist; hence ways and means of designing and fabricating production auxiliary attachments or jigs and fixtures are constantly explored by engineers, as proposed by Narasimha et al. [7].

3 RESEARCH METHOD

Manufacturing methods became obsolete with the emergence of programmable machines; production operations have to adopt a more economical approach to operations in manufacturing. These new economical methods are developed and implemented through better designs of auxiliary production systems such as the fixturing systems that employ jigs, fixtures, and other auxiliary production tools [6]. APSE such as jigs and fixtures are tools and devices used both in traditional manufacturing and in modern flexible manufacturing systems to improve machining quality, increase productivity and reduce cost of products. Auxiliary production equipment forms a system in which production improvement tools enable a faster and more profitable production process through a quick clamp or positioning of fixtures into a correct relationship with production process tools or machines [6].

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The research approach consists of a comprehensive literature review with an elaborate production flow analysis to establish the current status. Current production process flow maps will be established and analysed, and then suitable auxiliary equipment will be designed, manufactured, and assembled. Assembled auxiliary equipment will be applied to the production process for productivity improvement, with results measured to establish the improved status. The new production process flow will be established and compared to the old flows to determine the magnitude of change (i.e., productivity improvement).

The primary goal of the research is embodied in the third circumstance (i.e., the development and application of mechanical devices), which abridge labour and facilitate the ability for a single labour unit to complete the work of many and thereby achieve a productivity improvement. Therefore, this research will engage the three production circumstances in an experiment and a scientific process of either accepting the validation or nullifying it. Validation is fundamental to the research approach and the decision to engage the three production circumstances in the research.

Research Paradigm	Ontology (What is reality)	Epistemology (How can I know reality)	Theoretical Perspective (Approach used to know something)	Methodology (Process of finding out)	Method (Techniques used to find out)	Sources of data
Constructivism	There is no single reality or truth.	Knowledge of reality is used to discover the underlying meaning of events and activities.	Interpretivism i.e. reality is interpreted through analysis Historical studies	Action Research	Case Study	i) Document analysis and archival records ii) field notes and journal publications; iii) Process observation

Figure 3.1: Research approach (adapted from Crotty, 1998 & Jackson et al., 2012)

Action Research (AR) is the qualitative research method adopted for this technical change research, suitable because, according to Speziale et al [10], the research method seeks to improve practice and is appropriate when the intention is to scrutinise the effects of the action taken. In productivity improvement research, the main goal is to develop a solution that will improve operational practices. Therefore, action research is a perfect fit because Speziale et al. [10] declare that in action research, solutions are developed and applied to practice problems in a particular industrial setting. In action research, there are no delays in the implementation of the solution since the implementation is part of the research process [11].

4 DISCUSSION

Enhancing productivity is often examined from two broad perspectives, i.e., the industrial level and the corporate level, corresponding to macro and micro viewpoints, respectively. Nationally, productivity signifies an economic standpoint, whereas within an organisation, it mirrors the profitability of the specific entity [12]. Boosting productivity at the national economic level serves as the bedrock for economic advancement, national competitiveness, and gauge for living standards [12]. Meanwhile, at an organisational scale, productivity enhancement denotes the efficacy and potency of employing limited resources in the production process. therefore, elevating productivity on a micro level becomes a pivotal determinant for the sustenance of an organisation [12].

In practical and quantifiable terms, productivity is computed as the ratio between output and input. It is also recognised as the proficient utilisation of resources in generating goods and services [13]. The manufacturing sector employs diverse measurement techniques for assessing productivity. However, two widely utilized measures are total factor productivity (TFP) and partial factor productivity (PFP) [13]. TFP entails the ratio of total output to total input, where the latter encompasses labour, material, equipment, and capital [13]. The TFP equation is represented as shown in Equation 1 below.

$$TFP = \frac{Total\ Output}{\sum(Labor+Material+Equipment+Energy+Capital)} \tag{1}$$

Partial factor productivity pertains to the assessment of a specific group of input factors, as defined in equation 1. This metric is presented as the correlation between output and either a singular input or a designated subset of inputs [13]. An illustrative instance of partial factor productivity is observed in labour productivity, computed as the quotient of output quantity divided by input of labour hours. The equation for partial factor productivity can be expressed as depicted in equation 2.

$$PFP = \frac{Output\ quantity}{Labour\ hours} \quad (2)$$

Calculating TFP involves a certain level of complexity, yet its measurement process is more straightforward and manageable compared to the computation involving a PFP measure [13].

In this study, we quantify PFP across different quantities of labour hours and then proceed to juxtapose the outputs associated with varying labour inputs. The comparative analysis is further extended by evaluating the impact of the application of auxiliary production support equipment (APSE) on output. When dealing with the calculation of PFP in a maintenance production context, a more apt framework for experimentation is the law of returns to scale [14]. This concept finds better applicability as we manipulate labour input quantities, holding capital input constant, reflecting the dynamics of the production industry. Visual tools such as the consumer indifference curve or isoquants are effectively employed to depict the law of returns to scale in this context, serving as the business counterpart to the traditional indifference curves [14].

Production isoquants are analogous to consumer indifference curves in terms of a number of properties, although there are apparent distinguishable differences. When applying the indifference curve technique, utility cannot be measured, while with isoquants the quantities of inputs and outputs can be measured. Indifference curves will appropriately depict lower and higher levels of utility and isoquants will illustrate accurately the difference in quantities (i.e., by how much Q3 > Q2 and Q2 > Q1) (Figure 2.1).

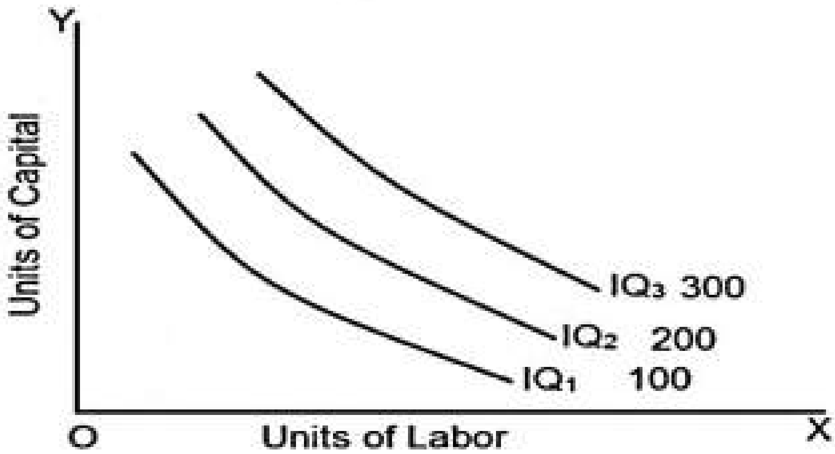

Figure 2.1: Indifference curves (adapted from Coelli et al., 2005)

In the indifference curve map in Figure 2.1, utility cannot be measured in terms of quantity in the indifference curve compared to the Isoquant map, but it is clearly depicted that utility in IQ3 is higher than in IQ2 and is higher in IQ2 than in IQ1. The attributes of the curve support the indifference curve theory that the further up and to right the indifference curve, the higher the utility [15].

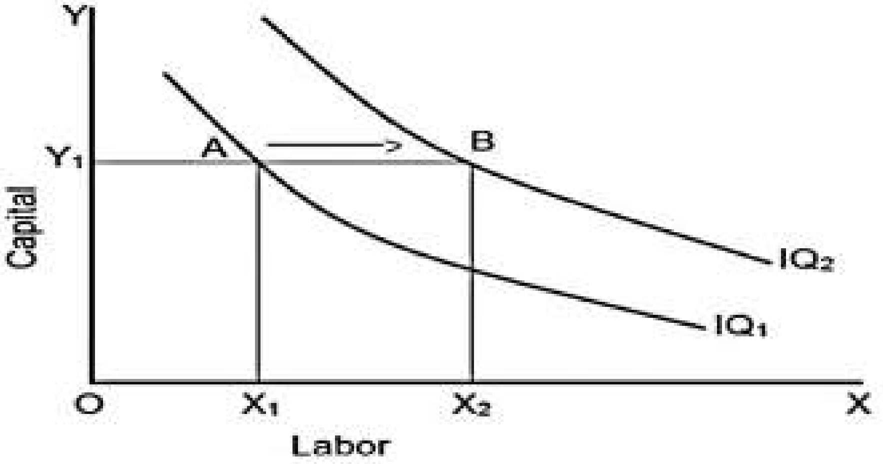

Figure 2.2: Production isoquant map (adapted from Coelli et al., 2005)

The isoquant curve in Figure 2.2 illustrates varying quantities of labour units used to achieve a higher utility. The application of the isoquant's technique enables a measurement of how much IQ2 actually exceeds IQ1. The isoquant curve IQ2 lies above and to the right of IQ1; IQ2 represents a higher output level. IQ2 curve represents a higher output achieved by increasing one of the input-factors of production from X1 to X2 so the output is increased from IQ1 to IQ2, albeit the other input factor of production remains constant. It is therefore apparent that isoquants are applicable and practical for PFP improvement research objectives.

Productivity improvement literature reflects an extensive study of productivity improvement in numerous organisational settings to identify opportunities for productivity improvement. Productivity improvement professionals and researchers are constantly searching for tools and techniques that will enable production firms to identify an efficient range of production input factor combination. This is an important characteristic of a production isoquant for it enables production firms to identify an efficient level of production [16]. Figure 2.3 illustrates a range of efficient and inefficient combinations of a production setup using an isoquant curve.

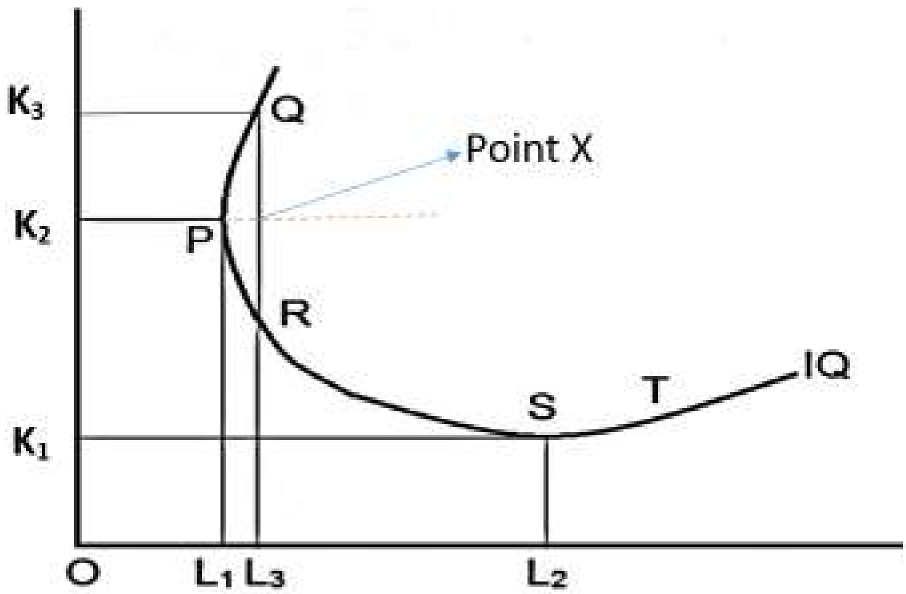

Figure 2.3: Production isoquant curve (adapted from Coelli et al., 2005)

The utility of the combinations at Q and P (Figure 2.3) is the same because the combinations of factors of production (K &L) lead to the same level of output although the combinations at point Q represent more capital and labour than combinations at point P (i.e., K3L3>K2L1). Therefore, production at point Q is inefficient compared to production at point P, and Production at point T, and all other points that lie on this portion of the isoquant, are inefficient. Since the slope of the isoquant in this portion of the curve is positive, all combinations of factors of production represented by this portion of the curve are inefficient.

It is perceptible that positively sloped isoquants denote an increase in both input factors of production (i.e., for production to increase from point P to Q, capital must increase from K2 to K3 and labour to increase from L1 to L3). Thus, it is expensive and inefficient. Efficient combinations of factors of production lie on the negatively sloped portions of the isoquant (i.e., P to S). Point X represents a higher utility, since the output is greater with an increase of one factors of production (L1 to L3), while capital is constant at K2. Thus, it represents a higher utility with a lower input combination and is an efficient combination of factors of production.

5 FINDINGS

The concept of production efficiency theory posits that any arrangement of production input factors, situated along the upward-sloping isoquant curve, signifies efficiency. The optimal combination lies exclusively along the downward-sloping segment of the convex isoquant (Murillo-Zamorano, 2004). This proficiency region necessitates a reduced quantity of production inputs such as L and K yet generates an equivalent or greater output level. As a result, there exists a persistent prospect for ongoing productivity enhancement, attainable through diverse methodologies, including the implementation of techniques like APSE within productivity enhancement endeavours.

Henceforth, production firms are constantly seeking to improve their production process so they can operate in an efficient portion of the production isoquant. This efficient region is called an economic region of production [14]. An indifference curve map contains numerous isoquants at varying utility levels. All these isoquants contain segments of economically feasible portions of a production isoquant. This economically feasible region is depicted by an area between a lower and a higher ridge-line (see Figure 2.4). The area is an economically feasible region for all production isoquants in the map (i.e., isoquants of lower and higher utility all contain a portion of economic feasibility).

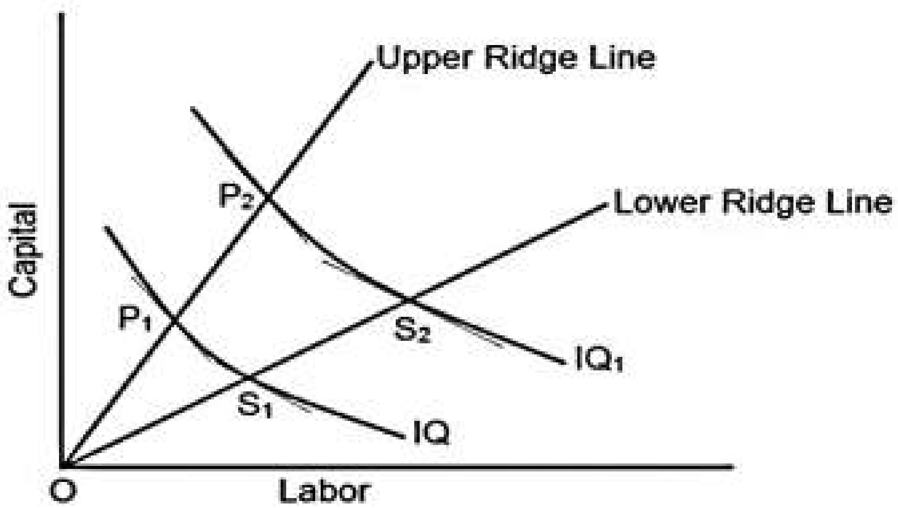

Figure 2.4: Economically feasible segments of a production Isoquant (Coelli et al., 2005)

Segments of the production isoquant depicted by P1S1 and P2S2 are the economically feasible portion of production and thus a producer seeking production efficiency will operate in this region [14]. Production firms will achieve efficient production in the economically feasible portion of the production isoquant. An economically feasible portion of the production isoquant illustrates a portion of production engineering in which the application of production economics is integrated.

At a micro-level, Farrel [17], in his seminal paper introduced the concept of decomposing overall production efficiency into technically efficient or inefficient. Farrell [17] is greatly influenced by postulates of [18, 19] deliberations on technical efficiency, characterised various ways in which production can be classified as efficient or inefficient [14]. Farrell postulates that production units are either technically inefficient (i.e., if they obtain less than maximum output available from a determined group of inputs) and allocative inefficient (i.e., if they do not purchase the best compendium of inputs given their prices and marginal productivity) [14].

The unit isoquant "YY" encompasses all the conceivable combinations of the production input factors (figure 2.5) that are technically efficient [14]. Therefore, production isoquant depicted by a curve YY' in Figure 2.5, demonstrate the technological set of a production unit that captures all the production points with a minimum combination of input factors needed to produce a unit of production output. This represents the quantity of input factors that can be divided without decreasing the amount of production output [14]. Therefore, the application APSE in production operation (see annexure 1 (i-to-iii)) enables production to achieve allocative efficiency, which by definition, involves selecting a mix of input production factors (e.g., labour and capital) that can produce a desired level of output at a minimum cost [15].

Analysis of efficiencies characterised by Farrell [17] is better explained by a production isoquant in Figure 2.5.

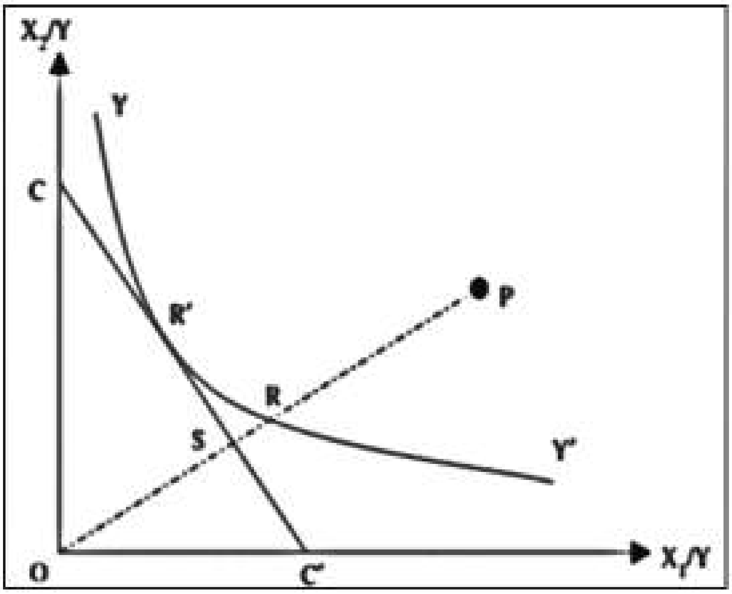

Figure 2.5: Technical and allocative efficiency measures (Source: Murillo-Zamorano, 2004)

In figure 2.5, the production isoquant is represented by the curve 'YY', demonstrating the technical scope of a production unit. This curve encompasses all production instances necessitating a minimum amalgamation of input factors to yield a solitary unit of production output. Every combination of production input factors defining the unit isoquant 'YY' denotes a state a state of technical efficiency [14]. I figure 2.5, Pointy P along with other points positioned above and to the right of the 'YY' isoquant, signifies a condition of technical efficiency in input factor utilization, these points situated beyond and above the 'YY' curve highlight a technically inefficient producer due to the redundant input factor combinations surpassing the requirements for producing a single unit of production [14].

Henceforth, at point P, the technical inefficiency of a producer is measured by the distance RP along ray OR this represents the quantity of input factors that can be divided without decreasing the amount of production output [14]. Since technical inefficiency is measured by the ratio RP/OP, then technical efficiency (TE) is measured by the ratio OR/OP, which is the equivalent to the ratio 1-RP/OP [14]. It is assumed that the iso-cost line is denoted by the slope of line CC' (for a cost-minimisation approach). If allocative inefficiency is expressed by the ratio SR/OR, then allocative efficiency is expressed by the ratio OS/OR.

It is common in production engineering to measure the performance of a production unit through the application of measures of allocative efficiency, in addition to technical efficiency measures [15]. Allocative efficiency can be applied as a measure of performance when market data is accessible and a negotiable assumption, such as cost minimisation or profit maximisation, is adopted [15]. In such cases, application of allocative efficiency is possible and appropriate. Allocative efficiency, by definition, involves selecting a mix of input production factors (e.g., labour and capital) that can produce a desired level of output at a minimum cost [15].

In the realm of productivity analysis, employing a production frontier proves suitable for illustrating the connection between input and output. This frontier serves as a representation of the utmost potential production output achievable at various levels of input factors [15]. Consequently, companies within the industry will align with the production frontier if they operate with technical efficiency or fail beneath it if they exhibit technical inefficiency [15]. Figure 2.5 stands as a visual depiction of technical efficiency or inefficiency as conveyed through the production frontier. Moreover, it inherently symbolizes the spectrum of all viable input-output combinations, constituting what is termed a feasible production set.

Postulates on efficient production frontier functions can be traced back to Farrel [17]'s seminal paper and since then, the concept of efficient isoquants has evolved into numerous propositions for specifying a technological set for a production unit [14]. The use of distance functions for measures of technical and allocative efficiencies has also evolved, although the underlying idea of using efficient frontier functions to measure productivity has been maintained for the last fifty years [14]. Henceforth, feasible production sets, maximum possible productivity and technical change concepts were established.

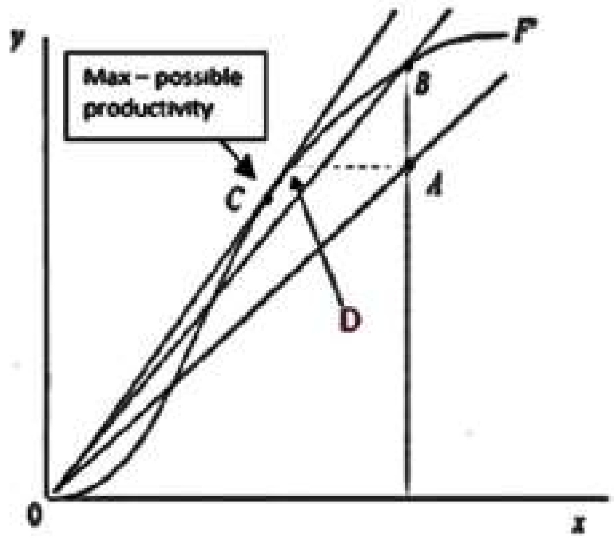

Figure 2.6: Technical efficiency and technical change (Source: Coelli et al., 2005)

Figure 2.6 presents absolute critical concepts in productivity improvement, concepts relating to a feasible production set, maximum possible productivity, and by an illustration that of technical change. A feasible production set, including all productivity combinations lying on the production frontier, is a set of all input-output combinations, feasible in a production unit [15]. As per the illustration in Figure 2.6, a feasible set consists of all points lying between the production frontier OF and the x-axis [15]. Primarily, the advantage of a set representation is the technology of the production unit since a technology change (technical change) implies an improved efficiency of the production unit. Hence, points laying on the production frontier illustrate an efficient subset of the feasible production set [15].

When measuring the productivity of a production unit at a point using a production frontier, a ray is drawn from the source through an efficient production frontier curve. The slope of the ray, Y/X, is a measure of productivity [15]. In Figure 2.6, point A illustrates a technically inefficient production unit. To improve the technical efficiency of the unit, the production unit must operate at point B. At this point, the slope of the ray drawn from the origin is greater, implying higher productivity at point B [15]. At point C, the slope of the ray from the origin is at a tangent to the efficient production frontier, this is a point of maximum productivity [15].

6 CONCLUSION

Engaging in production activities situated anywhere along the production frontier is bound to result in diminished productivity [15]. This is attributed to the fact that point C stands as an epitome of optimal technical scale and can solely be reached through efficient technical alteration, which exclusively stem form capitalising on economies of scale. This introduces another avenue for bolstering productivity termed as ‘technical change’ [15]. Technical change is attainable through technological advancements that lead to upward and rightward shift of an already efficient production frontier. This enhancement in the productivity of a specific production unit is visualised through the transition of the production frontier from OF’0 to OF’1, as illustrated in figure 2.7.

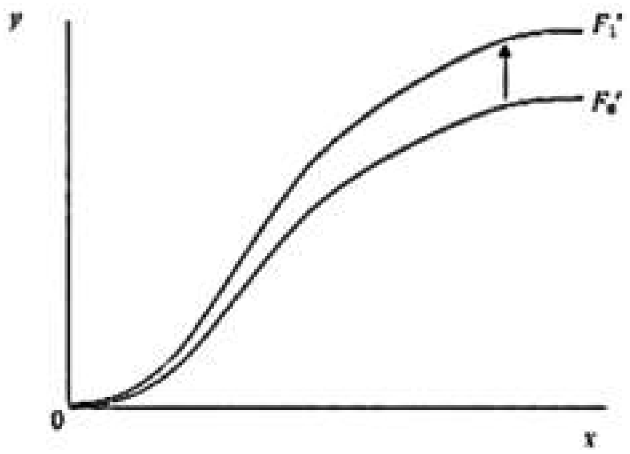

Figure 2.7: Production frontier and technical change (Source: Coelli et al., 2005)

In figure 2.7, for the curve OF’1, all production units have higher productivity than all production units in OF’0 due to a productivity change which results from the exploitation of economies of scale called technical change [15]. It is therefore concluded that, even though a production unit is technically efficient, there is still room for productivity improvement through constant exploration of ways and means of applying technical change [7], [20], in this case the application of APSE in productivity improvement.

Productivity enhancement in a production unit result from efficiency improvements or exploitations of economies of scale or technical change or a combination of all three productivity improvement techniques. A common example of technical change can be an addition of a new boiler in a coal-fired power plant, the results of which will be the extension of the plant productivity potential above and beyond current or previous limits [15]. In this research, technical change is experienced through the application of auxiliary production support equipment (APSE) such as jigs, fixture, and levers, which result in productivity improvement beyond current and or previous production unit limits.

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THE DILEMMA IN PRODUCTIVITY IMPROVEMENT THEORY

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ABSTRACT

Productivity measurement is not an end to itself but a process to ascertain facts and figures utilised in the decisions making processes with the sole purposes of influencing and changing behaviour of the human and technical elements of the production process. The dilemma in productivity improvement theory is that productivity measurement is a data collection process conducted in operational area of the production process to influence and change behaviour of the human and technical elements of the production process. This transactional nature of productivity improvement leads to the manifestation of the limitations inherent to all productivity improvement theories. This research focuses on the impact of the transactional nature of productivity measurement and the inherent limitations of the productivity improvement theory. A qualitative research approach is adopted to explore and explain the impact of this transactional nature on productivity improvement results.

Keywords: Productivity; Behavior; Technical; Dilemma; Theory

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1 INTRODUCTION

Implementing productivity enhancement methods and strategies to address production challenges stemming from limited and scarce resources leads to heightened utilization of the currently available resources. Consequently, this leads to a notable surge in overall productivity. The advent of computer numeric programming machines rendered traditional manufacturing techniques obsolete. To adapt to this shift, production operations had to embrace more cost-effective methodologies. These novel approaches were formulated and executed by refining auxiliary production systems, such as fixturing systems involving jigs, fixtures, and other related tools [1].

Auxiliary production equipment, including jigs and fixtures, plays a pivotal role in both conventional manufacturing and modern flexible manufacturing systems. Their purpose is to enhance machining precision, productivity, and product cost-effectiveness. Hence, these auxiliary production tools establish a cohesive system where productivity enhancement tools facilitate a swifter and more lucrative production process. This is achieved by promptly securing or positioning fixtures in accurate alignment with production tools or machinery [1].

The two sets of methods and techniques outlined here are not exhaustive in terms of productivity improvement approaches. While the enumerated tools and others not specifically mentioned exert a comparable impact on workflow efficiency and production output enhancement, it is important to acknowledge certain inherent limitations and shortcomings when employing these productivity enhancement strategies. This is evident from the fact that each individual tool or technique, whether mentioned or not, yields only minimal or sometimes inconsequential improvements when applied in isolation to production operations.

Technically speaking, this implies that implementing these tools and techniques solely to enhance the internal, tangible components of productivity results in marginal improvements. Similarly, when exclusively applied to the intangible, internal aspects of productivity, the impact remains modest. To achieve maximal productivity, a comprehensive application approach is necessary. This approach, when implemented in any industrial context, addresses both the tangible and intangible aspects of productivity. As a result, it facilitates optimized work methodologies, amplified process output, and enhanced overall productivity. By attaining this holistic approach to productivity enhancement, the limitations of current productivity theories can be surmounted and transcended [2].

2 BACKGROUND

The field of Industrial Engineering encompasses a wide spectrum of tools and techniques aimed at enhancing productivity across various industrial contexts. Its origins lie predominantly within the manufacturing sector, giving rise to a plethora of methods tailored for this domain. Nevertheless, transferring and implementing Industrial Engineering tools to boost productivity encounters challenges in heavy industries like Railway maintenance and mining due to their distinct complexities. In such sectors, the intricate nature of the problems faced complicates the application of these techniques. This study focuses on employing Industrial Engineering tools in the realm of equipment maintenance for railway locomotives.

The application of Industrial Engineering productivity enhancement tools and strategies within the railway maintenance lifting operations poses a considerable challenge, mainly due to the fixed and inflexible nature of the industrial environment. Railway locomotive workshops' lifting bays exemplify this, characterized by constricted space, limited resources, equipment, and a finite workforce. In these depots, a single lifting bay is common, usually comprised of two parallel pits and two overhead cranes—one for lifting and the other for transferring components between lifting operations and storage zones. The work area accommodates a predefined maximum workforce that can operate optimally within the provided space. Operations follow a linear and sequential pattern, minimizing variations to ensure risk management, safety, and cost control. Scaling up infrastructure and equipment swiftly to amplify production output without incurring substantial costs poses a near-impossible challenge.

3 LITERATURE REVIEW

Traditional manufacturing methods have become outdated due to the rise of computer numeric programming machines. Consequently, production processes needed to adapt to more cost-effective techniques. These novel approaches were formulated and put into practice through enhanced designs of auxiliary production systems, exemplified by fixturing systems that utilize jigs, fixtures, and other tools [1]. Jigs and fixtures, which find application in both traditional manufacturing and contemporary flexible manufacturing systems, play a crucial role in enhancing machining precision, efficiency, and cost-effectiveness. Essentially, these auxiliary production tools constitute a system wherein tools for production enhancement facilitate swift and profitable production by enabling efficient attachment or alignment of fixtures with production machinery [1].

The pursuit of augmented productivity is an ongoing challenge, as underscored by Narasimha, Kumar, and Moorthy (2013). Engineers consistently seek innovative avenues for developing attachments like jigs and fixtures, which provide auxiliary support in production (Narasimha et al., 2013). In a similar vein, Herrmann & Chincholkar [3] advocate for the concept of design for production (DFP), which involves assessing the manufacturing prerequisites of a product in comparison to existing capacity to identify opportunities for enhancing output.

Addressing the inherent constraints of productivity measurement theories, Adendorff [2] highlight two key limitations: the focus on effects rather than causes and an oversimplified linear relationship that doesn't align with real-world scenarios. They assert that productivity improvements are more likely to manifest in non-tangible aspects rather than tangible ones. Consequently, measuring productivity serves the purpose of gathering data that informs decisions aiming to reconfigure behavioural and sequential productivity components.

With these scholarly viewpoints in perspective, it's evident that productivity disparities exist across diverse industrial production contexts. Kahng [4]'s theory [4] posits that the delay in integrating cutting-edge publications into production processes results in industries grappling with contemporary challenges using outdated technological solutions. In line with this, Narasimha et al. [5] proposition of a continuous exploration of avenues for designing and fabricating auxiliary production equipment to enhance productivity gains credibility upon review. Their theory gains plausibility from the substantial literature surrounding the impact of production support auxiliary equipment on overall productivity.

4 RESEARCH METHOD

The methodology of qualitative case study offers researchers the opportunity to deeply investigate and elucidate a phenomenon within its specific context, drawing from diverse data sources [6]. This method ensures a comprehensive exploration of the subject through multiple perspectives, facilitating a profound comprehension of various facets of the case in question [6]. This approach aligns seamlessly with the current research objectives, which center on unraveling and explaining the mechanisms through which auxiliary equipment enhances productivity and overcomes the limitations of conventional productivity enhancement tools and techniques. The contextual conditions surrounding the phenomenon are also taken into account.

This study focuses on the impact of auxiliary equipment on augmenting productivity and surmounting the constraints of industrial engineering (IE) productivity enhancement tools within the framework of technological influence on industrial production. The chosen unit of analysis is the effect of auxiliary equipment on productivity enhancement, confined to its current technological implications in an industrial setup. The attributes of this study conform to the specifications of a case as defined by Miles & Huberman [7], consistent with the delineations set by Yin [8] concerning the establishment of case boundaries in a case study methodology (Baxter & Jack, 2008). Furthermore, the study adheres to stipulations regarding temporal and spatial boundaries [6].

Given the contextual delineations and the research question focused on the impact of auxiliary equipment on productivity and circumvention of IE tool limitations, the chosen type of case study corresponds to the explanatory, exploratory, or descriptive categories outlined by Yin [6]. The anticipated outcome of this research is the formulation of solutions or recommendations addressing the following propositions and issues:

- Conventional industrial engineering productivity tools and methods are outdated and inadequate for present and future needs.
- The incorporation of auxiliary equipment in productivity enhancement interventions can overcome the inherent limitations of conventional approaches.
- The transactional nature of productivity enhancement studies is a fundamental factor contributing to the limitations of existing tools and techniques.
- Propositions and issues serve as crucial components of a case study research, guiding the development of a conceptual framework [6].
- Data Collection Approaches

Case study research, as emphasized by Yin [8], relies on diverse data sources to bolster data credibility [6]. This study employs the triangulation of data sources, encompassing:

Document Analysis and Archival Records: The incorporation of document analysis is rationalized by its common use in tandem with other qualitative methods to attain triangulation – the convergence of evidence from multiple sources to enhance validity (Bowen, 2015). Prior research by Rossman & Wilson [9] utilized document reviews to deduce agency missions from documents and reports [10]. Sogunro [11] highlighted that document analysis elucidates history, goals, and substantive content of the subject [10].

Field Notes: Patton [12] contends that field notes facilitate a deeper understanding of the subject's perspective, allowing unobtrusive and nonreactive recording of observations [12]. These notes encompass comprehensive descriptions of activities, behaviors, conversations, and other aspects of human experiences [12].

Process Observation: Employing the observation method permits the researcher to decipher the practical application of theory, allowing the development of theoretical frameworks [13]. In this case, informal participant observation is employed, involving various tools like audio recordings, field notes, and video recordings [13].

By amalgamating these data sources, a holistic understanding of the observed phenomenon, the maintenance production process of railway bogies, is cultivated. This approach culminates in comprehending the "AS IS" state of affairs, acting as a foundation for applying productivity enhancement tools and techniques, comparing their outcomes, and ultimately determining the most effective methods. This evaluation extends to incorporating auxiliary equipment into the productivity intervention and comparing its results against the benchmark established by the most productive improvement methodology [14].

5 PRODUCTIVITY THEORY LIMITATIONS IN THE RAILWAY MAINTENANCE PRODUCTION PROCESS

In the context of locomotive maintenance, the operational setting involves the servicing of both diesel and electric locomotives within a shared lifting bay. The infrastructure and resources of this bay enable the maintenance depot to accommodate the servicing of up to four locomotives during a nine-hour production shift. The process of lifting to replace or repair a locomotive component, such as the traction motor, necessitates a two-hour duration. Thus, within one production shift, a maximum of four traction motor replacements can occur, accounting for a one-hour lunch break.

Presently, the productivity of the production process stands at four instances of locomotive lifting activities per shift. In order to surpass this current level, a strategy of introducing a three-hour overtime period per shift has been adopted. This addition results in a boost of one locomotive in production output, totalling five locomotive lifting activities during the shift. It's essential to note that the labour regulations within South Africa stipulate a maximum shift duration, including overtime, of 12 hours.

The final alternative at hand is the implementation of a night shift that mirrors the production cycle duration of the day shift. This adjustment would allow the maintenance lifting bay to accomplish up to eight component change-overs per day, effectively doubling productivity. However, it is imperative to recognize that enhancing productivity through overtime or introducing a night shift comes with considerable costs. These encompass a notable increase in production expenses, including doubled energy consumption, and the necessity to recruit a new team due to the limit on maximum weekly hours outlined in the labour relations act, as the day shift workforce would surpass this limit.

Evidently, addressing this productivity challenge necessitates resolving two fundamental issues inherent to the production process [15]: the constraints on capacity and the limitations of prevailing productivity theories. Adendorff and de Wit [2] provide a comprehensive insight into these problems. They assert that prevailing productivity measurement theories suffer from limitations, such as focusing on effects rather than causes, assuming linear relationships that may not align with practical scenarios and directing attention towards the softer components rather than the more tangible aspects of productivity improvement. Adendorff and de Wit [2], further emphasize that productivity improvement is transactional in nature – a means of gathering data for decision-making aimed at behavioural change. These challenges underlie the quandary in productivity enhancement theory [15]. Statistical data on productivity improvements indicate a modest enhancement with the implementation of TOC (25%), while the integration of auxiliary equipment yields substantial improvements in productivity [16].

6 DISCUSSIONS

Herrmann and Chincholkar [3] emphasize that suggestions for redesigning can enhance the maximum potential output through design for production (DFP). This approach evaluates the manufacturing needs of a product against available capacity [17]. Thus, it is valid that the constraints inherent in productivity theory necessitate a revamp of the production process [18]. Implementing a method for boosting productivity becomes essential to overcome these limitations and achieve optimal productivity enhancement.

The meagre progress resulting from method and time productivity enhancement studies provides proof of the inherent limitations in productivity theory and the constraints posed by infrastructure and equipment, particularly in heavy industries [19]. Similarly, the minimal productivity advancement stemming from the application of TOC supports the evidence of limitations in applying productivity improvement techniques and philosophies, especially in demanding sectors like railways and mining.

The outcomes attained through the integration of auxiliary equipment fundamentally uphold the concept endorsed by Adendorff & de Wit [2]. This concept posits that achieving maximum productivity necessitates a comprehensive approach that addresses both the internal hard and soft components of productivity across all industrial settings. It is evident that a systematic examination of the critical attributes of productivity improvement tools and techniques [20], coupled with the application of the work study method, can lead to substantial and optimal enhancements in productivity. The incorporation of auxiliary support equipment further bolsters these productivity improvement initiatives.

Leveraging auxiliary production support equipment within productivity enhancement projects offers significant advantages [21], given its capacity to simultaneously augment total production output and substantially elevate percentage growth in productivity (as illustrated in fig.3). The impact of auxiliary equipment on production cycle time within productivity improvement initiatives is evident.

The production process must be poised to curtail costs while enhancing proficiency [22]. Thus, streamlining production and exponentially amplifying productivity and output becomes exceptionally crucial.

To deeply comprehend the attributes of the production process, a method analysis must take precedence. This analysis furnishes accurate insights into the existing method process system. Method analysis proves vital in understanding the implications of existing process limitations and serves as a foundation for defining system problems. Once the attributes of the present system are comprehended, method enhancement can be introduced to minimize and, when feasible, eliminate inefficiencies while enhancing process cycle time.

6.1 Analysis

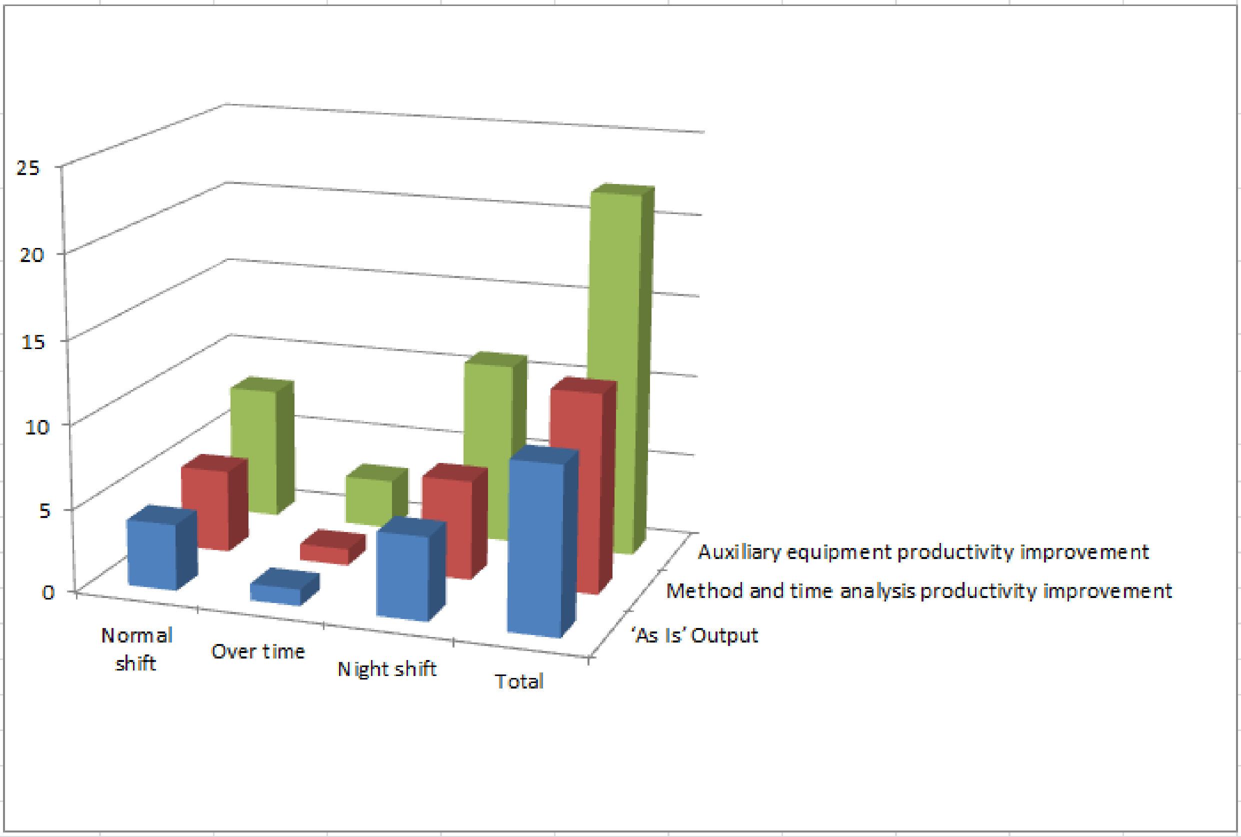
The main focus of this particular case study revolves around the examination of variable patterns within individual cases. The study utilizes a table (referred to as Table 1) where cases are represented as columns and variables as rows. This approach, known as case-oriented analysis, scrutinizes how variables interact within a case, identifies patterns, and subsequently compares these patterns across multiple cases. The objective is to uncover similarities, differences, and patterns that can either support or contradict propositions established in the theoretical framework. Table 1 is employed to categorize specific events and discern patterns within and across cases. This data presentation serves a similar purpose to a truth table based on Boolean algebra.

In this context, the insight gained from Table 1 is particularly enlightening. It reveals that the elasticity of productivity improvement output is influenced by the value-added over time, which is a result of productivity enhancement in a specific case. As depicted in Table 1, the variable 'over time' doesn't lead to output growth, despite a 20% improvement in overall productivity in that case. Consequently, in this specific instance, productivity improvement doesn't generate the necessary process capacity to amplify output.

Table 1: Output data for multiple productivity improvement initiatives

Analysis Theme	'As Is' Output	Method and time productivity improvement	Auxiliary equipment productivity improvement
Normal shift	4	5	8
Over time	1	1	3
Night shift	5	6	11
Total	10	12	22
% increase	0	20	120

Applying a "horizontal" logic to the case study analysis unveils that the variable 'over time' doesn't consistently lead to an output increase in all productivity improvement scenarios. By intrinsically exploring how variables interact within each case and comparing patterns across cases, a fundamental concept, termed external validity by Yin, comes into play. This concept refers to the ability to generalize findings to a broader theory. Table 1 exemplifies this concept by vividly indicating that, for the variable 'over time,' output remains constant across two cases, despite a 20% productivity improvement in one of them. This generalization suggests that not all productivity enhancements guarantee increased output. Hence, the interrelation of the variable 'over time' within the case 'Method and time productivity improvement' contradicts the competing hypothesis that all productivity improvements inherently boost output [23]. A crucial insight from Table 1 is that among the three cases, the auxiliary equipment productivity improvement initiative yields the highest output.



Data Display 1: Productivity output for similar themes (Input = time)

The above Data Display 1 highlights the influence of each variable on productivity improvement and the cumulative impact of each case on productivity enhancement initiatives. Data Display 1 unmistakably demonstrates that the magnitude of time value-added in a productivity improvement initiative is directly proportional to the output yield. Across all three cases, the output yield from productivity improvement is greatest when auxiliary equipment is involved. The overall output yield is highest in the case of auxiliary equipment, and the percentage increase likewise peaks in this case.

7 CONCLUSION

The findings of this case study provide evidence that productivity improvement is notably higher when auxiliary production support equipment is effectively integrated into the production process. The rate of productivity improvement, quantified as the percentage growth in productivity, remains consistently high across all cases and isn't contingent upon production process conditions. This consistency implies that the experiment's outcomes are replicable and consistent. Replication plays a vital role in confirming and validating the presented model. It allows for the assessment of whether the model accurately reflects the conceptual framework, prompting both the model developer and replicator to reevaluate assumptions made during development and application. Consequently, a shared comprehension of the productivity improvement model's design and application decisions can be established within the engineering research community. The concepts of validation and verification ensure that the research output isn't an outcome dependent on localized conditions but rather a result of rigorous application of scientific methodology.

7.1 Recommendations

In 2013, Narasimha et al [5] emphasized the perpetual challenge of enhancing productivity and the ever-present potential for its augmentation. This has led engineers to continually explore novel avenues for devising attachments, jigs, and fixtures, collectively referred to as production support auxiliary equipment. Consequently, the utilization of such auxiliary equipment to advance productivity has emerged as an unorthodox yet endorsed approach. The realm of productivity enhancement has witnessed various innovative design strategies, such as Design for Production (DFP), Design for Production and Manufacturing (DFMA), and Design for Optimization or Customer-Centred Design. Embedded within this design and productivity enhancement revolution is the incorporation of auxiliary equipment.

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CHALLENGES AFFECTING PROJECT TEAM COLLABORATION DURING A PANDEMIC

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ABSTRACT

This research confirms that a pandemic impacts collaboration between project team members by shifting their normal collaboration platforms. The shift comes with multiple challenges, which are presented in this paper. The findings reveal that the challenges most experienced by project team members when they shift to online collaboration are home interferences, communication barriers, difficulties with building effective online working relationships, connectivity issues and work-life balance challenges. This research provides mitigation strategies that can be used to better equip project teams for successful online collaboration. They can proactively utilise the identified strategies to avoid the challenges. Project managers and all project team members or stakeholders may use the knowledge gained to enhance their online collaboration experience.

Keywords: Collaboration, pandemic, project team members

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1 INTRODUCTION

Collaboration is more than just communicating. It is a planned process that creates value and relies on the trust of the team members. It is the desire to solve problems, create solutions and discover new methods of completing work [1]. Collaboration is considered an essential element of project management, which is the use of skills, knowledge, methods and instruments to outline tasks required for project success. Project success is determined by multiple factors, one of which is collaboration. It is evident from project management practices that effective team building, clear communication channels and effective monitoring and feedback (all elements of collaboration) form part of the critical factors required for a project's successful outcome [2].

A pandemic such as COVID-19 forces project team members to move from their normal collaboration environments when lockdowns are implemented. When organisations are faced with a pandemic that affects team collaboration and only leaves them with limited collaboration channels, i.e. online, people are forced to adapt to new technological changes, which may affect their work. Some team members do not adapt easily to the required technological advancements, which may lead to poor performance, delayed deadlines and lack of motivation, affecting project completion or resulting in project failure.

Existing research does not present enough knowledge on how to handle changing working environments enforced by a pandemic. The change in working conditions may result in negative and positive consequences regarding the collaboration of teams as different technology affordances are seen and actualised to support normal business [3]. This research aimed to investigate how a pandemic impacts collaboration between project team members when they are forced to move from their normal collaboration platforms.

Section 2 of this article covers the findings from the literature review and section 3 deals with the methodology used to achieve the objective of the research. Section 4 provides the analysis of the data collected and the findings are discussed. The conclusion of the research is drawn in section 5.

2 LITERATURE REVIEW

Collaboration can be accomplished in different ways concerning place, time and resources. Project teams may be set up differently and use different collaboration platforms to achieve the project goals. Some may be co-located, some may be online and some may be distributed, which is a combination of co-located and online teams.

2.1 Traditional collaboration platforms

Traditionally, project teams are set up on various platforms, which could be in the same physical location (co-located) if all project members are located close by. Some are set up in online teams where they can only collaborate online and some are set up to include a combination of both physically located and online teams. For this study, an online team meant that all team members were in the same time zone.

2.2 Collaboration during a pandemic (Forced online collaboration)

A pandemic might force team members to move away from face-to-face collaboration and only rely on computer-based technologies or online teams to collaborate [3-5]. Organisations are forced to implement remote working processes during a pandemic. Table 1 shows how collaboration changes during a pandemic compared to normal collaboration [3, 4, 6].

Table 1. Collaboration changes during a pandemic

Dimension	Co-located	Distributed	Online
Location	Shift from physically located teams to online teams	Shift from semi-virtual to fully virtual or online teams	No change
Collaboration	Shift from face-to-face to forced online collaboration	Shift from semi-virtual to fully virtual teams or online collaboration	No changes to collaboration
Communication	Shift from face-to-face communication to online interactions	Shift from some team members being able to communicate face-to-face to all team members communicating only online	Communication remains online
Knowledge sharing	Shift from informal face-to-face idea-sharing	Shift from informal face-to-face idea-sharing for physically located teams to all teams sharing knowledge online	Knowledge sharing is more difficult when all teams are now collaborating online

2.3 Collaboration challenges experienced by project teams during a pandemic

Project teams often talk about managing risks caused by unexpected events that may impact project delivery. Risk is defined as an uncertain event that is interpreted by individuals as a potential risk, threatening planned project delivery [7]. A pandemic may also bring risks that may negatively impact project success. During a pandemic, employees are forced to work from home, which means there is no form of office support, and all employees are expected to adopt the use of digital communication channels to maintain collaboration [3, 4, 8]. Arnison and Miller [9] refer to this kind of setup as a pure online team. Team members will no longer be able to meet face-to-face and share ideas, request assistance, or even have profitable collaborations [6].

There are common challenges that can be experienced by any online team. An enforced online working team that might have been created because of a pandemic may have to deal with these challenges. It is even more difficult for them as they might not have been prepared. Several authors have highlighted the common challenges as listed in Table 2 as being encountered by most online teams [2, 8, 10-15]. These challenges might also be experienced by traditional teams (F2F), but they are exacerbated when teams are operating in an online environment.

Table 2. Common challenges encountered by online teams

Challenge	Description
Trust issues	Creating and maintaining trust amongst online members is difficult as they are not able to observe the physical behaviour of their team members, which is used to establish trust in face-to-face interactions.
Poor communication	Online teams rely on technology to communicate with their team members. Poor communication amongst team members may result in less productivity, project failure, work stress and damaged working relationships.

Knowledge sharing	Members of online teams may find it difficult to share their knowledge, especially if there is no trust amongst team members.
Technology adoption	Getting used to the new technology and systems is a major challenge.
Less effective working relationships	It is difficult to build and maintain effective working relationships when using online teams.
Home interferences	There are many interruptions that might result in poor work.
Loneliness	Lack of informal social interactions may result in employees feeling isolated and not being included in the team.
Lack of motivation	The team members may not be motivated to use the available collaborative tools that are available during a pandemic.

2.4 Strategies used to increase the success of online collaboration

Technology presents the opportunity to move away from regular methods that individuals might have adopted for how certain things should be done [11]. With the digitalisation of the workplace, setting up online teams to perform work or collaborate is easy, as there are sufficient technology platforms. Organisations only need to understand the principles, which will make it easier to work from home during a pandemic [5]. Ensuring that the right electronic communication channel has been selected, properly managing all electronic files across all geographically dispersed members and building trust when members are unable to meet face-to-face [16] contribute to successful online teams. Communication is regarded as one of the critical elements leading to the success of any online team [16]. Project teams can deal with uncertainties through analysis and collaboration. Numerous studies have indicated the value of constant high-level team collaboration [7].

Table 3 highlights some of the strategies that can be used to address the challenges faced by online working teams listed in Table 2 [6, 14, 15, 17, 18].

Table 3. Addressing the challenges of online teams

Challenge	**Strategy**
Trust issue	• Team members must be open with each other and not withhold information from other team members • Conduct regular online meetings • Provide clear feedback • Increase knowledge sharing • Have a shared project that involves all team members • Establish an email or message response time policy
Poor communication	• Enable online communication channels • Provide regular feedback • Ensure high-quality online communication • Follow up on tasks • Listen, encourage and recognise all team members • Use social media platforms and other online collaboration tools
Knowledge sharing	• Trust each other • Establish good relationships and find ways to bond • Encourage the exchange of ideas
Technology adoption	• Provide training for online collaboration platforms as well as online working
Less effective working relationships	• Increase knowledge sharing • Encourage participation by all team members

	• Embrace differences of team members • Understand each other's challenges • Encourage all team members to express themselves • Consider and debate all shared ideas • Conduct peer evaluations and debriefing sessions • Managers must act as the glue that keeps all team members together
Home interferences	• Find a balance between work and home tasks and create boundaries • Plan on how and when to complete tasks • Develop and maintain self-discipline • Find time to rest after working
Loneliness	• Use online social platforms for engagements • Initiate and engage in online interactions • Managers to seek feedback and project status from team members
Lack of motivation	• Encourage all team members to participate • Clearly define company objectives

Based on the literature review, the following research questions were derived:

- How did the collaboration platforms used by the project team change during the pandemic?
- What are the collaboration challenges experienced by project teams during a pandemic?
- What are the strategies used by project teams to enable successful collaboration in online teams?

3 RESEARCH METHODOLOGY

To achieve the research objective, a qualitative strategy using structured interviews was selected. Interviews provided sufficient qualitative data to understand the lived experiences of the participants [19]. This allowed the researchers to conduct an inquiry-based conversation [19] with the participants to obtain primary data. The selection of this method was driven by the types of research questions asked. The use of interviews enabled the researchers to have an extensive and full view of the study context to achieve the research aim. The interviews therefore enabled the researcher to ask the participants that had experienced the impact of collaboration changes about their lived experiences and their coping strategies.

Purposive sampling was used to identify the participants. Interviews were conducted with participants that had been in the project management environment before and during a pandemic. The targeted participants had experienced collaboration changes within different project environments and consisted of a project sponsor, programme manager, project managers, operations managers, engineers, specialists and analysts, all involved in projects. This ensured that the information gathered was from participants that had experienced the impact of a pandemic in their collaboration environment.

The participants were interviewed after they accepted the interview invitation and signed the consent form. They were given the information document containing the details of the research study and the interview questions before the interviews were conducted. This was done so that they could familiarise themselves with the study and to ensure that they understood what was required. The interview questions were closed and the interviewees had to select certain options, as is the case with a questionnaire. For some of the questions a

Likert scale was used, e.g. to determine the level of trust. The questions were structured around the literature. This helped to enhance the reliability of the study and preparation. Background questions were also asked that confirmed that the interviewees had the required minimum of three years of experience in a project management environment, as well as to confirm that they performed certain project management functions before and during the pandemic. This ensured that the interviewees were the right candidates to provide relevant data to answer the research questions.

A thematic analysis method was used to analyse the collected data. Thematic analysis is a method used to identify and analyse patterns in qualitative research [20]. It consists of six phases, which were followed in this research study as shown in Figure 1.

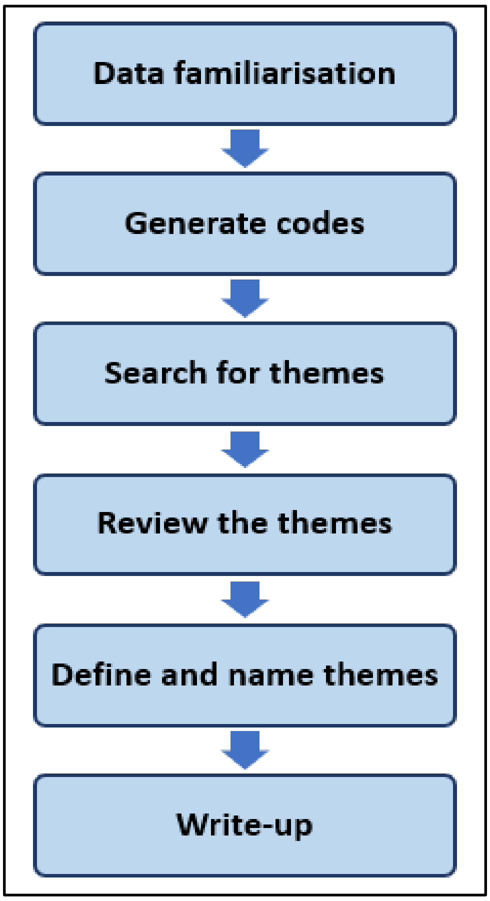

Figure 1. Thematic analysis phases

4 RESULTS, ANALYSIS AND DISCUSSION

The interviews used for data collection were conducted with 15 participants, who volunteered from the same organisation. This was to determine how the collaboration platforms changed, the collaboration challenges experienced by project team members and the strategies they used to maintain collaboration.

4.1 Changes in project teams' collaboration platforms due to a pandemic

It was found that a pandemic forces a shift in team members' collaboration platforms. Three collaboration platforms for project management were identified from the literature, as shown in Figure 2. The interviewees were asked about their platforms before the pandemic and whether they had experienced a shift from their normal collaboration platforms because of the pandemic. Figure 2 also indicates the number of people that were using the different platforms before and during the pandemic.

All the interviewees shifted from either co-located or distributed platforms to fully online platforms because of the pandemic. This means that all the interviewees were impacted by the pandemic with regard to collaboration with their project team members. They were not used to this kind of platform and may have experienced some challenges at some point.

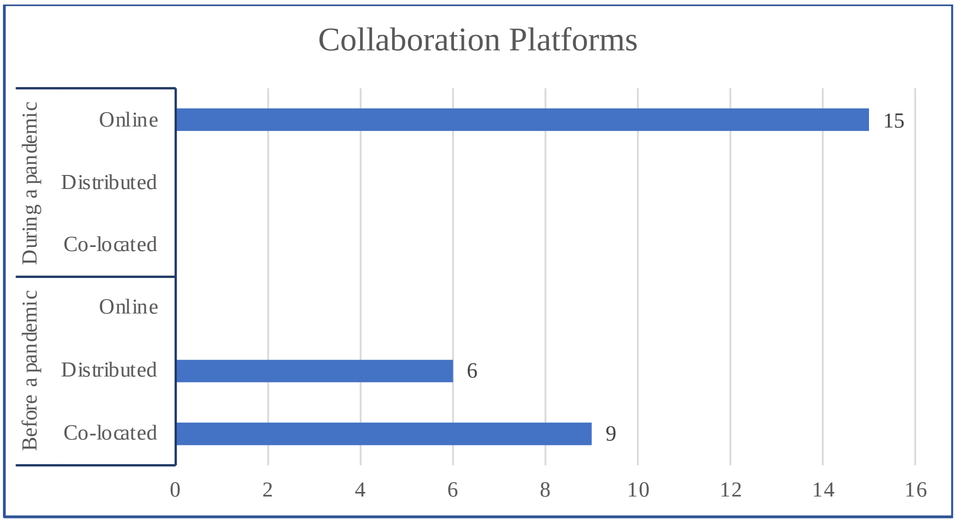

Figure 2. Interviewees' collaboration platforms

4.2 Collaboration challenges experienced by project teams during a pandemic

The project team members' experience, during a pandemic, of the collaboration challenges as identified in Table 2 are shown in Figure 3. Their experiences were measured on a 5-point Likert scale ranging from 'Never' to 'Every time'.

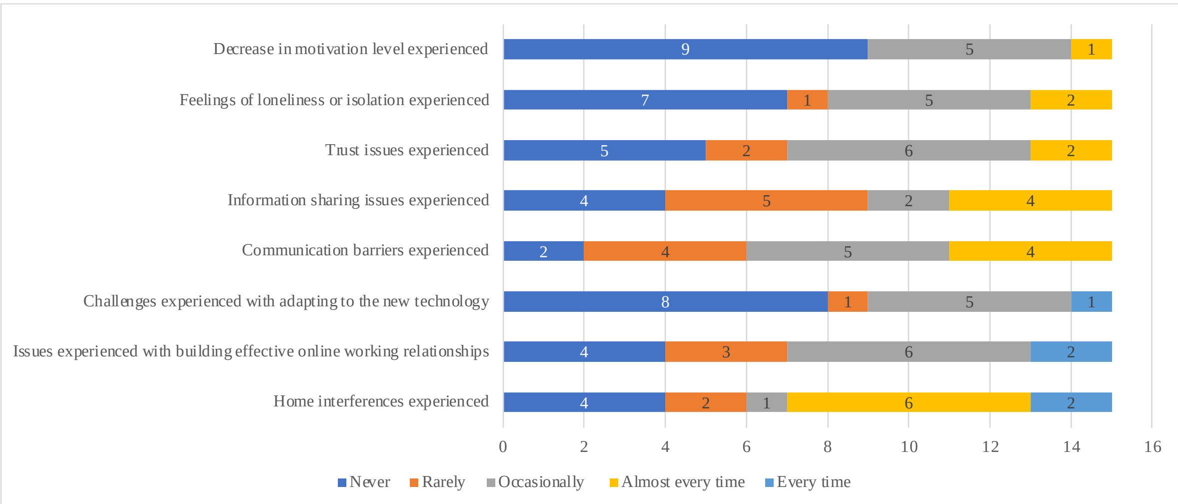

Figure 3. Collaboration challenges identified by project team members

Several steps were taken to analyse the data on the challenges identified in the literature review. The first step was to perform a descriptive analysis as illustrated in Figure 3. The findings were further analysed to determine which challenges were experienced the most by the interviewees. Weighted averages were calculated for more accurate findings, as the ratings were different. Weightings are used to determine the relative importance of each amount on average. They are equivalent to having many similar elements with the same average involved [21]. A weighted average is a calculation that considers varying degrees of importance of the various numbers in a data set [22]. A comparison of results was done and discussed based on the total weighted averages calculated.

To determine a confirmed challenge, Table 4 shows the total weighted averages for each collaboration challenge based on the weighted calculations.

Table 4. Weighted total of collaboration challenges

Challenges	Weighted Total
Home interferences experienced	3.00
Communication barriers experienced	2.73
Issues experienced with building effective online working relationships	2.53
Information sharing issues experienced	2.40
Trust issues experienced	2.33
Feelings of loneliness or isolation experienced	2.13
Challenges experienced with adapting to the new technology	2.00
Decrease in motivation level experienced	1.87

The greatest challenge was home interferences because of working from home. The second most prevalent challenge was communication issues caused by moving to fully online collaboration, and the third challenge was issues with building effective working relationships, especially with people the team members had not met in person previously. The other challenges were not experienced as often, as they had a total score of less than 50% (2.5 weighted average). Organisations that transfer their employees to working fully online because of a pandemic need to find ways to deal with these three challenges or minimise them if they want to maintain productive collaboration of team members.

4.3 Additional collaboration challenges experienced by project team members

The participants shared challenges they had experienced during the pandemic in addition to the ones already identified from the literature review. The thematic analysis process was followed to analyse the data collected. As an initial step in data analysis, the collected data was analysed repeatedly for familiarisation. Flick [23] mentions that interview data analysis entails three phases, namely data reduction, data reorganisation and data representation. The data was cleaned by discarding irrelevant information and organising it in a presentable manner. A process of generating codes, arranging them into categories and searching for themes was followed. Relevant data that was useful to identify additional collaboration challenges was extracted and codes were generated. Codes are generated to identify relevant parts of the data and present these in a meaningful and presentable way [20]. The codes generated were written in a way that would be understandable, as an identified challenge. To assess the quality of thematic analysis, it is crucial to take into account the extent to which the researcher has interrogated the generated codes [23]. The codes were reviewed repeatedly to ensure that they were a true representation of what was said by the interviewees and were organised into categories of similar codes to develop themes. The themes were reviewed to ensure that they were relevant to answer the research question. A name that defines a category of codes was given as a theme name for the different code categories. The given names were confirmed to ensure that they represented the collected data correctly [20], included all the codes and did in fact represent a challenge.

Six additional challenges were identified, namely work-life balance challenges, connectivity issues, many meetings, lack of discipline, emotional issues and absence of body language. The highest number of respondents identified the connectivity issue, i.e. 12 of 15 (80%)

interviewees indicated that they experienced connectivity issues while working online which interfered with their work and collaboration with their team members. In South African residential environments, some people do not have internet connections. Some have, but it is not stable in the areas where they live, which might be outside the network coverage. A study conducted [24] in South Africa reports various constraints in internet facilities, which include restrictions to certain network sites and very slow internet connection. Some people had to try different options until they were better connected. One of the interviewees also mentioned that it was difficult to get a solid internet connection for all the team members. Another factor that influences connectivity unavailability is load shedding. The electricity demand in South Africa has increased over the years, putting put a strain on the supply. Most of the country's population now has access to electricity [25]. The country's state-owned energy utility previously warned that it could not guarantee electricity supplies, and initiated load shedding which entails parts of the national grid being offline [26]. Load shedding resulted in most team members having connectivity issues or being unavailable for collaboration when needed.

Work-life balance challenges were also identified as an issue, and 46% of the interviewees mentioned that they were not able to find a balance between work and personal responsibilities when working from home, as they found themselves doing work even after working hours or when on leave. Some people mentioned that their team members expected them to be available all the time, meaning that there were no boundaries or knock-off times.

The other challenges identified were only experienced by a few people and are therefore not confirmed as valid challenges based on the total number of interviewees.

Organisations that move their employees to working fully online because of a pandemic need to devise strategies to deal with connectivity and work-life balance challenges or minimise them to maintain smooth collaboration between team members.

4.4 Strategies used to address the collaboration challenges

The literature review revealed some strategies to address the eight challenges as shown in Table 3. The identified strategies were used as a starting point for the interview questions. Interviewees were asked to indicate which strategies they also used in practice. An analysis was conducted to identify the strategies that were used by most of the interviewees. Data from each interviewee was analysed to identify those that used the listed strategies. For data accuracy, those interviewees who did not use the strategies were also identified. This was to ensure that the total responses equalled 15 (total number of interviewees) for each strategy. It was found that most of the interviewees used all the strategies, except for two, entailing trust issues and technology adoption issues:

- Trust issues: establish an email or message response time policy for emails, e.g. 48 hours.
- Technology adoption issues: provide training for online collaboration platforms, as well as online working.

It was also found that some of the interviewees did not experience most of the identified challenges as found in the literature, but used most of the identified strategies. In other words, they did not experience most of the challenges because they were already proactively using the identified strategies. It is therefore advisable for organisations in a similar situation to ensure that their employees are aware of the identified strategies and to encourage them to use these strategies to avoid the challenges. Home interferences, communication barriers and issues experienced with building effective online working relationships were found to be the challenges experienced by most of the interviewees. However, most of the interviewees had indicated that they used all the strategies that were identified in the literature to overcome these challenges. This indicates that the identified strategies might not be sufficient to address these challenges. It might also indicate that additional strategies are used which have not yet been identified.

4.5 Additional strategies used to address the collaboration challenges

A similar analysis process used for the additional challenges, as discussed in the previous section, was applied to the additional strategies identified. The interviewees mentioned strategies they used to deal with the additional challenges listed. Connectivity issues and work-life balance challenges were identified as additional challenges that were experienced by most of the interviewees. The two strategies that were identified for connectivity issues, namely 'get a better internet connection' and 'have a power backup plan', were used by most of the interviewees. Organisations can be advised to utilise these two strategies to avoid connectivity issues and maintain collaboration even when there are connectivity interruptions. The two strategies identified for creating work-life balance, namely 'set knock-off time' and 'switch off work notifications or equipment when on leave', were used by fewer people. Some of the interviewees also mentioned that they were still struggling with work-life balance and trying to find a way to deal with it. It is therefore advisable for organisations to prioritise this area and find ways to assist team members that are struggling. There is also a gap for future research to identify additional strategies to maintain work-life balance when working from home.

5 CONCLUSION

Based on the findings, the conclusion drawn is that a pandemic does impact project team members by forcing them to move from their normal collaboration platforms. It is therefore crucial for organisations to equip their employees with strategies that they can proactively use when they are transferred to online working. The five challenges experienced by most of the interviewees were home interferences, communication barriers, issues with building effective online working relationships, connectivity issues and work-life balance challenges. The findings confirm most of the mitigation strategies identified through the literature review for the challenges identified, except for work-life balance challenges. A confirmed challenge or strategy means that it has been experienced or used by at least 45% of the interviewees. Most people that experienced work-life balance issues were still struggling with this problem and had not found a way to deal with it. Organisations should therefore prioritise this area and find ways to assist team members that are struggling. There is also a gap for future research to identify additional strategies to maintain work-life balance when working from home.

The research study achieved the research objectives and all the research questions were answered. The impact of the pandemic on collaboration platforms, the challenges, as well as mitigation strategies were determined. The findings contribute to the existing knowledge on collaboration and provide additional insight into how to maintain collaboration during unforeseen circumstances. Project managers and team members will be better equipped for online collaboration. It is recommended that the findings be shared with project teams or any other teams moving to online working for them to proactively avoid challenges that might hinder effective online collaboration.

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SUSTAINABILITY TRANSITIONS AND THE AUTOMOTIVE INDUSTRY: A STRUCTURED REVIEW OF LITERATURE TO MAP THE CURRENT STATE

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ABSTRACT

Transport, and therefore also automotive manufacturers, contribute (either positively or negatively) to the transition towards increasingly sustainable ways of moving people and goods. Automotive manufacturing organisations are increasingly pressured to be more sustainable, and the guidelines for such 'sustainability' are becoming increasingly clear (i.e., ESG targets, etc.). However, the role of automotive manufacturers within the context of the sustainable transport transition is not yet fully explored. A vast amount of literature corresponds to the field of sustainability within the context of the automotive industry. However, literature related to the evaluation and contextualisation of the role of the automotive industry on the related sustainability transitions is limited. Consequently, this article presents a structured literature review regarding the role and impact of the automotive industry on sustainable mobility transitions.

Keywords: automotive industry, incumbent, sustainability transition, scoping review, socio-technical systems

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1 INTRODUCTION

The automotive industry is a critical sector in the global economy, contributing significantly to employment, income, and economic growth. However, the industry is also a significant contributor to environmental degradation, particularly regarding greenhouse gas emissions, resource depletion, and pollution [1]. Consequently, there is an urgent need to evaluate and contextualise the role of the automotive industry in related sustainability transitions.

This paper presents a scoping review that critically analyses the existing knowledge on the evaluation and contextualisation of the role of the automotive industry in sustainability transitions. The review explores the various approaches used to analyse, describe, or evaluate the industry's impact on sustainability transitions. The study also considers the contextual factors that influence the sustainability of the automotive industry, including regulatory policies, incumbent actors, consumer behaviour, and landscape-level changes.

Overall, this paper aims to provide a comprehensive overview of the current state of knowledge on the evaluation and contextualisation of the role of the automotive industry in sustainability transitions by identifying patterns and gaps in the existing literature and positioning intended contributions to the field of research. It plans to do so by answering the following research questions:

1. What are the main topics studied in the context of the automotive industry and the sustainable mobility transition?
2. Is there a trend in the number of publications?
3. Where has the research been conducted?

The remaining study is divided into four sections: Section 2 introduces essential themes in the research context and provides background information. Furthermore, in Section 3, the methodology used in this study is presented, followed by the results of the bibliometric analysis. This is followed by a comprehensive discussion of the study's results, culminating in a concluding synthesis of the findings.

2 CONTEXTUALISATION

The automotive industry is one of the most important and complex sectors of the global economy and is a major contributor to environmental degradation and climate change. The sector faces significant challenges in transitioning towards more sustainable modes of transportation, which requires fundamental changes in technology and behaviour [2, 3]. Scholars and policymakers have developed several models and frameworks to understand the dynamics of sustainability transitions in a system like the automotive industry. This chapter aims to provide a contextualisation of the key concepts and frameworks that underpin the study of sustainability transitions and the automotive industry.

Sustainability is an increasingly important concept in the face of global challenges such as climate change, resource depletion, and environmental degradation. The World Commission on Environment and Development [4] defined it as the ability of societies to meet the needs of the present without compromising the ability of future generations to meet their own needs. Sustainability involves a holistic approach that considers social, economic, and environmental factors and seeks to balance competing priorities and objectives.

Sustainability transitions, furthermore, refer to the fundamental transformation of socio-technical systems (STS) towards more sustainable outcomes [5]. STS are complex networks of actors, technologies, institutions, and norms that shape the development and evolution of industries and sectors over time. Sustainability transitions involve the co-evolution of technological and social elements and require changes at multiple levels, including individual, organisational, sectorial, and societal [6, 7].

The automotive industry, with its diverse network of actors and technologies, stands as an example of an STS. This industry encompasses an array of actors – auto manufacturers, parts suppliers, dealers, regulatory bodies, consumers, and non-governmental organisations. In terms of its economic scale, it's worth noting that, as of 2021, global car production accounted for over 80 million vehicles [8]. Hence, this industry is a major source of greenhouse gas emissions and air pollution, facing fundamental challenges in shifting towards sustainable transportation modes. The sustainability transitions within the automotive industry encompass shifts in technology and consumer behaviour, requiring concerted action across multiple sectors, including policy formulation, infrastructure development, and consumer behaviour modification [9].

Several frameworks have been applied to dissect the dynamics of sustainability transitions in the automotive industry, including the Multi-level Perspective (MLP) by Frank Geels [6], the Technological Innovation Systems (TIS), and the Strategic Niche Management (SNM).

The MLP provides a comprehensive analytical framework for understanding how transitions occur by examining the interactions between different levels of the system, including the niche level (where innovations emerge), the regime level (where dominant technologies and institutions are entrenched), and the landscape level (where broader societal trends and factors shape the context for change) [6].

On the other hand, the TIS framework pays attention to the complex interplay between different actors and institutions during technological innovation. This focus provides a deeper understanding of how sustainable technologies, such as electric vehicles, emerge and gain traction within the automotive industry [10].

Furthermore, the SNM approach focuses on the nurturing of 'niches' or protected spaces for novel technologies to mature without the pressures of market competition [11]. It offers valuable insights into how radical innovations can break through in the automotive industry and drive the transition towards sustainable transportation.

By using frameworks such as the ones mentioned above, researchers and practitioners can better understand and describe the drivers and barriers to change in a socio-technical system like the automotive industry and develop strategies to facilitate the transition towards more sustainable modes of transportation.

3 METHODOLOGY

To conduct this structured literature review, this paper adopted the framework introduced by [12]. The database Scopus was used as the literature base as well as a tool to analyse the bibliometric data. To identify relevant articles, this study utilised the following keywords:

Table 1: Keywords of the search string, including alternatives [author]

Keywords	Keyword Alternatives
automotive industry	"Automotive industry" OR "Automotive sector" OR "automotive sector" OR "automobile industry" OR "Automobile industry" OR "automobile sector" OR "Automobile sector" OR "automotive manufacturer" OR "Automotive manufacturer"
AND	
sustainable transition	"Sustainable transition" OR "sustainable transitions" OR "Sustainability transition" OR "sustainability transition" OR "sustainable mobility" OR "Sustainable mobility" OR "sustainable transport" OR "Sustainable transport" OR "Sustainable transportation" OR "sustainable transportation" OR "sociotechnical transition" OR "socio-technical transition" OR "socio technical transition"

The Preferred Reporting Items for Systematic Reviews (PRISMA) guidelines [13] were adhered to in conducting this study. In this literature review, no restriction was imposed on the commencement date in order to provide insight into how the role of the automotive industry has evolved over time and how this process has been covered in academic literature. However, the search was limited to publications until the end of 2022 to ensure the study's replicability. Using Scopus and the code presented earlier, 177 articles were identified, of which only 29 were deemed relevant and incorporated into the analysis. A visual representation of the selection process is shown in Figure 1.

The procedure for searching and selecting studies for this literature review was methodically delineated, as depicted in the flow diagram presented in Figure 1. The initial step (Identification) involved a comprehensive search on the Scopus database using the keywords specified in Table 1. This search yielded a total of 177 articles. In the subsequent step (Screening), the author meticulously screened the titles and abstracts of these articles based on their relevance to the review's topic. The criteria for inclusion at this stage were studies that either directly or indirectly addressed the role of the automotive industry within the context of sustainability. This screening culminated in excluding 121 articles, and an additional 17 articles were inaccessible. Moving to Step 3 (Eligibility), the remaining articles were subjected to an in-depth full-text evaluation. For inclusion, studies needed to discuss how the automotive industry either directly or indirectly facilitated the shift towards sustainability. This detailed assessment led to the exclusion of an additional ten studies.

Ultimately, a total of 29 studies met the set criteria and were consequently integrated into this review.

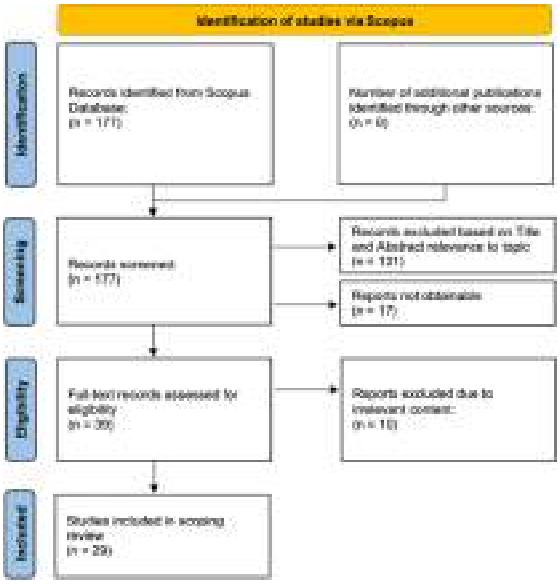

Figure 1: Flow diagram visualising the document selection process [author]

Data from the identified articles were systematically extracted and synthesised. The consolidation process focused on the overarching recurring theme of influential actors in the automotive sustainability context. Specifically, the primary categories of these actors emerged as incumbents, consumers, policymakers, and landscape-level events. These categories served as a lens through which the data from the studies were organised and interpreted.

The following sections will cover the bibliometric analysis (Step 4) and the further required analysis and discussion of the articles represented in Step 5 (charting, summarising, and reporting).

4 BIBLIOMETRIC ANALYSIS

A bibliometric analysis provided a comprehensive overview of the existing research landscape. This analysis examined the temporal trends by assessing the number of publications released each year. It also charted the geographical distribution of these publications based on country or territory, illuminating key research hubs globally. Additionally, the analysis categorised the literature by subject areas, highlighting the interdisciplinary nature of the topic and identifying dominant areas of scholarly focus. To further elucidate the thematic essence of the literature, a word cloud was generated, graphically representing the most frequently occurring and central keywords.

The bibliometric analysis shows that there has been a significant rise in interest in sustainability in relation to the automotive industry, particularly in recent years. This is evident from the sharp increase in publications over the past decade (visualised in Figure 2), which could be attributed to the growing recognition of the impact of climate change and sustainability concerns. For this study, only published literature up to the end of 2022 has been considered. No restriction was imposed on the commencement date.

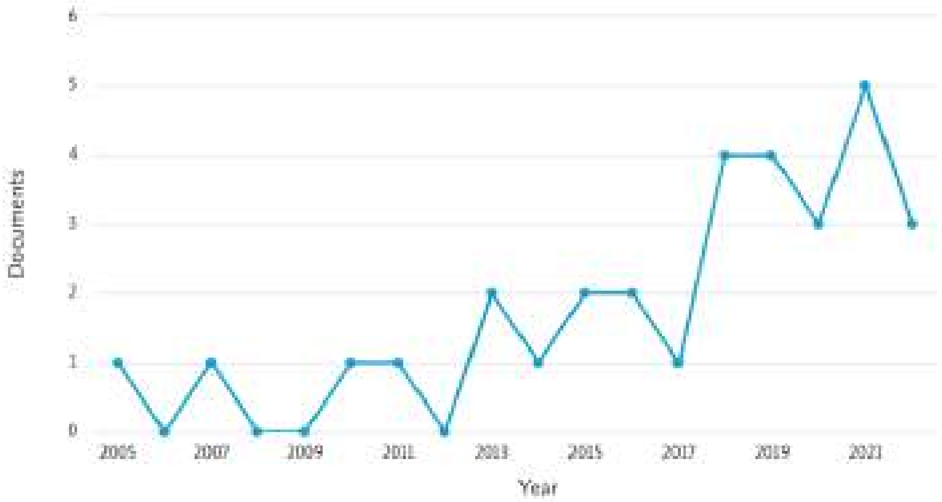

Figure 2: Number of publications by year [14]

Most published documents originate from developed countries such as the United Kingdom, Germany, and Italy, the top three publishing nations in this field. However, research activity has been markedly increased in developing countries like Brazil and China, as evidenced by their inclusion in the top 10 publishing countries, as shown in Figure 3.

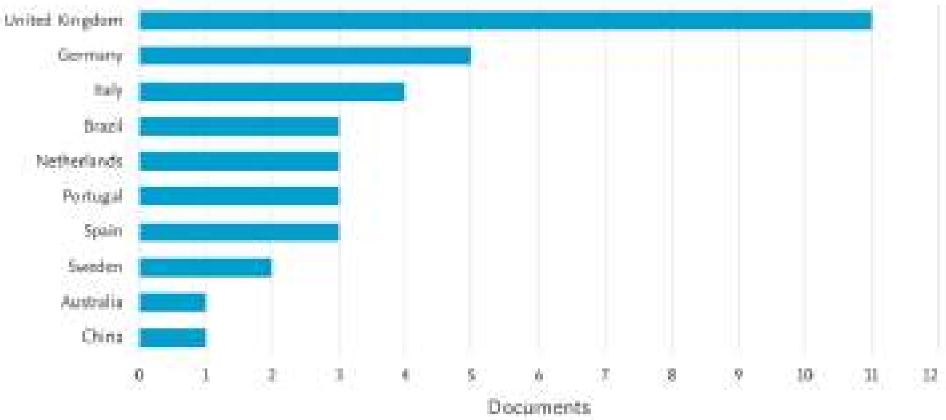

Figure 3: Number of publications by country or territory [14]

Figure 4 entails the subject areas in which articles have been published, including Business/Management (20.0%) and Engineering, Environmental Science, and Energy, covering 18.9% each, as the most prevalent. This trend could be attributed to the continuous advancements and innovative technologies in the engineering field. Additionally, the close association between environmental science, the energy sector, and the pursuit of sustainable solutions to combat climate change has played a significant role in the socio-technical transformation of the automotive industry.

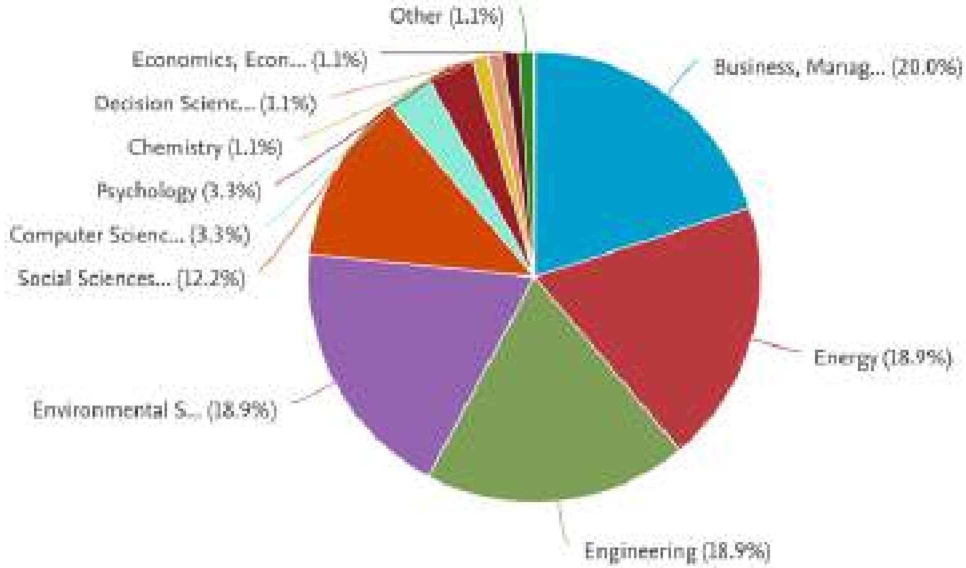

Figure 4: Fraction of documents by subject area [14]

The fifth figure depicts the most popular keywords mentioned in the articles under examination in this study and their significance in the frequency of mentions. The figure demonstrates that the core themes of this study are innovation, technology, transition, and policy.

Figure 5: Word cloud of most relevant keywords

Moreover, the figure shows that the term "innovation" is the most frequently mentioned keyword, indicating the importance of this concept in the context of sustainability transitions. The emphasis on innovation suggests a need for new and creative solutions to address the industry's challenges. Similarly, the significance of the terms "technology" and "transition" reflects the role of technological advancements in facilitating the transition towards a more sustainable future. The inclusion of the term "policy" also highlights the importance of government regulations and policies in driving change in the automotive industry. Overall, the figure provides valuable insights into the key themes and priorities for the industry and underscores the need for continued research and development in these areas.

5 CONTENT ANALYSIS

As suggested by bibliometric analysis, the literature on the role of the automotive industry in sustainable transitions is multidisciplinary, spanning engineering, business, and social sciences.

Within the field, it is widely acknowledged that, due to the complexity of the industry, a comprehensive, multi-level approach is imperative to elucidate the automotive industry's contribution to facilitating sustainability transitions [3, 15–17]. This approach should account for all the influencing factors that impact the overall shift toward a more sustainable mode of transport, incorporating the role of incumbent firms, policymakers, consumers (as representatives of the societal perspective), and landscape-level events.

Incumbent firms are an essential driving agent of sustainable transitions. The literature recognises that established firms can act as either a resisting/defending or driving/innovating force for sustainability [6]. Berggren et al. [3] provide a multi-level perspective of how established firms in the heavy vehicle industry act on various levels, including niche creation, niche protection, regime destabilisation, and regime reconfiguration. Similarly, Bohnsack et al. [18] showed how incumbents could drive sustainable innovation, specifically electric vehicles, by combining their technological capabilities, legitimacy, and market position. Krätzig et al. also highlight how German original equipment manufacturers (OEMs) can facilitate sustainable transition by adopting multi-level perspective that enables them to explore and exploit new opportunities, using the electric vehicle market as an example [16]. Furthermore, Magnusson and Werner [17] used organisation theory to extend the dimensions in which an incumbent regime-level actor can act in a sustainable transition and that they can drive sustainable innovations not only incrementally but also radically. They argue, though, that incumbent firms must respond proactively to sustainability transitions to survive and thrive [17]. According to Marletto [19], existing companies may be hesitant to adapt because they are deeply rooted in the existing car regime, utilising their current infrastructure and extensive knowledge of the dominant technology. An example of this behaviour can be seen in the case of the electric mobility company 'Better Place', examined by Sovacool et al. [20]. They argue that the company's failure was partly due to the defensive reaction of the incumbent automakers triggered by statements and actions of Better Place's CEO and the technological uncertainty at that time. Another topic discussed in the literature is the hype around hydrogen fuel cell technology and how incumbents' efforts affected sustainable transitions. Van Den Hoed [21] examined the motives and strategies of carmakers investing in fuel cell technology, suggesting that while they have invested significantly in the development, their commitment is often shaped by external factors such as policies, regulations, and market conditions rather than intrinsic motivation, which highlights the importance of government intervention in promoting sustainable technologies. Bakker [22], on the other hand, provides a critical perspective on the automotive industry's role in the hydrogen hype context. He argues that the sector has overhyped the potential of fuel cell technology and that the technology faces significant challenges. Furthermore, Bakker suggests that the hype around fuel cell technology has distracted attention and resources from other promising sustainable technologies, such as battery electric vehicles.

Several articles highlight the need for policy and regulation to create the necessary conditions for sustainable transportation, such as by setting emission standards, providing incentives for new sustainable innovations (like electric vehicles), and supporting the development of new technologies. For example, Nilsson and Nykvist [23] showed how governments can govern the electric vehicle transition by intervening in the market through regulations and incentives. In contrast, Alvarenga Santos et al. [24] argue that the internal combustion engine can still play a significant role in the transition towards sustainable transport when combined with biofuels and suggest that policies should support the use of alternative fuels instead of only focusing on one technology. Moreover, Hopking and Schwanen [25] argued that governments could influence the development and deployment of automated mobility technologies, presenting the UK automotive industry as a case study. They noted that the UK's government's approach to automated mobility has been reactive, fragmented, and focused solely on technical solutions. The authors suggest that governments need to develop more proactive and strategic approaches that address social as well as environmental concerns. Skeete [26] supported the importance of regulation by examining the dominance of incumbent automakers and suppliers in automotive socio-technical transitions and the role of policy in shaping these transitions.

Consumers' values and preferences can also shape demand for sustainable technologies, products, and services. Moragdinho et al. [27] take a consumer perspective in their study. The authors analyse European consumers' perception of the automotive industry's contribution to reducing greenhouse gas emissions. The study found that consumers have limited knowledge about the automotive industry's efforts towards sustainability and that firms need to communicate more transparently to enhance the adoption of sustainable technologies. Schwedes et al. [28] chose a similar approach by examining the public perception of electric vehicles in Germany, emphasising the role of customer demands in driving sustainable transitions. The article also highlights the need for more effective communication and education to increase public acceptance of electric vehicles and new technologies in general. Higueras-Castillo et al. [29] explored the role of perceived value in customer adoption of electric and hybrid vehicles. They found that perceived value, including financial, functional, social, and environmental value, influences consumers' adoption decisions. Dalla Chiara and Pellicelli's [30] approach points in a similar direction highlighting how the automotive industry can contribute to sustainable road transport by producing products and services that focus on the changing needs and preferences and therefore considers energy and modern society perspectives. Leviäkangas and Ahonen [31] suggest that when consumers learn more about the effects and implications of the services they utilise, their actions and willingness to adopt new technology could be influenced. This reinforces the importance of prioritising the evolving needs of this group.

Another driving force identified by the literature is landscape-level events. Landscape-level events are non-human-induced events that can significantly influence the development and adoption of sustainable technologies [32]. Marletto [19] explored the role of structure, agency, and change in the car regime. She showed how landscape-level events, such as the 1973 oil crisis and environmental regulations, have influenced the development and adoption of sustainable technologies. De Stefano et al. [33] argue that a natural resource-based view of a landscape-level event, such as climate change, can help identify the innovation challenges the automobile industry faces in accomplishing sustainable mobility. The authors reason that the automobile industry is particularly reliant on materials and energy, making it essential to identify innovations that reduce their use. Another significant landscape-level event can be seen in the Volkswagen diesel scandal (Diesel-gate). Andersen et al. [15] explored its implications on the automotive industry's technological response options. They noted that the scandal had triggered a shift towards electric and hybrid vehicles and increased scrutiny of diesel engine emissions. Furthermore, the authors state that it deeply harmed the trust between policymakers and incumbent firms. Additionally, Wang and Wells [32] discussed automobility after the SARS-CoV-2-Pandemic, arguing that the pandemic's social and behavioural changes could have a significant impact on the future of sustainable mobility transitions, providing a lot of rare data and the opportunity to gain insight into the consequences of a major landscape-level event. Marx et al. [34] take a landscape-level approach by analysing the interaction between landscape-level events, such as urbanisation and climate change, and the strategies of firms trying to cope with these system changes. They suggest that firms should consider the broader social-economic contexts when developing sustainable strategies. Furthermore, they criticise the multi-level perspective framework for not considering the spatial context of a socio-technical system.

Finally, the review has identified various frameworks used and introduced by the authors to understand sustainable transitions. For example, Magnusson and Werner [17] proposed a framework conceptualising incumbent firms in sustainability transitions, drawing on organisation theory. Their framework conceptualises incumbents as multi-level actors instead of being only defensive and path-dependent, as suggested by Frank Geels [6] in his 'Multi-level Perspective Framework'. Berggren et al. [3] also use a multi-level perspective to examine established firms as multi-level actors in the heavy vehicle industry. So did Wu et al. [35] to develop a socio-technical transition path for new energy vehicles (NEV) in China. A different approach to the topic was introduced by Vergragt and Brown [36], who present a framework for sustainable mobility that emphasises the need for societal learning and transformative change. Moreover, De Stefano et al. [33] use a natural resource-based view framework to study how the automotive industry is dealing with the challenges of climate change. They offer a method for looking into how the availability of natural resources affects how businesses respond to this issue.

6 DISCUSSION

The literature highlights several key insights about the multifaceted role of the automotive industry in sustainable transitions. It confirms that sustainable transitions are multi-dimensional and require a comprehensive, multi-level approach to understanding them by acknowledging various influencing factors.

The literature underscores the ambivalent role of incumbent firms within sustainability transitions. They have the capacity to either resist and defend the status quo due to existing infrastructure and investment in current technologies or act as driving and innovative forces for sustainability through their market position and technological capabilities [6].

Established firms can influence sustainable innovation incrementally and radically to drive the transition of a socio-technical system, like the automotive industry, towards sustainability. However, it is also clear that they may resist change due to deep entrenchments within the existing regime, which then hinders the progress of innovative and sustainable technologies, such as hydrogen fuel cells or electric vehicles, particularly when incumbent firms overhype or fail to commit to such technologies [3, 6, 16–22].

Similarly, policy and regulation are found to be instrumental in promoting sustainability transitions. According to several sources, policies can directly influence the course of sustainable transitions by setting emission standards, providing incentives for sustainable innovation, and supporting new technology development [23, 25, 26]. However, the literature also indicates that a single-technology focus may not be sufficient, and policies should support a range of sustainable technologies [24].

The literature also highlights the consumer perspective as significant in shaping the demand for sustainable technologies. Consumers' perceptions and knowledge about the automotive industry's sustainability efforts directly influence the adoption of these technologies [27–31]. As such, companies must effectively communicate their sustainability efforts and align their offerings with consumers' changing needs and preferences [28, 31].

Furthermore, landscape-level events, such as the oil crisis, environmental regulations, and significant scandals, have been found to influence the course of sustainable transitions drastically [15, 19, 32–34]. These events can spur changes in industry practices and policies, emphasising the need for companies to be adaptable and resilient.

Lastly, the literature demonstrates the use of various frameworks to understand and navigate sustainable transitions, highlighting the complexity of these transitions. It emphasises the need for comprehensive approaches that consider all influencing factors, including incumbent firms, policymakers, consumers, and the landscape level. These frameworks underscore the importance of considering the broader context of a system when developing strategies for sustainable transitions.

7 CONCLUSION

According to this study, recent years have increased interest in this topic. Most cited sources pertain to technology, engineering, and innovation but can also apply to various industries.

Many authors have stated that even though people have tried to measure and understand the role of the automotive industry in sustainable transitions, it is regrettable that the results still need to catch up to expectations [3, 6, 17, 19, 34]. Thus, future studies could further examine the role of the automotive industry by, for example, utilising and extending the frameworks identified in this study or introducing a completely new approach to the field. Furthermore, the bibliometric analysis revealed that research in this field focused on the automotive industry in developed countries. Therefore, future research could instead focus on developing countries, examining whether the utilised frameworks are similarly applicable in different contexts or whether different spatial contexts require adjustments of existing frameworks or the development of entirely new ones.

This research contributes to understanding how the automotive industry plays a part in sustainability transitions and which other factors need to be considered. The findings can assist researchers and practitioners in comprehending and tackling the key areas to concentrate on or contemplate when evaluating the automotive industry's role in sustainability transitions. By identifying these areas or influential factors, this study can serve as a starting point for addressing them and enhancing the body of knowledge and organisations' effectiveness.

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EMPLOYEE ACCEPTANCE OF REMOTE WORK

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ABSTRACT

The development of Information and Communication Technologies caused an increase of remote work. This was followed by COVID pandemic which encouraged businesses to use it in even larger scale. However, not all employees accepted that change well. Previous studies indicated that employees feel more stressed and in conflict at their remote workstations when they had to telework during the lockdown, and that this negative output was significantly related to the deterioration of some work dimensions like SPACE, QUALITY and DESIGN proposed by Rymaniak et al.[1]. This current article presents the results of a research carried out in Lithuania regarding remote work acceptance by employees. Research results lead to employee profiles which define conditions for better acceptance and less resistance in workplace environment changes. This helps to identify necessary measures for employee's education, preparation for changes or other type of managerial solutions in order to increase productivity.

Keywords: Remote Work, Distant work, Virtual work, Telework, Workplace, Employee profile, Change acceptance, Change management

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1 INTRODUCTION:

The advent of Information and Communication Technologies has led to an increase in remote work. The pandemic further accelerated this trend, prompting businesses to adopt remote work on a larger scale. However, not all employees embraced this change positively. According to a previous study conducted during the lockdown, employees experienced higher levels of stress and conflict while working remotely, resulting in a decline in various work aspects such as workspace, quality, and design[1]. In a US study on working forms, it was found that 9 out of 10 virtual workers want to continue with this form of work after the pandemic ended, and only 9% would like to return to traditional offices [2], [3]. However, some companies are discussing quality and efficiency of this form with regard to coming back to traditional work places. This article presents the findings of a research conducted in Lithuania that focuses on the acceptance of remote work among employees and behavior specifics. The research outcomes provide employee profiles that outline the peculiarities. Such profiling aids in identifying necessary measures for employee education, preparation for changes, or other managerial solutions aimed at enhancing productivity. The research results empirically demonstrate the opinions of employees. The research approach involves literature review, analysis, and synthesis on the subject. The data was collected from an online survey conducted among employees and analysed with descriptive and multidimensional statistics.

2 REMOTE WORK IN CHANGING ENVIRONMENT: LITERATURE REVIEW

Information and communication technologies (ICT) has caused the new forms of work called virtual teams. The use of virtual teams is important for organizations because they allow team members to communicate despite distance and time constraints. They allow organizations to hire the most talented people regardless of the location, which will increase the efficiency of the team [4].

However, Virtual team work, sometimes called remote work or Telework was usually acceptable on a voluntary basis, but they stopped being acceptance-based due to the lockdowns[5], [6]. There is a previously detected deficiency in literature in remote work research from the perspective of the organisation and management [7], which is emphasised by the appearance of the new and unique conditions of the pandemic and lockdown, and a resulting deficiency of appropriate research in scope of theory and accumulated practical experience. So the global pandemic lead to a situation that most of the employees had to adapt to new ways of working.

There come 3 terms such as virtual teams, telework and remote work. In the contest of research it means that they are considered as synonymous despite the fact that in literature these can be found as definitions for different phenomenon's. VT is defined as "*Virtual team work is an alternative work arrangement in which employees perform tasks at a location other than their regular primary or central workplace, working at least part of their work schedule using electronic media to communicate with others inside and outside the organization.*" ([8]). The term telework was originally coined in 1973 by Jack Nilles and discussed as an activity which "*includes all work-related substitutions of telecommunications and related information technologies for travel*"[9]. Remote work is defined as "*a flexible employment setup in which individuals carry out their tasks from locations that are separate from their main office or production sites. In this arrangement, workers do not have face-to-face interactions with their colleagues, but they can effectively communicate with them through the use of technology.*"[10].

The authors identified several factors that affect Employee Acceptance of Remote Work. Employee acceptance of remote work is influenced by several factors, including flexibility, work-life balance, autonomy, trust, job characteristics, technological infrastructure, and social support [3], [5], [11]–[14]. According to the findings of Hislop, Axtell, and Daniels [1],

[15], telework comprises five key elements: the physical work location, the level of ICT (Information and Communication Technologies) usage in the work process, the extent of communication with external individuals, the level of communication with colleagues and supervisors within the organization, and the knowledge intensity involved in the work.

The concept of remote work has been viewed as mutually beneficial for both organizations and employees, creating a win-win situation. For instance, the theory of the flexible firm highlights the importance of adjusting work hours and the workforce size (numerical flexibility) as well as diversifying employees' skill sets (functional flexibility) to effectively adapt to changes in production levels and technologies [1], [16]. Organizations recognize the significance of utilizing virtual teams as they enable seamless communication among team members, overcoming challenges posed by geographical separation and time limitations. This approach also empowers organizations to recruit the most skilled individuals without being restricted by their physical location, thereby enhancing team efficiency [17], [18]. Organizations aiming to implement remote work successfully should consider these factors and tailor their strategies accordingly. By understanding and addressing employees' concerns and needs, organizations can enhance acceptance, productivity, and overall well-being in remote work environments. It is important to note that individual preferences and organizational contexts may vary, so ongoing research and adaptation of best practices are essential for optimizing remote work arrangements.

Scholars analyses the influence of demographic factors on remote work acceptance, however most of the research questions were targeted to psychological aspects. For example: aspects including remote work impact on work-life balance, job satisfaction, and organizational outcomes taking in consideration gender dynamics analysed by Shockley K, Allen T and coauthors [19]; Sabine Sonnentag's with colleagues focuses on work-related recovery, job stress, and the interface between work and non-work life [20], [21]. Discussions on age-related perceptions of remote work explore such topics as the role of personality, age, and organizational support in remote work success, and remote work impact on creativity and innovation[22]–[24]. Golden has researched how factors like individual characteristics, including age and gender, interact with remote work arrangements [22].

In this article, we focused on tasks and how employees perform in the context of changes. Are there any conflicts like for example rising new technologies or changing environment can cause personal conflicts. The idea came from other studies, where diversity of ICT, culture, team size, and task function all are determinants of task and relationship conflict between team members[17], [24], [25]. Remote work involves a mix of topics, including psychology, organizational behavior, technology, communication, and more. This interdisciplinary nature led to research being conducted across different fields, but still fragmented, and missing significant knowledge about latest employee experiences and perceptions. The question what effects and in what range the remote work is forced are still missing. The focus is on some correlations and dependencies having in mind employees age, gender, working experience or type of organization.

3 RESEARCH METHODOLOGY

The research aimed to collect quantitative data and employee opinions concerning remote work challenges and opportunities, as well as their various aspects, including efficiency. During the study, the motivation to quickly adapt to changing requirements, the speed of a person to take action whenever there is an opportunity, the analysis of various options to improve the work process depending on age, length of service, gender and type of organization were evaluated.

The data for this study were collected from an online survey questionnaire sent to remote employees in Lithuania. It was held in 2022, after the pandemic. The data collecting was in October; a sample of 166 responses were reached. However necessary amount of respondents was not reached, so confidence level is 80 percent while margin of error is 5 percent. The roughly similar group sizes considered as an advancement ensuring balanced statistical power across groups.

The Kruskal-Wallis test was used to identify statistically significant differences in assessment between all groups. The Kruskal-Wallis test is a non-parametric statistical test used to compare three or more independent groups to determine if there are statistically significant differences among their population distributions.

After identifying the differences between the evaluations of all groups, the Mann-Whitney test was additionally applied to identify statistically significant differences in evaluation between pairs. The Mann-Whitney U test, also known as the Wilcoxon rank-sum test, is a non-parametric statistical test used to compare two independent groups and determine if there are statistically significant differences between their population distributions.

This article presents the results of evaluating the statements: "I act quickly when I see an opportunity for change", "Changing requirements motivate me to adapt quickly" and "I analyze various options to improve the work process". Dependence on age, length of service, gender or type of organization was tested.

Data were coded in order to simplify the representation: Educational organizations are denoted by the word "Education", manufacturers are denoted by the abbreviation "Manufact", trading organizations - "Retail", organizations providing services to businesses "Serv2B", organizations providing services to end users "Serv2C", and Public organizations „Public".

4 RESULTS AND DISCUSION

Figure 1 presents the attitudes and perceptions of surveyed employees and their reaction to work conditions changes.

Despite the lack of statistically significant correlations (see the tables for values) with age, gender, or length of service, the obtained results are intriguing. Notably, employees consistently demonstrate a tendency to adapt, acquire new skills, innovate processes, and enhance working conditions across various cases. Conversely, younger and less experienced individuals exhibit a higher likelihood of hesitating or disagreeing with such statements. It is plausible to anticipate that individuals with more work experience would be the actors who will offer improvement of processes. However, it is crucial to investigate in future whether the changes would initiate the reactions of younger and less experienced employees pertain specifically to the workplace or to other decisions like changing position or employer. Furthermore, it is worth highlighting that both men and women, who hold equivalent positions, provide highly comparable responses.

Figure 1: Employees survey results, where significant relations are not detected

The study showed that statistically significant evaluations of the statement "I quickly take action as soon as I see the possibility of change" are not observed depending on age, length of service, gender or type of organization.

Meanwhile, the evaluations of the statements "Changing requirements motivate me to adapt quickly" and "I analyze various options to improve the work process" differ significantly only depending on the type of organization, see Tables 1,2,3, and 4. No statistically significant differences were observed in the evaluations either in the case of age, gender, or length of service.

Table 1: Mean Rank of employees behaviour and reactions during remote work (CRMA)

Ranks			
	Organization	N	Mean Rank
CRMA	Education	61	91,71
	Manufacturing	8	83,50
	Retail	14	63,82
	Serv2B	33	100,27
	Serv2C	14	65,18
	Public	35	66,21
	Total	165	

Table 2: Kruskal-Wallis test results (CRMA)

Test Statistics[a,b]	
	CRMA
Kruskal-Wallis H	17,295
df	5
Asymp. Sig.	0,004
a Kruskal Wallis Test	

Table 3: Mean Rank of employees behaviour and reactions during remote work (ADO)

Ranks			
	Organization	N	Mean Rank
ADO	Education	61	83,33
	Manufacturing	8	80,31
	Retail	14	59,25
	Serv2B	32	94,67
	Serv2C	14	56,07
	Public	35	90,30
	Total	164	

Table 4: Kruskal-Wallis (CRMA)

Test Statisticsa,b	
	ADO
Kruskal-Wallis H	14,501
df	5
Asymp. Sig.	0,013
a. Kruskal Wallis Test	
b. Grouping Variable: Organization	

Analyzing the differences in assessment for the statement "Changing requirements motivate me to adapt quickly" between pairs of organizations (see table 5), we see that the statistically significant differences are observed in assessments of education-retail, education-serv2C, education-public, retail-education, retail-serv2B, serv2C-serv2B, serv2B-public.

Meanwhile, when analyzing the differences in evaluation for the statement "I analyze various options to improve the work process", statistically significant differences are observed in pairs education-retail, education-serv2C, retail-serv2B, retail-public, serv2B-serv2C, serv2C-public (see table 6).

Table 5: Mann-Whitney test (Changing requirements motivate me to adapt quickly)

		Education	Manufact	Retail	Serv2B	Serv2C	Public
Education	Mann-Witney U		214,500	280,500	893,000	293,000	732,500
	Wicoxon W		250,500	385,500	2783,000	398,000	1362,500
	Z		-0,618	-2,185	-0,996	-1,987	-2,753
	Asymp. Sig. (2-tailed)		0,537	0,029	0,319	0,047	0,006
Manufact	Mann-Witney U			40,500	100,000	41,500	104,500
	Wicoxon W			145,500	136,000	146,500	734,500
	Z			-1,163	-1,171	-1,059	-1,192
	Asymp. Sig. (2-tailed)			0,245	0,242	0,289	0,233
Retail	Mann-Witney U				130,500	97,500	238,500
	Wicoxon W				235,500	202,500	343,500
	Z				-2,535	-0,024	-0,153
	Asymp. Sig. (2-tailed)				0,011	0,981	0,878
Serv2B	Mann-Witney U					139,500	345,000
	Wicoxon W					244,500	975,00
	Z					-2,285	-3,038
	Asymp. Sig. (2-tailed)					0,022	0,002
Serv2C	Mann-Witney U						236,000
	Wicoxon W						341,00
	Z						-0,210
	Asymp. Sig. (2-tailed)						0,833
Public	Mann-Witney U						
	Wicoxon W						
	Z						
	Asymp. Sig. (2-tailed)						

Table 6: Mann-Whitney test (I analyze various options to improve the work process)

		Education	Manufact	Retail	Serv2B	Serv2C	Public
Education	Mann-Witney U		234,500	299,500	840,000	286,000	976,000
	Wicoxon W		270,500	404,500	2731,000	391,000	2867,000
	Z		-0,213	-2,052	-1,345	-2,178	-,827
	Asymp. Sig. (2-tailed)		0,831	0,040	0,179	0,029	0,408
Manufact	Mann-Witney U			41,000	104,500	38,000	122,500
	Wicoxon W			146,000	140,500	143,000	158,500
	Z			-1,172	-0,986	-1,297	-0,635
	Asymp. Sig. (2-tailed)			0,241	0,324	0,195	0,525
Retail	Mann-Witney U				123,500	86,500	151,000
	Wicoxon W				228,500	191,500	256,000
	Z				-2,895	-0,565	-2,392
	Asymp. Sig. (2-tailed)				0,004	0,572	0,017
Serv2B	Mann-Witney U					123,500	531,000
	Wicoxon W					228,500	1161,000-
	Z					-2,704	0,439
	Asymp. Sig. (2-tailed)					0,007	0,661
Serv2C	Mann-Witney U						146,000
	Wicoxon W						251,000
	Z						-2,400
	Asymp. Sig. (2-tailed)						0,016
Public	Mann-Witney U						
	Wicoxon W						
	Z						
	Asymp. Sig. (2-tailed)						

The observed results are quite interesting and somewhat unexpected, as they show that the differences between how changing demands motivate people to adapt quickly and whether people tend to analyze different options to improve the work process do not depend on personal characteristics such as gender or age, but on which organization they work for.

This, in turn, leads to the conclusion that the readiness to change in the face of external (pushing) circumstances is determined by internal factors of the organization, such as e.g. organizational culture, which means that it can be managed. It should also be emphasized that the first statement "I quickly take action when I see the possibility of change" presupposes a voluntary action or initiative, and most of the evaluations are concentrated above the tag "neutral evaluation", that is, the majority of respondents evaluate this statement positively without clear differences in terms of signs and belonging to a specific category of organizations. Meanwhile, the second statement "Changing requirements motivate me to adapt quickly" emphasizes that the necessity of changes during adaptation is determined by external factors such as requirements, while the third one emphasizes more the constant state and readiness to improve the work process. In both cases, despite the overwhelming majority of positive evaluations, differences in the distribution of evaluations are already visible, as mentioned above, depending on the affiliation of the respondents to a certain category of organizations.

In conclusion, it can be said that employees in different organizations are not equally ready to change, both in the face of external pressure and on a permanent basis. The fact that differences occur precisely because of the nature of organizations suggests that the reasons lie in internal factors of organizations, such as organizational culture. In order to gain a deeper understanding of this phenomenon, additional research is necessary to evaluate the internal factors of organizations for the readiness of employees to change.

5 CONCLUSION

After research and results analysis presented by descriptive statistics, more insights and evidence for virtual teams' employees' motivation in terms of changing environment were identified. Employees age, gender, working experience and type of organization were the main focus of the survey trying to extend knowledge on dependency of the reactions and actions in context of changes in remote work, is this motivating to adopt or to search for the work process improvement. Remarkably, employees consistently exhibit a proclivity for adaptability, skill acquisition, process innovation, and improvement of working conditions across multiple instances. Conversely, individuals who are younger and possess less experience display a greater inclination towards transitioning between organizations.

It can be concluded that employees across different organizations exhibit varying levels of readiness to embrace change, both in response to external pressures and on a consistent basis. The existence of such differences, particularly influenced by organizational characteristics, implies that internal factors within organizations, such as organizational culture, play a significant role. To gain a more comprehensive understanding of this phenomenon, further research is needed to assess the internal factors within organizations that impact employees' readiness for change.

A limitation of this study worth mentioning is the inconsistency in the sample composition regarding the age groups. Nevertheless, the primary objectives of the exploratory study were successfully achieved.

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USING OPTICAL METROLOGY IN INJECTION MOULDING

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ABSTRACT

Suitable Quality control is integral in injection moulding to ensure that poor-quality products are monitored and controlled. Developments in optical metrology promise more accurate measurements and faster turnaround times in quality control checks than current tactile measurements. This study investigates the efficacy of optical metrological devices as a quality control tool for injection moulding. The study adopts a quantitative and experimental research design. Measurements of 4 different injection moulded products were taken, these measurements include different variables of each product. Tests were conducted on 2 samples of each product, utilising a 3-D scanner and contact measuring devices, such as a vernier and a coordinate-measuring machine. The validity of the experiment was through the calibration of all measuring equipment utilised. The repeatability and reproducibility method were used to measure the reliability of the data. The results of this study have shown that the use of a 3-D scanner as a measuring device for routine quality control testing is not efficient or effective in injection moulded products. The output of this study contributes to the knowledge of the use of optical metrology in injection moulding and its comparison to tactile metrology.

Keywords: injection moulding, quality, optical metrology

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1 INTRODUCTION

Injection moulding is one of the most common and preferred methods of converting polymers into finished products [1]. The injection moulding process is used to create an array of products. Plastic injection moulded products are widely used in the food, beverage, chemical, medical, automotive, electronics and textile industries. Injection moulded plastic products include items such as tubs, bottles, jars, closures, drums, electronic casings, combs, automotive interiors, and machine parts. Plastic injection moulded products are used in the food, beverage, and chemical industries because they can be hygienic, lightweight and impervious. Quality control is an integral process to monitor and control defective or poor-quality products. Each injection moulded product has a set of variables and attributes that needs to be achieved and maintained. The dimensions of manufactured products must have accurate dimensions. It is essential, especially if the product has different components that fit together to create an assembled one, for example, a tub and a lid that fit together. To mitigate defective or poor-quality products, routine quality testing is conducted on the injection moulded products that are manufactured [2]. There are a variety of variable attribute tests that are conducted on injection moulded products, which are dependent on the type of product manufactured, functionality of the product and the type of material utilised in the manufacturing process. These quality tests on the manufactured products may include but are not limited to, the weight of the product, dimensions (height, diameter, breadth, width) and thickness.

The most commonly used tools for the measurement of finished products are contact measuring devices. These include both tactile and mechanical measuring tools. Tactile metrology is a science that consists of a probe that is in contact with the surface to take measurements of the product. Optical metrology is the science and technology that utilises light for measurements [3]. Developments in optical metrology promise more accurate measurements and faster turnaround times for quality control than current tactile measurements [4]. In the last few years, manufacturers have been increasingly using 3-D laser scanners, white light scanners, and laser trackers for dimensional metrology. Newer optical scanners are steadily gathering more confidence from manufacturers because they are touted to be more versatile, portable, faster and have more accurate outputs [4].

With the rise in demand by consumers for the use of injection moulded products in the plastic manufacturing industry, there is an increased demand for manufacturers to produce quality products at a faster output. Over the years, there has also been an increased demand for the complexity of the design of injection moulded products which has resulted in the design of more convoluted moulds and products. The increase in the complexity of the design of injection moulded products has resulted in the need for more accurate and quicker measurement methods and instruments [5].

This study investigated the use of optical metrology as an alternative tool of measurement in injection moulded products and to determine the efficacy of a 3-D scanner as a quality check tool on injection moulded plastic products. Measurements of 4 different plastic injection moulded products (closures and tubs) were undertaken. These measurements consisted of 4 different attributes of the closures and 3 different attributes of the tubs. Tests were conducted on 2 samples of each product, utilising a 3D scanner and contact measuring devices, such as a vernier and a coordinate measuring machine (CMM).

Optical metrology has been widely utilised as a tool of measurement in the aeronautical and automotive industries. However, there are no studies or research available on the use of optical metrology in injection moulded products. This study is unique as the results of this study will enable an understanding of the use of optical metrology in injection moulded products and if they provide any advantages over the use of tactile measuring devices in injection moulded products.

2 METHODOLOGY

The experimental framework of this study was based on the use of 3-D optical metrological equipment and contact measuring equipment as measurement devices on injection moulded plastic products. Quality checks (measurements) conducted on the samples collected, used both optical and tactile metrological equipment. The extrapolated data was analysed to determine if the use of optical metrological equipment on injection moulded products may add value to the process of measurement during routine quality checks.

The study adopted a quantitative and experimental research design methodology [6].

A probability, simple random type of sampling was utilised [7]. The samples used in this study consisted of injection moulded products manufactured by a plastic manufacturer in South Africa. A data list of all injection moulded products was created. The products used in this study were then randomly selected from the list and were manufactured on four different types of injection moulding machines. The samples selected were a 38mm C3 closure (sample A) as depicted in Figure 1, a 250ml tub (sample B) as depicted in Figure 2, a 125ml tub (sample C) as depicted in Figure 3 and a 1 kg tub (sample D) as depicted in Figure 4. Two samples were selected for each product.

Figure 1: Sample A 1 and A 2: 38mm C3 Closure

Figure 2: Sample B1 and B2: 250ml tub

Figure 3: Sample C1 & C2: 125ml Tub

Figure 4: Sample D1 & D2: 1kg Tub

Data sets were taken from measurements of injection moulded products, using a tactile probe measurement (vernier and coordinate measuring machine) and a blue-light 3-D Scanner. The data from both sets were analysed and a comparative study was conducted to determine if there are any benefits to the use of optical metrology as a measurement device during routine quality checks on injection moulded plastic products.

The 3-D scanner utilised both infrared and blue laser technology. The technology utilised a parallel infrared laser for scanning large surface areas. The parallel blue laser crosses were used for fast scanning or quick scanning and the single blue laser was used for the scanning of objects that have depth or deep holes. As per the manufacturing specifications of the 3-D scanner, the scanner is touted as having a scanning accuracy of 0.02mm and 0.03mm/m of volume accuracy. As shown in Figure 5, before the commencement of the scanning with the 3-D scanner, the samples were prepared by placing laser markers on the individual products.

Figure 5: Samples prepared with laser markers

Laser markers were required for the handheld 3D scanner as it provided dedicated laser points or reference points on the samples scanned, which facilitated accurate measurements of the samples. The laser markers were dots that contained a special coating that rendered them retro-reflective. Once the samples were prepared with the laser markers, the 3-D scanner was calibrated. Calibration was required each time the scanner was switched on.

The 3-D scanner was calibrated, using a calibration board and the appropriate scanning software. As shown in Figure 6, the calibration process included aligning the 3-D scanner with both the circle and trapeze shape on the scanning software.

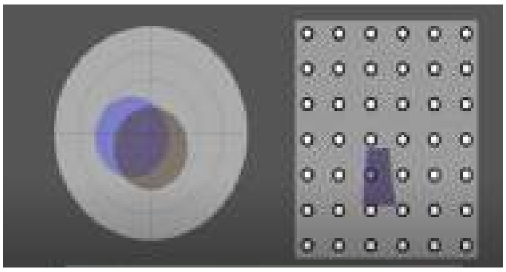

Figure 6: Calibration of the 3-D Scanner.

Once the circle and trapeze shapes had been aligned with the 3-D scanner, the calibration accuracy was calculated. Once the 3-D scanner was calibrated, the surface, where the sample was to be scanned, was set up with laser markers. The surface with the laser markers, was then scanned to set up the outer parameters within which the samples were scanned. The parameter settings contained different advanced settings options. The parameter setting selected was dependent on the type of sample that was scanned.

Once the applicable parameters were set up, the samples were scanned, using the 3-D scanner in conjunction with the 3-D scanner software. The scanned image from 3-D scanner software was then imported into a second software program. The original Computer-Aided Design (CAD) drawing of the product was also imported into the second software program. The 3-D scanned image was then aligned to the original CAD drawing on the second software program. Several surface points were then plotted onto the aligned drawings where points on the scanned image and the CAD drawing were calculated to determine if there were any deviations along those points, between the scanned image of the product and the CAD drawing.

The second metrological equipment utilised in this study was a vernier. Before commencing with the measurement, the sample products were visually inspected to ensure that there were no damages to the sample products (i.e., no high or low spots on the sample products), all measuring surfaces were 100% flat and the measuring surfaces of the sample products were sturdy. All measurements conducted were repeated to verify accuracy. Each sample was measured a total of 10 times for each variable.

The third metrological equipment utilised in this study was a coordinate-measuring machine (CMM). The CMM took readings in six degrees of freedom and presented these readings in a mathematical form. The CMM measured the physical geometrical characteristics of the samples. This machine was computer-controlled, using the software. A probe attached to the third-moving axis of the CMM was utilised for the measurements. Products or components were placed on the measurement table into a fixture that secured the product to ensure it did not move during the measurement cycle. The type of fixture used during the tests was dependent on the type of sample that was measured. A generic fixture was used for samples B, C and D, and a vacuum fixture was used for sample A. The products were then measured using the touch probe.

All measuring equipment utilised in the study was calibrated prior to use. This ensured the accuracy of the instrument and that the measuring instrument measured what it was designed to measure. Repeatability and reproducibility methods were used to determine the reliability of the data obtained from the tests conducted in the study. Repeatability was conducted with the same experiment, same person, and same setup of the experiments on the same day to determine if it yields similar results.

Each sample was measured a total of 10 times for all 3 measuring devices.

3 RESULTS AND DISCUSSION

There were 10 images for each sample scanned by the 3-D scanner (due to the critical quality variables for samples A1 & A2 being located on both the inside and outside, these samples were scanned 10 times on both the inside and outside of the sample), resulting in a total of 100 scanned images captured. Figures 7 – 11 are 4 images from the 3-D scanner, which were superimposed and aligned to the original CAD image. The 3-D scanned images comprised of over a million surface points of the sample, which resulted in point clouds. A point cloud was the structure that was produced when the sample's shape was captured using a 3-D scanner. A point cloud, for each scanned sample was created by the 3-D scanner and the software program. Each point cloud comprised of a collection of spatial data points, each of which represented an individual location on the surface of the scanned sample. The surface points consisted of the coordinates width (X), height (Y), and depth (Z). Various point clouds from the scanned image and the original CAD drawing of the sample were aligned and combined into a single point cloud. Utilising the software program, the point clouds were segmented according to shape, colour, or features (edges, corners, planes, and forms).

Even though over a million points were scanned for the surface points to be plotted on its X, Y and Z planes, the 3-D scanner had failed to capture the samples in its entirety while critical points on the samples were missing on the scanned images. As shown in figures 7-11 there were grey areas on the images scanned. These grey areas depicted the parts of the original CAD drawing that the 3-D scanner had failed to capture on the samples. Even though the 3-D scanner contained the feature of a single blue laser for the scanning of objects that have depth or deep holes in them, the single blue laser failed to capture sufficient surface points of the depth of the samples that were scanned. An anti-glare spray was then used on the samples to determine if that would assist the single blue laser in capturing the depth of the samples, however, the 3-D scanner still failed to capture sufficient surface points of the depth of the samples. From a visual analysis of the scans, it was noted that the smaller the sample was, there were fewer surface points captured for depth as the 3-D scanner could not detect the surface points for depth in the smaller samples.

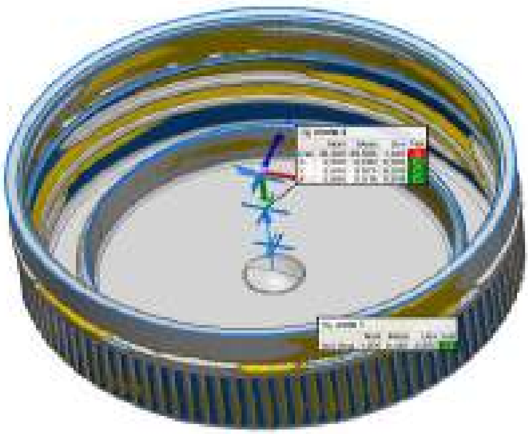

Figure 7: Scanned image of the inside of sample A with the 3-D scanner

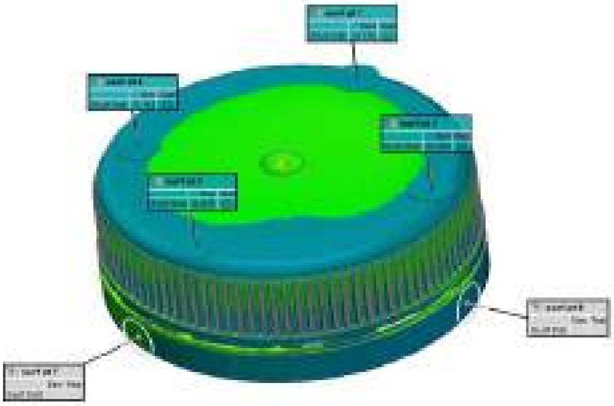

Figure 8: Scanned image of the outside of sample A with a 3-D scanner

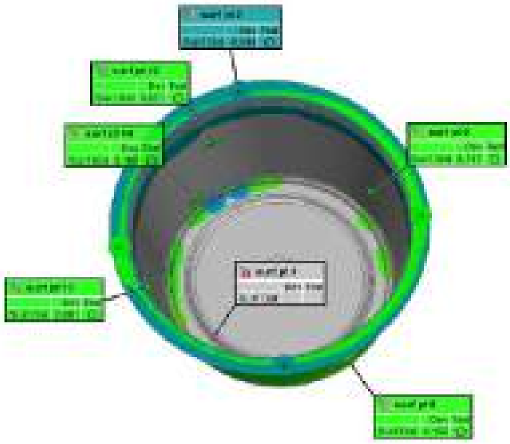

Figure 9: Scanned image of sample B with the 3-D scanner

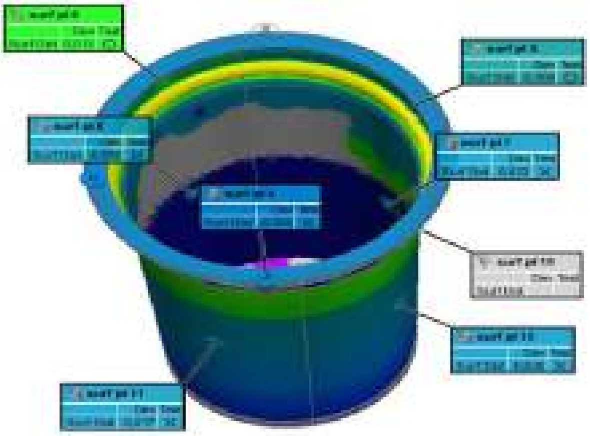

Figure 10: Scanned image of sample C with the 3-D scanner

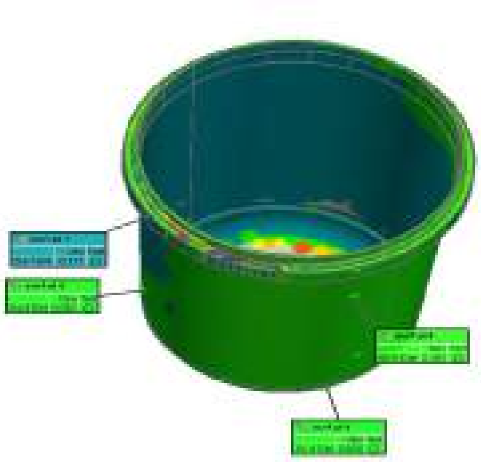

Figure 11: Scanned image of sample D with the 3-D scanner

Once the scanned 3-D image was aligned to the original CAD drawing, the software program then calculated the comparison of the surface points of the scanned 3-D image to that of the original CAD drawing of the samples.

The software then calculated how many surface points were taken on the samples, how many points were measured from the number of points taken, how many points had passed, how many points had failed and how many points had resulted in a warning that it was either at the lower end or top end of the specification. Table 1 depicts the average number of surface points scanned for each sample that was measured by the 3-D scanner. As shown in Table 1, there was an average of 23 circle points and 12 surface points that were captured by the 3-D scanner for each sample. From the 23 circle points and 12 surface points that were captured, only 92.45% of the circle points and 88.07% of the surface points were measured. The points measured were then categorised into passes or failures. From the points measured, 75.85% of the circle points and 72.40% of the surface points had passed, 16.47% of the circle points and 15.34% of the surface points had failed and 0% of the circle points and 36.61% of the surface points had been marked as a warning. The warning category is for those points within the specification that were either at the bottom end or top end of the specification. Statistically, only 92.45% and 88.07% of the points that were captured, were measured. The 3-D scanner had failed to measure all points that were captured with the scanner, in all samples that were scanned.

Table 1: Average results of the number of points scanned with the 3-D scanned

Sample	Circle Points					Surface Points				
	Number of points taken	Points measured	Passed	Failed	Warning	Number of points taken	Points measured	Passed	Failed	Warning
A1 (inside)	20	18	18	0	0	10	9	9	0	4
A 1 (outside)	12	7	6	1	0	8	4	4	0	4
A 2 (inside)	15	15	13	2	0	11	10	9	1	5
A 2 (outside)	15	15	13	2	0	11	10	9	1	5
B 1	27	25	24	1	0	15	15	14	1	7
B 2	27	25	23	1	0	16	16	16	0	6
C 1	28	27	17	10	0	18	13	6	8	3
C 2	28	27	16	11	0	18	14	6	8	3
D 1	22	21	17	4	0	10	9	8	1	4
D 2	36	36	30	6	0	11	10	10	0	6
Average	23	21	18	4	0	12	11	9	2	5
Average % of points from number of points taken		92,45	75,81	16,47	0,00		88,07	72,40	15,34	36,61

Furthermore, when a sample was scanned and aligned with the original CAD drawing, a statistical report of the scanned image was generated. The statistical report contained measurements of the surface points of the sample that was scanned. Table 2 shows the measurements of the surface points for Figure 11. A comparison of the scanned image (Figure 11) to the generated statistical report (table 2) showed on the statistical report that 8 surface points were measured, however, figure 11 only identifies 4 surface points (points 1, 4, 5, and 8). Therefore, all points that were identified by a number on the statistical report were not graphically represented on the accompanied scanned image. This made it difficult to correlate the data from the statistical report to the scanned image.

Table 2: Statistical report of the scanned sample

Control View Name	Surfaces
Units	Millimeters
Coordinate Systems	world
Data Alignments	best-fit to ref 1
All Statistics	Total: 8, Measured: 7 (87.500%), Pass: 7 (87.500%), Fail: 0 (0.000%), Warning: 5 (62.500%)

Char No.	Object Name	Control	Nom	Meas	Tol	Dev	Test	Out Tol
	surf pt 1	Surface Distance		-0.111	±0.500	-0.111	Pass	
	surf pt 2	Surface Distance		0.217	±0.500	0.217	Pass	
	surf pt 3	Surface Distance		-0.119	±0.500	-0.119	Pass	
	surf pt 4	Surface Distance		0.101	±0.500	0.101	Pass	
	surf pt 5	Surface Distance		0.050	±0.500	0.050	Pass	
	surf pt 6	Surface Distance		0.122	±0.500	0.122	Pass	
	surf pt 7	Surface Distance	N/A	N/A	N/A	N/A	N/A	N/A
	surf pt 8	Surface Distance		0.006	±0.500	0.006	Pass	

The variables considered for sample A (closures) were the external diameter, minor thread, internal clip diameter and height. The variables considered for samples B (250ml tub) and C (125ml tub) were the height, orifice, and diameter. The variables considered for sample D (1kg tub) were the height, clip ring, diameter, and neck ring. These variables were selected as they were critical quality aspects of the samples selected, as per the manufacturer's specifications. Tables 3-6 are the comparison of the average results for each variable taken for each sample using the 3 different measuring devices.

For samples A1 and A2, no results were obtained from the scanned images of the 3-D scanner for the external diameter, minor thread, and height. For samples B1, B2, C1 and C2, no results were obtained from the scanned images of the 3-D scanner for the orifice. Similarly, for samples D1 and D2, no results were obtained from the scanned images of the 3-D scanner for the clip ring and neck ring. Results for these critical quality variables were not obtained from the scanned images, because the 3-D scanner failed to measure the surface points at which these variables were located. Due to the failure of the ability of the scanner to determine all surface points, the data for the critical variables required for Quality control testing of the samples measured were incomplete and the scanned images could not determine if, in fact, those critical variables were in specification or not. The vernier and the CMM measuring devices produced results and values for all the variables that were critical for Quality control purposes.

Table 2: Average measurement results of samples A1 and A2

	Sample A 1				Sample A 2			
Instrument of Measurement	External Diameter	Minor Thread	Internal Clip Diameter	Height	External Diameter	Minor Thread	Internal Clip Diameter	Height
	Specification				Specification			
	39,8-41,8	35,55 – 35,95	37,2 - 37,6	16,15 – 18,16	39,8-41,8	35,55 – 35,95	37,2 – 37,6	16,15 – 16,16
	mm	mm	mm	mm	mm	mm	mm	mm
Vernier	40,33	35,94	37,24	16,54	40,32	35,945	37,104	16,56
CMM	40,28	35,94	37,38	16,57	40,32	35,90	37,245	16,53
3-D Scanner	no result	no result	37,60	no result	no result	no result	37,58	no result

Table 3: Average measurement results of sample B1 and B2

	Sample B 1			Sample B 2		
Instrument of Measurement	Height	Orifice	Diameter	Height	Orifice	Diameter
	Specification			Specification		
	113-116	62,4 - 62,8	70 - 70,6	113-116	62,4 - 62,8	70 - 70,6
	mm	mm	mm	mm	mm	mm
Vernier	114,02	62,42	70,38	114,04	62,44	70,45
CMM	114,01	62,40	70,37	114,02	62,41	70,48
3-D Scanner	113,70	no result	69,72	215,82	no result	66,00

Table 4: Average measurement results of C1 and C2

	Sample C 1			Sample C 2		
	Height	Orifice	Diameter	Height	Orifice	Diameter
Instrument of Measurement	Specification			Specification		
	77-79	61,75-61,95	69,6-70,4	77-79	61,75-61,95	69,6-70,4
	mm	mm	mm	mm	mm	mm
Vernier	78,23	61,85	70,32	78,27	61,85	70,32
CMM	78,19	61,84	70,31	78,26	61,84	70,30
3-D Scanner	74,17	no result	69,88	74,02	no result	69,79

Table 5: Average measurement of results for sample D1 and D2

	Sample D 1				Sample D 1			
Instrument of Measurement	Height	Clip Ring	Diameter	Neck Ring	Height	Clip Ring	Diameter	Neck Ring
	Specification				Specification			
	133 - 136	116,7-117,5	98,2-99	124,6 - 126	133 - 136	116,7-117,5	98,2-99	124,6 - 126
	mm	mm		mm	mm	mm		mm
Vernier	133,74	117,24	98,34	124,95	133,78	117,12	98,28	125,02
CMM	133,73	117,23	98,34	124,95	133,146	117,11	98,27	125,01
3-D Scanner	133,76	no result	97,23	no result	117,83	no result	98,57	no result

A time study comparison was conducted on all 3 measuring devices. The time study comparison was conducted to determine if the 3-D scanner was much quicker in capturing critical quality control data as compared to the vernier and the CMM and if the 3-D scanner could save time during routine quality control checks. Table 7 shows the time study comparison between the 3 measuring devices. Table 7 contains the average time that was taken for the routine quality control tests of each sample, and the cumulative average time that was taken for the routine quality control checks of all the samples that were measured.

The 3-D scanner and the CMM required one scan, or one measurement taken to obtain all the values required for the routine quality control checks and the vernier required measurements to be taken separately or manually for each variable itself. Even though the vernier required each variable to be measured individually, it was still the quickest in obtaining the measurements required for the routine quality control test. Based on the cumulative average time taken to conduct the routine quality tests on the samples provided, the vernier was 9.06 times quicker than the 3-D scanner and 5.15 times quicker than the CMM to obtain the required results.

Table 6: Average time taken for the measurement conducted on each measuring device

Average Time Taken to conduct tests			
Sample	3-D Scanner	CMM	Vernier
A1	203,28	183,719	17,917
A2	128,82	183,723	17,855
B1	107,84	64,151	19,272
B2	138,78	64,101	19,278
C1	133,56	63,494	17,154
C2	138,3	63,261	17,164
D1	265,68	105,326	26,343
D2	346,8	105,119	26,382
Total Time Taken (seconds)	**1462,86**	**832,894**	**161,465**

4 CONCLUSION

The 3-D laser scanner that was tested during the study, showed that, it was ineffective as a measuring device for quality control testing, as it had failed to scan all critical variables required to manufacture a quality product that is within the required specifications of the samples tested. The 3-D laser scanner is touted to be faster and more time efficient than during routine Quality control testing, however, as compared to the tactile measuring devices, the 3-D scanner was less efficient as it was more time-consuming to measure the samples tested and therefore it did not add any benefit to reducing the time taken during routine Quality control testing. Based on the study conducted, it can be concluded that even though there are established and emerging optical metrological technologies such as 3-D scanners, which are versatile and fit for industries, such as automotive and aeronautical manufacturing, it is currently not effective or adequate for routine Quality control testing in selected injection moulded plastic products.

5 RECOMMENDATIONS

Although the 3-D scanner proved to be an inadequate quality control measuring device for plastic injection moulded products in this study, it is recommended that further investigation is required as to the reason why the 3-D scanner did not effectively measure the samples tested. Aspects such as product size and composition must be taken into consideration when conducting these studies to determine if they affect the results achieved. With the advent of technology, various types of 3-D scanners have been developed by different manufacturers, whose technology may differ. In this study, only 1 type of 3-D scanner was utilised, therefore it is recommended that further studies are required with the use of multiple 3-D scanners, from different manufacturers, to determine if the type of 3-D scanner used may affect the results achieved.

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AN EXPLORATION OF THE PROBLEM OF SELECTING MEANINGFUL AND MANAGEABLE IMPROVEMENT PROJECTS IN MANUFACTURING

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ABSTRACT

Operations improvement is strongly correlated to increased profitability of companies and the process of improvement project selection is, in turn, correlated to the success of operations improvement. As a multi-criteria decision-making problem, project selection, at a basic level, involves identifying the project that will yield the greatest benefit given limited available project resources. A multitude of project selection methodologies exist to address the problem of selecting meaningful and manageable improvement projects.

This paper explores the field of project selection from both an academic, as well as an industry perspective, with a specific focus on the South African business context. The approach followed is two-pronged. Firstly, literature is reviewed to gain insights into, and critique, the range of project selection methods available. Secondly, interviews are conducted with operations improvement practitioners to ascertain the realities of improvement project selection.

Keywords: Operations, Improvement, project, selection, South, African, empirical, grounded, AHP, linear, programming, MCDM

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1 INTRODUCTION

Operations improvement is strongly correlated to increased profitability of companies [1] and the process of improvement project selection is, in turn, correlated to the success of operations improvement [2-4]. Lynch, et al. [5] define an improvement project as a project that “address[es] an organizational performance problem that has an unknown solution”.

In the field of operations improvement, many tools and concepts can be used to identify improvement opportunities such as benchmarking, value stream mapping, statistical process control, etc. When multiple improvement opportunities are identified, and the resources with which to convert these opportunities into improvements are limited, operations management is forced to prioritize the opportunities by considering various constraints and criteria [6, 7]. The topic of the selection of improvement projects that are “meaningful and manageable” [8], is well represented in the literature.

During the process of project selection, improvement practitioners can use objective or subjective prioritization methods or a hybrid of both methods. Objective prioritization methods are more analytical in nature, often employing quantitative decision-making models, whereas subjective decision-making tends to use intuition and feelings, but is generally considered less desirable [9].

Operations improvement literature has comprehensively articulated guidelines and constraints to the selection of projects to prioritize them for maximum business impact, while considering resource limitations. Subsequently, these parameters have been translated into sophisticated decision making models using a variety of approaches such as adaptive neuro fuzzy inference systems, linear programming, analytic hierarchy process (AHP), fuzzy weighted additive goal programming, etc. [7, 10]. In fact, most of the literature on project selection is dedicated to proposing objective project selection tools and methodologies [11].

In a survey of 74 organizations, however, Kornfeld and Kara [12] found that companies seldomly apply the sophisticated models propagated in academic literature when selecting projects, and rather used subjective or unstructured project selection methods (PSMs). The research of Kirkham, et al. [11] of 203 European manufacturers reported that 51% did project selection subjectively only, 28.6% used both subjective and objective methods and 20.4% reported only using objective methods. In this study, large firms were more likely to do objective selection, whereas the Small and Medium Enterprises (SMEs) opted for subjective methods. Cost Benefit Analysis, Pareto Analysis, and a group that includes Judgement, Experience and Feelings, were the three most used project selection approaches amongst the companies surveyed by Kirkham, et al. [11], also confirming the finding by Kornfeld and Kara [12] that the models designed by academics are not being used in industry.

The research of Kirkham, et al. [11] explored the reasons why companies do not use the available objective selection methods and report the following responses: a) Lack of awareness (23.8%), b) lack of resources (15.9%), c) preference towards subjective methods (15.9%), d) no perceived benefits of objective methods (13.5%), e) difficult or complicated theory (12.7%), f) extensive education/efforts needed (7.9%) and g) difficulty to analyse results (7.1%) and other (3.2%). Considering that reasons e, f, g, and possibly also b have to do with the objective selection methods being perceived as too difficult or cumbersome for the current context, this ‘too difficult’ theme would constitute 43.7% of the responses. Reasons c and d could similarly be grouped to form a ‘subjective methods work well enough’ group, which would then be the second most dominant theme at 29.4%, and lack of awareness still at 23.8%.

Jung and Lim [13] also postulate that management might not have the data that will help them estimate project costs, schedules, and benefits, which might add to the reason why data-reliant prioritization methods are not used, and even the popular Cost Benefit Analysis and Pareto Analysis methods might not always be feasible.

The Kirkham, et al. [11] study focused on project selection in the Six Sigma context, whereas the Kornfeld and Kara [12] study covered both Six Sigma and Lean deployment. Another study by Banuelas, et al. [14] also surveyed manufacturing companies in the United Kingdom implementing Six Sigma, but the focus was primarily on the selection criteria. As a secondary research focus, Banuelas, et al. [14] also surveyed PSM usage and their findings laid the foundation for the more focused PSM usage surveys done by Kirkham, et al. [11] and Kornfeld and Kara [12], who confirmed that industry mostly does not use the mathematical PSMs.

Apart from the three studies already cited, no further empirical studies were found that investigated how industry approaches project selection. A Google Scholar search using the search term ‘industry survey on project selection’ revealed that of the first 55 search results, only 5 articles described an empirical study of PSM usage in practice, with only one focusing on operations improvement project selection – the study by Kornfeld and Kara [12]. A further Google Scholar search using the search term ‘industry survey of project prioritisation’ reached the irrelevance plateau after 25 articles, but delivered only the two studies by Kirkham, et al. [11] and Banuelas, et al. [14] already described above. An in-depth reading of a total number of 47 project selection related articles did not reveal any further mentions of empirical studies done in industry on PSM usage. Considering the prevalence of PSM development taking place in academia and the lack of research on whether the developed PSMs are being used, reveals an imbalance between what Hevner [15] refers to as the rigor (academic or theoretical) cycle and the relevance (target domain or industry) cycle of design science research.

Although the empirical studies on PSM usage described so far [11, 12, 14] covered a large number of manufacturing companies in Europe, the United Kingdom and the Asia-Pacific region, they were all focused on companies deploying Six Sigma or Lean. This means that PSM usage in industry in its more general improvement context seems not to have been covered, which is the research gap explored by this paper.

Furthermore, the existing literature tends to describe the improvement process of project identification and selection as a clean, staged process, or it assumes that a list of alternative projects exists from which to select the best one. This is indeed one of the strengths of Six Sigma, which is a project-based improvement approach with a well-defined project execution methodology [16]. Improvement approaches based on the Toyota Production System, such as Lean, however, tend to follow a more decentralised approach to identifying and selecting improvement projects and focus on workforce mobilisation in the improvement effort instead of selecting a few high impact projects [17]. Companies without a structured improvement approach, however, tend to be mostly reactive in their project selection by launching projects as and when management becomes aware of a repetitive or serious problem.

Indeed, the studies of Kirkham, et al. [11] and Kornfeld and Kara [12] both found that Six Sigma companies tend to do more objective project selection than other companies surveyed, but stop short of explaining how the inherently different improvement approaches correlate to the finding. Their studies, however, also revealed that the majority of companies, regardless of light the improvement approach employed, are not satisfied with their current project selection approaches. This research aims to expand the scientific body of knowledge on how industry approaches project selection in its general and wider context and summarises interviews conducted with seasoned operations improvement practitioners on the topic of project selection. The outcome of the research is to create a descriptive model of project selection in operations, which can be used to guide further research in the field.

2 RESEARCH METHODOLOGY

Grounded theory was selected as the research methodology with which to gain an understanding of how operations approach improvement project selection. According to Charmaz and Belgrave [18] grounded theory is a systematic method of iterative, comparative and interactive data collection and analysis with the aim of theory building. It is often used in a field of study where little is known about the field and approaches data collection and analysis with an open mind so that theory formation is 'grounded' in (as opposed to uninformed about) the realities of the target domain [19].

As good problem solving starts with a thorough study of the problem and its environment, and in light of the fact that so little empirical research has been done to build an ontology of the target domain and its project selection process, grounded theory was deemed the most promising research approach. The iterative, interactive data collection approach of the method allows for the systematic formulation and refinement of an ontology of project selection in operations specifically. This paper describes the results of the exploratory phase of the grounded theory process.

2.1 Data collection method

The aim of the exploratory data collection phase was to cast a wide net to gather insights into and examples of both successful and failed project selection attempts in industry. To achieve this aim, semi-structured interviews were conducted with experienced operations managers and operations improvement practitioners. The following questions were used as prompts during the interview:

1. Reflecting on your experience in operations improvement, please describe your observations on how improvement projects are selected.
2. Which project selection methods have you used yourself, or as part of a team?
3. Which factors, do you believe, influence the choice of project selection method?
4. What do you believe are the challenges in project selection?
5. What have you noticed works well in terms of project selection?
6. What have you noticed does not work well in project selection?

The interviews were conducted in May 2023. Ethical research clearance for the proposed methodology was obtained from the researchers' academic institution.

2.2 Sample

Experienced manufacturing stakeholders with more than 20 years of operations improvement experience were selected as the target population as they would most likely have been exposed to various improvement contexts and approaches, and, with the advantage of hindsight and comparative experiences, would be able to critically discuss the various project selection approaches.

The researcher started with a list of 20 names of operations improvement practitioners from her personal business network in South Africa and prioritized the participants to cover a variety of perspectives and operating scenarios within the manufacturing sector. Further snowball sampling could be used to extend this data collection phase if required.

The first 10 interviews, lasting one to two hours each, described a collective 328 years of operations improvement experience and generated 332 lines of examples and insights. Towards the tenth interview, the researcher started perceiving a repetition of concepts and insights with which to start formulating themes for a more targeted round of data collection.

Table 1 shows the breakdown of the participants' background, experience, and exposure.

Table 1: Breakdown of interview participants

Participant	Operations experience	Operations roles fulfulled	Participant academic background	Large company	Medium company	Small company
1	24 years	Operations management 19 years Operations improvement consultant 5 years	Industrial Engineer MBA	Yes	Yes	Yes
2	36 years	Operations management 19 years Operations improvement consultant 17 years	Industrial Engineer	Yes	Yes	Yes
3	48 years	Operations management 32 years Operations improvement consultant 16 years	Industrial Engineer MBA	Yes	Yes	Yes
4	45 years	Operations & supply chain management 20 years Operations & supply chain improvement 25 years	Industrial Engineer	Yes		
5	27 years	Operations management 27 years	No formal qualification	Yes	Yes	
6	24 years	Operations management 2 years Financial management: manufacturing 22 years	Chartered Accountant MBA	Yes	Yes	Yes
7	37 years	Operations Improvement 37 years	Statistician	Yes	Yes	Yes
8	29 years	Operations management 4 years Operations improvement consultant 25 years	Industrial Engineer PhD	Yes	Yes	Yes
9	31 years	Operations Improvement 31 years	Economist	Yes	Yes	Yes
10	25 years	Operations & supply chain management 21 years Operations improvement 4 years	Chemical Engineer MBA	Yes		
	328 years	**CUMULATIVE YEARS OF OPERATIONS EXPERIENCE**				

As grounded theory consists of an interaction between theory formulation and returning the conceptualisations to reality to be tested with further data collection, the collected data was deemed enough for the constructing of a descriptive model which could enable more targeted empirical research going forward. This paper describes the results of this exploratory research into how improvement project selection is done in the South African manufacturing industry.

The participants could relate examples and approaches from a wide variety of manufacturing companies. The sample of companies included parastatals, publicly listed, and privately owned companies, multi-nationals, and SMEs. The sample also covered the spectrum of companies with an established continuous improvement culture, to companies with a purely reactive improvement approach. Manufacturing sectors included fast moving consumer goods, metals, agricultural and timber processing, automotive, textile, chemical, and other smaller sectors.

2.3 Data analysis

The 332 lines of insights and examples were iteratively coded into evolving categories. Eight distinct cycles of data coding took place. As qualitative coding software such as Atlas.ti tends to hide large parts of the data from view, it was decided to use Microsoft Excel instead for the ease with which data and categories can be moved, inserted, and deleted. The data is also relatively easily viewed and searched. The next section discusses the findings of this data collection phase of the research.

3 RESULTS AND DISCUSSION

The first observation from the interviews was that project identification and selection are often done simultaneously in industry and hence participants struggled to discuss project selection in isolation. This finding thus already differs from the distinct steps described in project theory. Sometimes an identified problem would become an immediate project without any project selection being done. Other examples would describe project identification techniques that fulfill some of the prioritization role of a selection process. Only in the case where a list of potential projects existed, was project selection being done in isolation. There thus seems to be a spectrum of approaches based on the proximity of the project identification process to the project selection process in terms of both time and method. This concept is demonstrated in Figure 1.

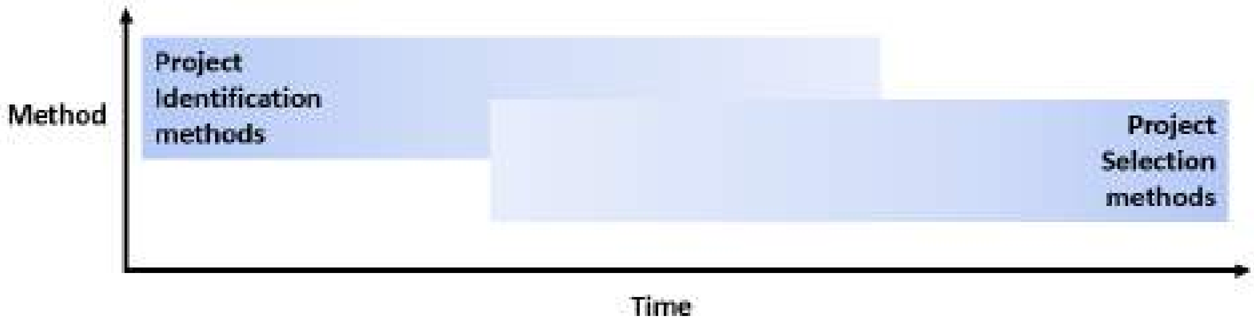

Figure 1: Overlap between project identification and project selection methods.

The second observation during the interviews was that the process of improvement project selection in operations is complicated: often situational and dependent on a wide variety of factors. Although the data seemed to diverge wildly during the initial stages of the interviews, the many insights and inputs from the participants eventually converged around several themes. When the rate at which new approaches or principles were being mentioned also started plateauing, the first round of data analysis could be done to create a descriptive model, an ontology, of the target process in the target domain.

As mentioned in section 2.3, eight iterations of theme extraction took place before the identified themes accurately described the collected data set. The identified themes were project identification / selection approaches, impediments, and enhancements, with influencing themes being organization size, improvement approach, organizational level, improvement culture, and decision maker profile. Figure 2 shows the proposed descriptive model of project selection in industry and shows the system within which project selection is done, as well as the factors that influence which tools, impediments and enhancements are at work. For example, two participants described 'bloated' head offices as being an impediment to project identification / selection as resources would generate and sell projects to improve their utilization. This scenario typically plays out in large corporate companies where educated and dynamic stakeholders are involved.

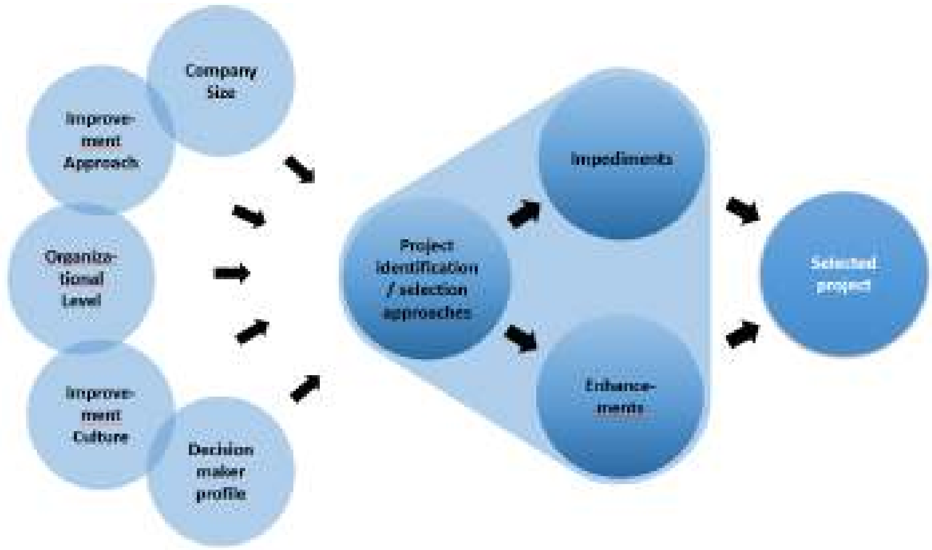

Figure 2: Hypothetical ontological model of improvement project selection in operations

A third major finding to be mentioned before launching into the detail description of the model's elements, is that, although research to date has found little evidence of operations research (OR) PSMs in industry (and this study confirmed the finding), echoes of OR techniques abound in the stories told by the interviewees. Rational decision makers in industry use the *heuristics* of linear programming, analytical hierarchy process, and multi-criteria decision making informally, and usually unconsciously to think through project selection on a frequent basis. This finding confirmed the choice of grounded theory and interviews to be a fresh approach to the study of industry project selection.

The rest of the results section will be dedicated to unpacking the elements of the descriptive model based on the participants' responses. The interview questions focused on the types of PSMs used, and what is seen to work (enhancements) and not work (impediments). Although the independent variables of the model were mentioned frequently during the interviews, they were not the focus of the interviews, and therefore will be mentioned where relevant, but should rather be further explored in targeted research.

3.1 Project identification / selection approaches

The approaches described below are ordered in line with the frequency that they were mentioned and described by the interview data, but readers should keep in mind the nature of the research was to describe themes and patterns found in project selection in industry, and not quantify and rank responses like one would in a survey from a representative sample of industry.

3.1.1 Problem-based project identification / selection

Problem-based project identification / selection is a reactive approach that relies on the operations team becoming aware of a persistent problem that requires a more focused effort to solve than normal corrective action would require. These projects could last hours or days to do a root cause analysis and draw up an action plan or could include months-long investigations requiring data collection, analysis, cost estimations, and eventually implementation and monitoring.

All participants witnessed this approach in all sized and types of companies they were involved with, stating that this was the main source of improvement projects. A spectrum of approaches within this category were however identified, mostly based on the time it took to detect the problems. The examples mentioned were grouped into the following categories:

- Problems identified gradually over time.
- Problems identified by monitoring deviation from standard, typically through Statistical Process Control.
- Projects selected through formalised problem escalation frameworks.

This approach will sometimes generate a list, which triggers a project selection process, but often an identified problem becomes a project by default without further consideration of systems thinking or the opportunity cost of such a project. Although this approach existed across all company sizes, the quality of this process was influenced by the improvement approach and culture, organizational level, and stakeholder profile. For example, the type of supervisor that walks the floor regularly, was said to be better at generating lists of possible projects. Companies with a mature improvement culture, and structured approach (often larger companies) tend to be more structured in identifying and handling process non-conformance.

3.1.2 Strategy-based project identification /selection

This approach entails an approach that starts with a *"clear and intelligent company strategy that is well communicated"* in the words of Participant 1. In this category, three sub-approaches were identified:

- Identifying projects through the tracking of Key Performance Indicators (KPIs).

- Selecting projects at an annual strategy review session where a list of major projects identified throughout the year are presented.
- Identifying and selecting projects at an annual strategy review session where the strategic thrusts produce *'swim lanes of improvement projects'* (again in the words of Participant 1).

Medium and large companies seem to be more prone to these approaches, which identified projects that typically would be driven at the senior level.

3.1.3 Finance-based project selection

Where projects had to be checked for viability, the following techniques were used: internal rate of return (IRR), net present value (NPV), return on money / investment (ROM / ROI), and payback period. However, these techniques were usually only the basis for a quick "back of a cigarette box" calculation during the selection process but used in depth to scope and plan the project once the selection had been made. As PSMs they would thus only provide a basis for quick sifting. Participants 3 felt strongly that a project that is not obviously viable (through quick calculation), should not be pursued. He also mentioned that by the time 60% of the data for the calculation are collected, the answer usually becomes apparent and further data collection and analysis does not add value. This is an important observation confirmed by other participants, as it could explain why mathematical PSMs are not formally used in industry and should be confirmed by further empirical research.

3.1.4 General management science-based project selection

Pareto analysis and impact-effort matrices were frequently used when a list of projects had to be prioritised. Cost-benefit would also be used to prioritise but was also frequently mentioned as a project viability checking technique even when only one project was being considered. In no example was the cost-benefit calculated in detail as unquantifiable benefits and costs would also be considered. It was also mentioned that the relative comparison of the cost-benefit of projects is difficult as the projects themselves are usually very different in both the set of costs, as well as the set of benefits they affect. These management science based PSMs were used at all levels, in all types of companies,

3.1.5 Benchmarking-based project identification / selection

Benchmarking against other lines, factories, or against best practice was considered an effective approach to both proactively identify and prioritise potential improvement opportunities. This approach was present in larger organisations but said to only work in a relatively mature improvement culture.

3.1.6 Structured improvement programmes-based project identification / selection

Structured improvement programmes such as Lean and Six Sigma were used to proactively identify and prioritise potential improvement opportunities. The Theory of Constraints, Value Stream Mapping and Value Analysis were mentioned to be used to both identify and prioritise projects.

Approaches such as Lean focus on mobilising all levels of the workforce to identify and select projects. With workforce mobilisation, and Kaizen, or continuous incremental improvements being the focus, less emphasis is placed on optimal project selection. Six Sigma is a project-based approach which, when driven at the higher levels, generates lists which trigger PSMs, but when driven through training, tends to not involve PSMs at all as each trainee is required to identify and execute an improvement project as part of a training assignment. Here the maturity of the organisation culture has a strong correlation as to the effectiveness of the roll-out. These structured approaches are not limited to, but tend to be more prevalent in, medium and large companies.

Another important finding was that in companies that have some level of understanding of continuous improvement fundamentals such as standardisation, visual management, 5S etc. would allow any improvement projects that fall into these themes to automatically be selected for implementation. This seemed to come mostly from conviction but was also below a selection radar due to the fact that these projects typically involve no expenditure.

3.1.7 Consultant-based project identification and selection

A less frequent, but valued approach was the regular, but not frequent, involvement of consulting companies to assist in systematically identifying improvement opportunities in the system and was found to be a good antidote to some of the impediments mentioned below such as politics and cognitive bias within the company. The consultants tend to follow different approaches, but are mostly systematic, analytical, and objective.

3.2 Common impediments to project identification and selection

If academia aims to assist industry to select more meaningful and manageable projects, it is important to understand the decision-making impediments faced in the process. Table 2 lists the impediments identified in the interviews.

Table 2: Project selection impediments described by industry.

Impediment	Description
Data availability	A major reason why some PSMs are not fully used, or used at all, is the availability of data. Mature, as well as larger organisations tend to control their process better through measurement and hence have more data with which to make decisions.
Unquantifiable costs and benefits	Not all project costs and benefits are quantifiable and thus render certain PSMs unusable and adding a certain level of subjectivity to the decision-making process.
Dirty data	Several examples of failed, break-even, or low return projects were the result of PSMs being fed incorrect assumptions, wishful thinking, or manipulated data to accomplish a non-enterprise orientated agenda.
Flogging a dead horse	Many examples could be given where weak or failing projects were continued for too long before the projects were shut down. The cognitive bias called the sunken cost fallacy, also known as the irrational escalation of a commitment [20] disguises the fact that project continuation also requires a PSM to be done anew.
Add-ons	One example was given where a rigorously scoped USD5 million capital expenditure project allowed a USD25 000 machine to be ‘added’, which was never used. This company would normally do a similar rigorous PSM on the smaller amount, but due to the relative size of the larger project, the latter slipped through the cracks. This was one of two such examples mentioned.
Silos	Goals that promote local improvements without considering the cost to the value chain were mentioned frequently as an impediment, for example

	measuring line efficiencies vs order fill rate, where line efficiencies motivate longer production runs instead of changeovers based on customer demand.
Politics	More than one example was mentioned where one or two personalities would manage to 'sell' irrational projects. Either no PSMs were used, or their outputs were ignored. This impediment was especially prevalent in large organisations.
Throwing money at a problem	For several participants red flags go up when old equipment is proposed as the 'root cause' of a problem. The PSMs used seldomly consider the diminished returns and inflated costs that will be inherited when the systemic root causes are not first addressed.
Lack of systems thinking	This impediment is the project identification twin of the silo goals impediment, where an identified problem, perhaps identified during a process walkabout, turns into an improvement project without the consideration of whether it is a local or system improvement.
When government gets involved	Government policy / incentives such as the South African skills levy was mentioned as an impediment to business decision making as it would add weighting towards skills training as opposed to projects essential for business growth.
When the customer is king	Many examples were mentioned where machines had to be bought or a new product launched to satisfy an existing customer's order, but where that project would not be viable when tested through a PSM. Some of these decisions essentially weakened the company overall for the sake of keeping a customer or improving cash flow from the new order.
Survival mode	Crisis management was said to be an enemy of rational business decision making. Managers of struggling companies tend to go into survival mode, just doing the next thing instead of stepping back to consider a problem objectively. Small companies are especially vulnerable to this impediment as decision makers have little extra time or resources to assist with analysis.
Percentages do not pay the bills	PSMs such as net present value, or internal rate of return are expressed as percentages, which makes the decision more abstract. As Participant 6 said: "*percentages do not pay the bills*" and percentage based PSMs are only one part of the decision-making process.
Smoke and mirrors	Although trained in operations research PSMs, the participants were cynical about the use of these in industry, saying that they would suspect a user of trying to make a poor decision look more credible than it really is by hiding a project's incorrect logic in complicated mathematical calculations. Participant 6, the seasoned chartered accountant, shared the same sentiment about the financially based PSMs, emphasising the importance of understanding the mathematical levers intrinsic in the calculations, as well as the biases of the person making the assumptions.
Frankenstein creations	When larger projects are signed off by several functions, the signatories tend to understand only their part and not those of their colleagues,

	making an enterprise-wise decision difficult. For example, the accountant will do the PSM calculations without a view of the assumptions in the data, collected by operations. This essentially results in a decision designed by a committee where no one has a view of the bigger picture.
Bloated Head Offices	Idle head office resources, typically post-merger, are known to come up with, and then sell, projects that are not necessarily aligned to company needs or strategy.

3.3 Effective enhancements in project identification / selection

Many of the decision-making enhancements are the corrective action to the impediments and thus will not be listed here. Table 3 contains enhancements not yet covered in Table 2.

Table 3: Project selection enhancements described by industry.

Enhancement	Description
Standardization and process control	The degree to which the company is monitoring its processes against a standard was reported to have a strong enabling influence on the identification of problems as process control flagged deviations. The process also collected impact and frequency data that could guide rational selection.
Visual management	Visual management of process parameters was also said to have an enhancing effect on the ability to identify / select projects.
Problem solving culture	A large and mature manufacturer is said to give immunity to operators who report problems and mistakes quickly, with two examples costing the company USD 100 000 each, but also saving the company millions due to quick corrective action taken. A culture of curiosity was also said to enable benchmarking as a project identification / selection tool, as the level of defensiveness that the approach could trigger was less than in less mature cultures.
The commander’s intent	The definition and communication of clear strategic focus areas was listed by all participants as the most important enhancement to project selection, regardless of which tool or approach was used. Participant 3 referred to this as ‘the commander’s intent’: the one liner written on a piece of paper by the commander to the troops to guide their decision making on the battlefield.
Climbing as high up the tree as possible	A number of participants emphasised the practice of first thoroughly understanding the cause-effect relationships of a problem – what Goldratt [21] referred to as climbing as high up the Effect-Cause-Effect logical tree as possible. This practice avoids launching into a solution, and project, that will lead to a superficial outcome.
Balance	A balanced scorecard approach was said to enhance decision making from a sustainability point of view. Another kind of balance mentioned was that between input and output KPIs, or leading and lagging indicators which insulate decision making against a short-term focus. A third type of balance recommended was a combination of line- and enterprise-based

	KPIs for managers in order to fight the silo-impediment described in Table 2.
Viability rules	Many companies have rules around the payback period of large projects, with 24 months being mentioned by a few participants. These rules guard against pet projects of powerful stakeholders as well as projects open to cognitive bias.

This section described the experiences and observations of 328 years of operations improvement experience within the manufacturing sector in South Africa and has laid the foundation for some global observations and further research, which is described next.

4 CONCLUSION

This research aimed to add to the empirical research done to date to describe how industry approaches the selection of improvement projects. The research produced the descriptive PSI1 model (Figure 2), constructed during the first phase of grounded theory research, which describes the project selection in industry as a system of influencing factors, project identification / selection methods, as well as decision-making impediments and enhancements. The PSI1 model and its descriptions can be used to guide the following research opportunities:

- Further refine the descriptive model towards a high level of completeness, accuracy, and freedom from conflict [22].
- Expand the descriptive model to include mediating and moderating variables such as the availability and aptitude of improvement resources.
- Verify and quantify the correlations between the various model elements.

Four major global observations from the research are:

- Project selection in industry is a complex process, dependent on a combination of a range of contextual variables, decision making impediments and enhancements, as described by the PSI1 model presented in Figure 2.
- Project identification is often synonymous with project selection because of either cognitive biases or problem identification techniques with inherent prioritization features (Figure 1).
- The *heuristics* of linear programming, analytical hierarchy process, and multi-criteria decision making are often followed unconsciously by rational decision makers in industry, but never mathematically.
- Lists of potential improvement projects are not ubiquitous in industry, thus also not triggering the use of PSMs.

Building a bridge between two domains requires a thorough understanding of both. How academia approach project selection is well published, but little is known in literature about how industry approaches it. This research was a study of the ‘other side’, in other words, the industry, and aims to enable further research to close the gap between academia and industry with the ultimate aim of equipping industry in consistently selecting meaningful and manageable improvement projects.

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FACTORS THAT TRIGGER PHYSICAL ASSET MANAGEMENT PRACTICES AT WATER BOARDS IN MALAWI

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ABSTRACT

Physical asset management (PAM) has evolved considerably with time. Several factors drive PAM yet not much is revealed in the literature. This study analyzed data from a survey of experts in all Water Boards in Malawi to expose factors that influence PAM. The results uncovered 6 key factors i.e. response to incidents, financial constraints, increasing system demand, legislation/regulation by the government, the need to optimize the value of assets throughout their life cycle, and investor attitudes towards PAM. Five themes emerged through exploratory factor analysis: local context, entrepreneurial approach, globalization, and compliance and demand. Compliance and demand played a dominant role in this study, with legislation by the government as the highest-loaded factor on this theme. The research suggests that governments should introduce policies and laws to stimulate PAM practices. The study was done for the first time hence it raises industry awareness amongst policymakers, scholars, and PAM practitioners.

Keywords: Physical asset management, drivers, practices, value, Water Boards, Malawi

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1 INTRODUCTION

Generally, globalization is raising the anticipation of people regarding the advanced quality of life. Physical assets, such as those used in utilities, transportation, health, and education, are crucial to ameliorated and sustained quality of life. For instance, in utilities, the prominence of potable water supply cannot be exaggerated, “safe drinking water, sanitation, and hygiene are pivotal to mortal health and well-being” [1, p. 4]. Furthermore, modern businesses are competitive in nature and hence their success largely depend on super-efficient and cost-effective processes. Business processes are supported by different types of asset classes which include the following; real estate and facilities, plant and production, mobile assets, infrastructure, information technology and human asset [2, 3]. Assets are very critical when it comes to aiding business performance. For asset-intensive industries, most challenges emanate from how to increase output, reduce plant downtime, lower costs with less risk to safety and environment [4]. For such industries to perform, effective physical asset management (PAM) is crucial in order to realise value from the assets, overcome current and future challenges, and also achieve business goals [5]. This claim aligns well with the resource based view (RBV) [6], [7], [8], which views performance primarily as a function of a firm’s ability to utilize its resources. For example, water supply systems require various assets in water treatment processes and distribution, and these assets as pointed out by Schuman and Brent [9, p. 566] require “operational reliability and systems engineering as a way to attain optimal value over their lifecycle”. The International Organization for Standardization (ISO) 55000 [10], defines an asset as an item that has factual or implicit value for an organization. This explains why it is widely recognized that PAM is best understood as getting the utmost value out of assets. Literature reveals four lifecycle stages of physical assets namely; “creation, establishment, exploitation, and divest” [11, p. 1156]. Although the operation phase is considered the most cost-demanding, literature acknowledges that most costs incurred at this stage were formerly determined during creation and establishment [11], [12] hence it's important to ensure that every stage of the asset is wholly utilized to profit the investment, customers and the environment. The failure of physical assets in asset-intensive organizations results in heavy burdens to numerous parties, “customers are directly or indirectly affected” [13, p. 4], there's generally a loss of business and most often the environment is impacted with lots of possible legal threats. Presently, because of the growing challenges such as economic hardships, resource constraints, and aging infrastructure, for every asset-intensive institution, “PAM is becoming an area drawing much attention at an executive level” [14, p. 509].

Globally, there are numerous delineations of asset management (AM) due to its holistic and multi-disciplinary nature [15]. It's methodical and coordinated conditioning and practices through which an enterprise optimally and sustainably manages its assets and asset systems, their associated performance, pitfalls, and expenditures over their life cycles to realize enterprise goals [16]. It's concerned with the balancing of costs, opportunities, and risks against the desired performance of (physical) assets, to achieve the organizational objectives [10], [17], [18]. Amadi-Echendu et al. [15] promote a flexible definition to accommodate new areas as they become applicable but also to be as general as possible so as not to omit useful and intriguing work in AM. Ngwira and Manase [8], point out that AM is characterized by the espousal of an integrative approach, defining service levels and performance standards and limiting them to strategic goals, an optimized investment decision-making approach, promoting a long-term (lifecycle) approach to AM, demand, and risk management. PAM in this study is defined as “the process of utilizing physical assets from creation to disposal to strike the right balance between performance, cost, and risks in pursuing the enterprise goals” [19, p. 1]. This is the authors’ collated interpretation of the delineations of AM set up in literature. Although the description is simple, it's loaded with all rudiments of AM. This simplicity makes it easier to understand the practice especially due to its multi-disciplinary and holistic nature.

Physical asset management has evolved with time and several factors have contributed to its preface in various industries. Response to incidents, investor attitudes towards physical AM, publication of global AM standards, and legislation by the government were crucial in initiating AM practices across the globe [12]. Chin et al. [20], state that AM was motivated by advances in the maintenance, repair, and recovery market, changes in account reporting regarding infrastructure asset values, the need for performance-based maintenance, limitations of government finances, growing openings for private-public partnerships, perpetration of life cycle cost analysis for maintenance, and information technology use for massive and complicated asset inventory management. Alhazmi [21], points out that, growing system demand for care, reconstruction performance, and maintenance, recognition of fiscal payoffs for better real asset management, accountability to the public sector, and enhanced interaction at all levels of the organization are drivers of PAM in the industry. Maletic et al. [22] point out the need for an integrated and holistic approach to PAM, the need to optimize the value of assets throughout their life cycle, the necessity to recognize the business value, the need to reduce business threats, and the anticipation to reduce whole-life costs of assets were crucial in the development of PAM practices in industries. Commercial climate, regulations, dilapidating structures, network effect, multi-stakeholder perspective, and silo mentality were also outlined as factors impacting AM [23]. Although PAM driving factors are presented in the literature, little is known about how each of those factors is presently ranked in the industry and whether they have common themes. This would help to prioritize and increase focus on some factors and themes amidst constrained budgets. This would also help to relate how each of those prioritized factors drives PAM in unborn studies. Thus, this study sought to examine factors that stimulate PAM practices at Water Boards (WBs) in Malawi. This study as supported by many researchers utilizes RBV to promote PAM practices in the study area which has influence over performance of any asset-intensive enterprise [24, 25, 26, 27]

2 METHODOLOGY

This is a quantitative research study (refer to Figure 1) and the methodology is adapted from [19] and [28]. The research utilized data from a survey of water supply professionals in all Water Boards in Malawi. The survey used potential drivers that were identified through a literature review and experts' opinions. The questionnaire was preferred because of its suitability and cost-effectiveness. It is highly recommended, especially in social science research, and the main objective of its use is to source pertinent information in the most reliable and valid manner [29], [30]. The objectives of the research and the pattern of the questions were clearly explained to ensure that the respondents understand the study so that they respond appropriately. The study applied validity and reliability tests to questionnaire items. Validity explains how well the collected data covers the actual area of investigation, while reliability concerns the extent to which a measurement provides stable and consistent results [31], [19]. Respondents were asked to rate according to the aggregated experience in their company on a Likert scale of 1 to 5, 1 for not important and 5 for very important, how each of the listed factors drive PAM practices in their company. The mean score for each item was considered for further analysis. To identify key drivers in the study, the natural cut-off point method was used [32], i.e., all drivers whose average scores are above the average of the upper and lower mean score of the sample were picked. This was preferred as opposed to other methods presented in literature which considers average of the ranking scale in the questionnaire [33, 34] i.e. for a 5-Likert Scale, (1+2+3+4+5)/5 equal to 3, therefore all factors with average score above 3 are considered critical. The method was also used by authors in earlier studies [28]. Exploratory factor analysis (EFA) was employed to categorize which factors are measured by a (much larger) number of observed variables [35]. Kaiser-Meyer-Olkin (KMO) Measure of Sampling Adequacy and Bartlett's Test of Sphericity were used, KMO value over 0.50 and Bartlett test significance level below 0.05 were considered suitable [36]. A principal component factor analysis with Varimax rotation was conducted on the shortlisted drivers, factor extraction was based on eigenvalues greater than 1 [37], [38], [35]. The rotation was done to reduce the number of factors on which the variables under investigation have high loadings, which interprets the analysis easier [39]. Hair et al. [40], state that a minimum factor loading of 0.50 is acceptable while [39] and [41], promote 0.40 and above, this study adopted 0.40. The analysis of data was done using SPSS V 20.0.

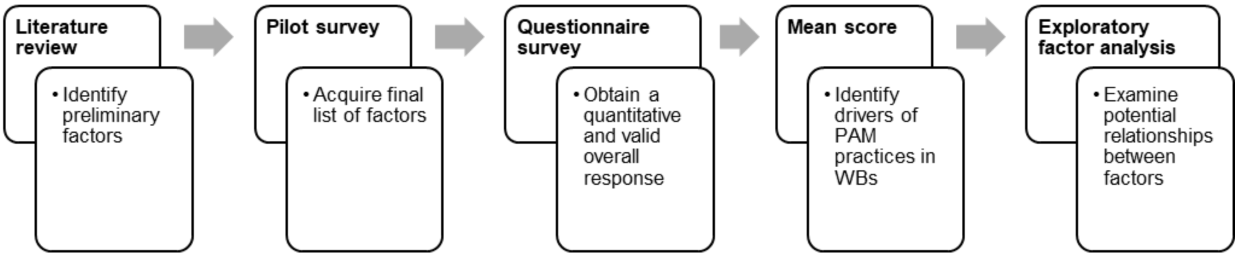

Figure 1: Research methodology flow chart

3 RESULTS AND DISCUSSIONS

A total of 15 questionnaire items were developed using a 5-point Likert scale. The pilot test was done for 10 water utility professionals followed by a questionnaire review. Out of 141 questionnaires distributed to all water utility professionals managing water supply systems in all five WBs in Malawi, 106 were completed and were declared valid, representing a 75% response rate. This reflected the importance the respondents put on the research area. All 15 factors had 2-tailed significance values of less than 0.05, therefore, all the 15 items were valid, also, had Cronbach's Alpha of 0.725, which suggests high reliability [42]. For an exploratory or pilot study, the literature reveals that reliability should be equal to or above 0.60 [43]. Figure 2 shows the distribution of respondents in the WBs, their positions (designations), and qualifications.

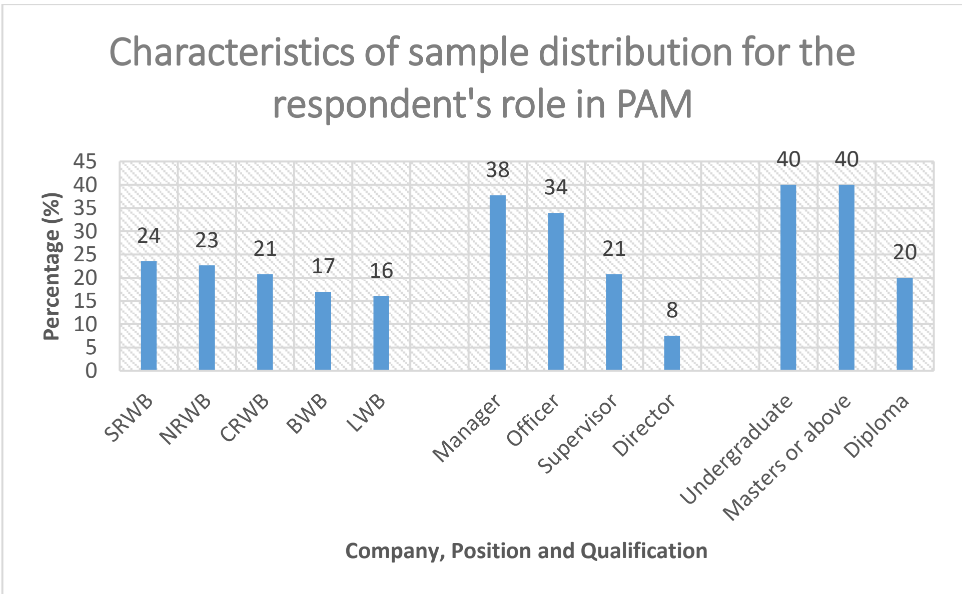

Figure 2: Characteristics of sample distribution for the respondent's role in PAM; Company, Position, and Qualification

From Figure 2, 16% of the respondents work with Lilongwe Water Board (LWB), 17% with Blantyre Water Board (BWB), 21% with Central Region Water Board (CRWB), 23% with Northern Region Water Board (NRWB), and 23% with Southern Region Water Board (SRWB). There is a minor difference in the percentage distribution of respondents across WBs in this study, this shows that the results fairly represent all the five WBs in Malawi. The majority of the responses were from managers (37%) and officers (34%), supervisors (21%), and directors (8%). Furthermore, respondents with a master's degree and above represent 40% of the responses, with an undergraduate degree representing 40% and with a diploma representing 20%. The results in Figure 2 show that all the respondents possessed diplomas and above but also were at supervisory level and above. Therefore, it would be expected that such respondents could understand the contents of the questionnaire and interpretation of the results, and have considerable knowledge of water supply and PAM. The level of education is also crucial in integrating new knowledge and implementation of PAM projects.

3.1 Descriptive Statistics and One-Sample T-Test

Table 1 shows ranked descriptive statistics and a one-sample T-Test of survey results. The means for the 15 drivers range from 2.594 to 4.651, hence the cut-off point for key drivers in this study was (2.594+4.651)/2, i.e. 3.623. The other method would have given a cut-off point of 3 i.e. (1+2+3+4+5)/5 [33, 34]. Therefore, all factors with mean scores above 3.623 in Table 1 are considered key in this study. The standard deviation varies from 0.393 to 0.743, which is generally low and this shows some kind of consensus among water supply experts on the assessment of PAM drivers in the water supply. The standard error mean, varies from 0.038 to 0.072, which is small, this shows that the sample means closely represent the true population mean.

Table 1: Descriptive statistics and one-sample T-Test of Drivers of physical asset management in Water Boards in Malawi

Descriptive Statistics and one-sample T-Test (test value = 3) of 15 PAM Driving Factors											
Rank	Driving Factors	N	Mean	Std. Deviation	Std. Error Mean	t	df	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
		Statistic	Statistic	Statistic						Lower	Upper
1	Response to incidents or high profile events	106	4.651	0.479	0.047	35.49	105	0.000	1.651	1.560	1.740
2	Financial Constraints	106	4.387	0.489	0.046	14.595	105	0.000	0.67	0.580	0.760
3	Increasing system demand for maintenance, reconstruction, performance and management	106	4.340	0.476	0.048	-8.466	105	0.000	-0.406	-0.500	-0.310
4	Regulation and legislation by government	106	4.189	0.393	0.038	31.132	105	0.000	1.189	1.110	1.260
5	Need to optimize the value of assets throughout their life cycle	106	3.868	0.731	0.048	8.301	105	0.000	0.396	0.300	0.490
6	Investor attitudes towards PAM	106	3.670	0.473	0.048	29.179	105	0.000	1.387	1.290	1.480
7	Need to reduce business risk	106	3.443	0.518	0.063	4.655	105	0.000	0.292	0.170	0.420
8	The necessity to recognize business value (financial payoff)	106	3.406	0.714	0.046	28.986	105	0.000	1.34	1.250	1.430
9	Advances in the maintenance, repair, and rehabilitation market	106	3.396	0.491	0.070	2.822	105	0.006	0.198	0.060	0.340
10	Under-investment in AM	106	3.387	0.489	0.072	0.261	105	0.794	0.019	-0.120	0.160
11	Advances in ICT use for massive and complicated asset inventory management	106	3.292	0.647	0.069	0.815	105	0.417	0.057	-0.080	0.190
12	Accountability to public sector	106	3.198	0.723	0.071	12.219	105	0.000	0.868	0.730	1.010
13	Need for an integrated and holistic approach to PAM	106	3.057	0.715	0.069	5.848	105	0.000	0.406	0.270	0.540
14	Decentralization	106	3.019	0.743	0.050	8.815	105	0.000	0.443	0.340	0.540
15	Publication of international standards in AM such ISO 55001, BSI-PAS 55	106	2.594	0.493	0.048	8.138	105	0.000	0.387	0.290	0.480

3.1.1 Response to incidents or high-profile events

This result from the perception of respondents in the study area was expected and is in agreement to what is reported in literature. Regrettably, many organizations are reactive when it comes to PAM. They tend to bring an intervention following an accident or incident. For example, literature reveals that the real acceleration of modern AM in the UK was due to the Piper Alpha disaster and oil price crash in the late 1980s [44]. Also, Hatfield train accident in the UK in 2000, the 'Black Saturday' bushfires in Australia in 2009, the Deepwater Horizon incident in the Gulf of Mexico in 2010, and the Grenfell Tower fire in London in 2017 [12], as some of the examples globally where the organizations began to respect PAM practice so that further asset risks associated to their businesses are managed. Unfortunately, this type of approach is costly to any business, can be fatal, and also can bring irreparable damage to the asset and environment due to its reactive approach.

3.1.2 Financial constraints

This result was also expected as many organizations are currently facing insufficient financial resources to realize their business goals. Economic hardships and the need to realize profits are forcing organizations to look into areas where they can realize savings. PAM, for every asset-intensive organization, is being prioritized for such savings. Successful PAM implementation in any asset-intensive enterprise and as pointed out in literature can lead to improved financial and safety performance, reduced environmental impacts, and improved ability to demonstrate socially responsible and ethical business practice [45, 18, 46, 47].

3.1.3 Increasing system demand for maintenance, reconstruction, performance, and management

Water supply systems and indeed many other systems because of the sudden boom in technology, are increasing in physical asset and asset system complexity. This is compounded by ageing of the assets which is a long time challenge and the asset deficit in many enterprises due to lack of financing [48]. The PAM which was traditionally known as 'maintenance' was effective to a certain level of asset integration with business success. As demand for the assets increased, there was a clear need for PAM that could match complexity, technology, and business demands. This stimulated the need for an improved level of asset care which is predominantly known as asset management.

3.1.4 Regulation and legislation by the government

This plays an important role in the development of AM practices. The ever-increasing costs of renewing or rehabilitating aging infrastructure assets and systems require more transparent ways of justifying these costs and this has become increasingly important for regulators and governments. For example, in RSA, public institutions must include in their annual reports how assets have been managed in the year [49], this gives stimulus to PAM practices. Regulations, pieces of legislation, and policies are being introduced to improve decision-making and transparency around investments in critical infrastructure, as well as to generate better outcomes from limited resources [12]. Therefore, governments must deliberately introduce AM regulations, legislation, and policies that should make PAM practice mandatory for asset-intensive institutions.

3.1.5 The need to optimize the value of assets throughout their life cycle

Asset-intensive organizations face pressures to sustain the performance of assets, pay back asset investment loans, meet institutional targets, and improve service delivery. This is accelerating the need to optimize the value of assets throughout their life cycle and consequently forcing companies to place AM among the key areas that need attention.

3.1.6 Investor attitudes towards PAM

Financiers consider physical assets as reliable long-term investments hence they are putting up measures and conditions on enterprises regarding their investment. Apart from requiring organizations to receive certification in AM, some financiers are assessing the asset management maturity of businesses they invest in and then setting challenging targets to improve this and show better control and management of costs and risks [12]. In short, the conditions financiers are putting on asset-intensive organizations to fulfil in order to access funds are stimulating PAM practices as non-compliance results in failure to access loans.

3.1.7 Publication of international standards in AM such as ISO 55000 and BSI-PAS 55

Although this factor was rated the least in this study, it has contributed substantially towards introduction and implementation of PAM across the globe especially in developed countries [12]. The low rating of this factor in the study area may be attributed to lack of industry awareness on PAM practices which this study intends to address. The contribution of global standards on PAM is not only the mere introduction and compliance requirements but the public awareness it brings to key stakeholders and the opportunity to benchmark within and outside the various industries. Many enterprises have developed and improved their PAM frameworks and practices based on these standards and therefore there is need to widely populate their existence to benefit various enterprises.

3.2 Exploratory factor analysis results

The results show a KMO of 0.663 and Bartlett's Test of Sphericity with a significance value of 0.000. Therefore, all conditions to conduct factor analysis were met. From Table 2, SPSS generated four underlying factors with eigenvalues greater than 1 from the data, which accounted for a substantial amount of variance toward what the instrument purports to measure. The factor analysis showed that the five-factor solution represented the major constructs that were measured in the combination of the original variables.

Table 2: Factor analysis results for the factors affecting PAM practices in WBs in Malawi

Rotated Component Matrix[a]

Drivers of PAM Practices	Component			
	1	2	3	4
Under-investment in AM	0.765			
Decentralization	0.746			
Accountability to public sector	0.649			
Need to optimize the value of assets throughout their life cycle		0.743		
The necessity to recognize business value (financial payoff)		0.732		
Need for an integrated and holistic approach to PAM		0.588		
Advances in ICT use for massive and complicated asset inventory management		0.460		
Need to reduce business risk		0.421		
Publication of international standards in AM such ISO 55001, BSI-PAS 55			0.730	
Response to incidents or high profile events			0.676	
Investor attitudes towards PAM			0.649	
Advances in the maintenance, repair, and rehabilitation market			0.603	
Regulation and legislation by government				0.811
Increasing system demand for maintenance, reconstruction, performance and management				0.769
Financial Constraints				0.665

Extraction Method: Principal Component Analysis.
Rotation Method: Varimax with Kaiser Normalization.
a. Rotation converged in 8 iterations.

3.2.1 Component 1: local context

Of the four components in the analysis, this component has the highest eigenvalue of 3.247 with a variance loading of 21.647%. Under-investment in AM, at 0.765, was the highest loaded variable in this component. This indicates that local context aspects are strongly affected by under-investment in AM as per the perception of the respondents. This variable can help to explain the other two variables in component 1. Adoption of AM practices is affected by AM maturity level of an organisation [50], [51], [52]. The local context component reflects how AM is organized and practiced in the study area.

3.2.2 Component 2: an entrepreneurial approach

This component has an eigenvalue of 2.343 with a variance loading of 15.622%. The need to optimize the value of assets throughout their life cycle, at 0.743, was the highest loaded variable in this component. This indicates that entrepreneurial aspects are strongly affected by this variable as per the perception of the respondents. This variable can help to explain the other variables in component 2. Currently, every business is looking for survival and any opportunities that could bring savings such as those in PAM are being implemented. PAM ensures that all assets owned by businesses are fully utilised in their entire lifecycle. For example, entrepreneurial approach in water supply means that every drop is accounted for and that business as usual attitude is eliminated.

3.2.3 Component 3: globalization

This component has an eigenvalue of 1.548 with a variance loading of 10.323%. Publication of international standards in AM such as ISO 55001, BSI-PAS 55, at 0.730, was the highest loaded variable in this component even though it was ranked the least in the study area. This indicates that globalization aspects are strongly affected by this variable as per the perception of the respondents. This variable can help to explain the other three variables in component 3. The low ranking of publication of international standards in the study area may mean that PAM practices at WBs are at its infancy level and may also reflect lack of awareness in the field. Globally, many enterprises are implementing PAM practices because of the availability of international standards [12].

3.2.4 Component 4: compliance and demand

Although this component had the least eigenvalue of 1.330 and a variance loading of 8.870%, it was the most dominant. Regulation and legislation by government, at 0.811, was the highest loaded variable in this component. This indicates that compliance and circumstances aspects are strongly affected by this variable as per the perception of the respondents. This variable can help to explain the other two variables in component 4. As previously pointed out, for state-owned enterprises such Water Boards and other asset-intensive enterprises in general, deliberate introduction of policies, regulations and legislation by governments that emphasize on PAM would help accelerate the practice and bring much needed gains in asset-intensive industries [49].

4 CONCLUSION

This study analysed factors that drive PAM practices at WBs in Malawi using a survey. The questionnaire was used to collect data which was analysed using SPSS v 20.0. From the results, the key factors that influence PAM practices are; response to incidents or high-profile events, financial constraints, increasing system demand for maintenance, reconstruction, performance and management, legislation/regulation by the government, need to optimize the value of assets throughout their life cycle, and investor attitudes towards PAM. These factors should be prioritized by all key players especially senior management for the best probability of a successful PAM at WBs in Malawi and beyond. Surprisingly, publication of international standards in AM was least ranked in the study area yet it is widely known in literature as one of the key factor that has motivated PAM practices in many industries. This low ranking may be attributed to lack of industry awareness on PAM. Four themes emerge from factor analysis which accounts for 56.460% loading of all the factors and these are; (1) local context, (2) entrepreneurial approach, (3) globalization, and (4) compliance and demand. Compliance and demand played a dominant role in this study, and regulation/legislation by the government had the highest loading on this theme. This shows that this factor is key in PAM practices hence it should be prioritized in the study area. The dearth of AM empirical data in the study area affected the method used in the study. Nevertheless, the study carries significance in that it has not been done before hence it raises awareness of the factors and themes that may be taken into consideration when planning the implementation of PAM at WBs in Malawi and beyond. The results can also be included in educational and career development programs.

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