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A Study of System Development in a Research and Development Environment with a focus on Radar Systems

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Abstract. The objective of this study was to analyse the development of radar systems in a government research and development environment from a systems engineering perspective and identify which, if any, systems engineering tools and methods are used. The practical portion of the research took a mixed methods approach where both qualitative and quantitative data collection techniques were used. The quantitative portion of the research assessed aspects of systems engineering in the context of the research environment the participant is working in using categories of the Systems Engineering Capability (SECM) EIA/IS 731 model. Analysis of the data indicated that, in principle, systems engineering methods and tools are supposed to be applied in this research area, however this was not done consistently across projects. Some of the challenges in this research area included eliciting clear customer requirements, resource constraints and budget and schedule overruns. Recommendations were made based on the findings from a systems engineering perspective.

Introduction and Background

Safety and security has become a global concern due to the persistent and varied attacks on human and other life forms. In light of these threats, observation of one's environment is important to gather information and prevent attacks before they occur (Nahum 2015). Radar technology can provide significant advantages to security systems due to properties such as day-night, all-weather and wide-area surveillance (Weber, Premji, Nohara & Krasnor 2004). Therefore there is a need for radar systems that are affordable, easy to use, flexible and easy to deploy. However, several factors other than technical capability need to be considered for the successful development, deployment and operation of these systems. These factors include affordability, availability, ease of maintenance, and completion of the system according to the development schedule (Adrian, Ferrier & Ricci 2007). It is therefore important to assess effectiveness of the methods used to develop these systems.

Engineered systems came to be as a result of the needs of society as well as new opportunities that presented themselves as a result of advancing technology (Kossiakoff, Sweet, Seymour & Biemer 2011). The system development process is the complex effort required to recognize this need, find a realistic technical solution and develop and introduce the system into operation. Systems engineering revolves around reducing risk by addressing the problem in smaller steps. It also determines the technical skills needed to achieve the desired system; therefore it plays an important role in determining the correct combination of performance, budget and schedule and can act as an integrator between the various functions (Botha, 2016). Systems engineering can enable the delivery of successful systems as it focuses on evaluating the complexity of a system early in the project thereby leading to a better understanding of requirements and mitigating risk (Mabelo & Sunjka 2017).

Research Objectives

Many projects are driven by the need to replace old systems with systems using new technology. The complexity of modern projects often requires the integration of various systems into a larger system and including functionality that was not possible before (Bar-Yam 2003). There are various stages to the system development process and also an assumption that management is clear about the requirements at each of these stages. A project is considered a failure if these specifications are not met. The objective of this study was to assess the development of radar for safety and security in a government research and development environment from a systems engineering perspective and identify which, if any, systems engineering tools and methods are used. The study attempted to discover whether these methods had an impact on the development of radar systems. Aspects such as sustainability, project management and the research and development environment were also examined in order to understand the influence of such factors. Based on the results of the data gathering process, common factors and issues in the design, development, integration and deployment of radar systems for safety and security were extracted and analysed.

Research Questions

In order to achieve the objective of the research topic, the following questions had to be answered:

1. What are the primary systems engineering tools and methods used in radar system development?
2. Is the systems engineering process being used effectively along with project management to deliver successful radar systems?
3. What barriers exist to using systems engineering methods in a research and development environment?
4. Does a use of systems engineering tools and methods lead to successful radar system development?

Theoretical Framework

According to Hamid, Raza & Naqvi (2013), research shows that the use of systems engineering in research and development projects not only enables better management, but also better technical solutions, requirements development and management, and system development and testing. Successful application of systems engineering according to Blanchard & Byler (2016) is dependent on the proper implementation and management of the simplified process illustrated in Figure 1. The various tools necessary to enable these steps form an intrinsic part of the process.

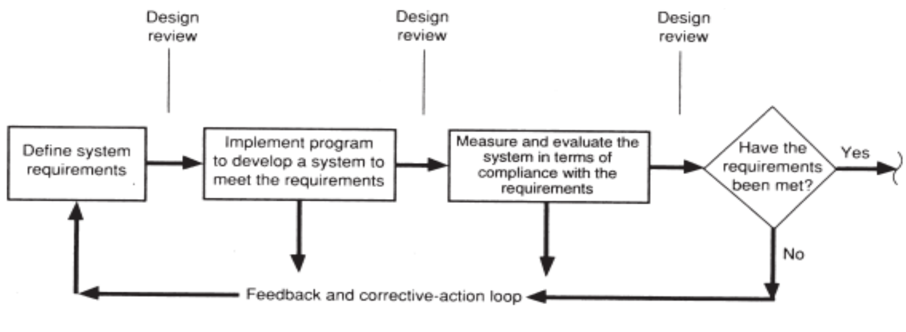

Figure 1. Simplified Systems Engineering process

(Blanchard & Byler 2016)

In the development of a system using radar technology, the radar engineer often takes the role of a system engineer (Hill 2001). The role of a system engineer is to transform operational requirements into a functioning system, a role similar to that of a project manager (Hill 2001). Systems engineering forms a part of project management as it guides the technical effort required to develop the system. According to Hamid et al. (2013), a project manager is responsible for a project failing due to unclear requirements, scope creep, insufficient reviews at the completion of a phase and overloaded schedules. The use of systems engineering methods such as requirements engineering and design reviews could therefore prevent this. Elm, Goldenson, El Emam, Donatelli & Neisa (2008) state that in many projects systems engineering is not segregated as a separate activity and is therefore hard to evaluate. Since the benefits of systems engineering are not always readily known, it can be hard to make a case for dedicated systems engineering activities. Many project managers are tempted to limit these activities to reduce cost and schedule. An understanding of systems engineering is therefore necessary to justify expenditure on related tasks and resources (Elm et al. 2008).

Systems Engineering Capability Model (SECM) EIA/IS 731 is an instrument that can be used to measure the capability of system engineering processes (Malik, Erasmus & Pretorius 2017). The quantitative portion of this case study assessed aspects of systems engineering in the context of the research environment the participant is working in using certain categories of the SECM EIA/IS 731 model. Figure 2 below illustrates the categories and focus areas of the model.

EIA/IS 731.1 SECM	
1.0 Systems Engineering Technical Category	
FA 1.1	Define Stakeholder & System Level Requirements
FA 1.2	Define Technical Problem
FA 1.3	Define Solution
FA 1.4	Assess and Select
FA 1.5	Integrate System
FA 1.6	Verify System
FA 1.7	Validate System
2.0 Systems Engineering Management Category	
FA 2.1	Plan and Organize
FA 2.2	Monitor and Control
FA 2.3	Integrate Disciplines
FA 2.4	Coordinate with Suppliers
FA 2.5	Manage Risk
FA 2.6	Manage Data
FA 2.7	Manage Configurations
FA 2.8	Ensure Quality
3.0 Systems Engineering Environment Category	
FA 3.1	Define & Improve the Sys. Engineering Process
FA 3.2	Manage Competency
FA 3.3	Manage Technology
FA 3.4	Manage Sys. Engineering Support Environment

Figure 2. SECM categories and focus areas
(Widmann, Anderson, Hudak & Hudak 1999)

For this study, the questions on systems engineering will focus on the following categories of the SECM EIA/IS 731:

- Systems Engineering Technical Category:
  Define Stakeholder & system level requirements, Define Technical Problem, Assess and Select, Verify System, Validate System
- System Engineering Management Category:
  Monitor and Control, Integrate Disciplines, Manage Risk, Manage Data, Manage Configurations, Ensure Quality

Research Design and Methodology

Research begins with the formulation of the research question(s) which strongly influence the rest of the research process including methodology, data collection and analysis methods (Wohlin & Aurum 2015). These methods may be qualitative, such as semi-structured interviews or participant observation, or quantitative such as surveys (Zahle 2018). Case studies provide an analysis that is in-depth and focussed on one or few cases and can give insight into causality, however it can be argued that the degree to which the results can be applied to an outside environment is unknown (Elm et al. 2008).

Research into systems engineering is growing, hence data gathering tools such as surveys will be increasingly used (Smartt & Ferreira 2013). The data collected from these surveys are useful in understanding, for instance, the effect of using best practice systems engineering methods on project performance, or building a business case for using these methods (Smartt & Ferreira 2013). An explanatory mixed methods design was used where an initial quantitative phase was followed up by a qualitative phase. The results of the quantitative phase was used as a framework to analyse the data collected in the qualitative phase (Borrego, Douglas & Amelink, 2009).

Research Instrument

An online questionnaire was used for the quantitative portion of the practical research. The questionnaire was used to assess the perspective of team members on the methods and tools used during various radar system development projects they have been involved in. These experimental radar systems are intended primarily for safety and security.

The qualitative portion of the research, the semi-structured interviews, was conducted with senior engineers in the radar research and development field who have systems engineering experience. The primary focus was to understand the methods used in radar system development.

Online Questionnaire. An online questionnaire was sent out to engineers working in the radar research area of a government research and development organisation with the number of possible participants being 33. The engineers are differentiated based on their seniority with senior engineers primarily taking a lead design role while more junior engineers take on a development role for the various sub-systems. Several projects run concurrently and the size of the project team may vary as resources are shared across projects.

The intention behind the format of the questionnaire was to start with questions that could help categorise the data. These were questions on the amount of years' experience working in the research area as well as the standard project duration. The next set of questions focussed on various categories of systems engineering and an ordinal scale was used. Ranked or ordinal data is used when wanting to assess how strongly a respondent agrees with a statement (Saunders, 2016). The last three questions were used to allow the respondents to rate project success in terms of meeting budget, schedule and requirements. Furthermore, optional comments were allowed on certain questions. This allowed respondents to corroborate or expand on the option selected for that question.

Semi-Structured Interviews. The questions for the semi-structured interviews sought to gain more information on certain aspects of systems engineering such as requirements definition, scope creep, sustainability, verification and validation as well as project management involvement in system development. The data gathered during the interviews gave more context to the results of the quantitative data gathering phase. The interviews were recorded and transcribed for further data analysis.

Data Analysis

Quantitative Data Analysis. The main aim of quantitative research is to show causality, here the terms independent and dependent variable come into play, i.e. the dependent variable has an effect on the independent variable (Brayman & Cramer 2011). The ordinal data from the online questionnaire was analysed by calculating the mean values, the standard deviation and the consensus level. The consensus level uses probability distribution and the range between the highest and lowest categories to produce a value that spans the unit interval (Tastle & Wierman 2007). This can be used for any ordinal scale to determine the level of agreement, i.e. consensus. The data gathered using an ordinal scale can therefore be given a value of dispersion that is logical and also theoretically sound. The consensus level formula as defined in Tastle & Wierman (2007) was used where a consensus level of 1 indicates complete agreement in that category.

The test for significance on the results was done using Fisher Exact Test. The Fisher Exact test is used in 2 by 2 tables especially for small sample sizes (StatisticsSolutions 2019). The formula for the Fisher Exact Test as defined in StatisticsSolutions (2019) was used. The formula computes the probability of the combination of frequencies that was obtained.

Qualitative Data Analysis. A key aspect of qualitative data analysis is the use of inductive reasoning which produces ideas from the collected data. The data is used to develop conclusions, a mental picture is created that tries to explain relationships between concepts and why they occur and link it back to previous knowledge (Harding & Whitehead 2013). As discussed, the online questionnaire had a written comments section. Those who chose to comment may have a different viewpoint in general and so it was important to consider the category they fell into when analysing the data (O'Cathain & Thomas 2004). Therefore the written comments on the questionnaire were analysed qualitatively. Thematic narrative analysis was used to analyse the data gathered in the semi-structured interviews where analytical themes were identified that focussed on the content of the analysis rather than the structure (Saunders 2016). The interviews were recorded and transcribed for analysis. Key words and phrases were searched for in the written and transcribed data to find data relevant to the research questions and to determine whether the results corroborated, elaborated, contradicted or complemented the results of the online survey.

Results

Quantitative Data Results

The questionnaire was first sent out to engineers actively working on various radar system development projects, the survey responses were kept anonymous. Out of the 33 people the survey was sent to, 12 people responded. The majority of respondents have worked in the research area for 10 years or more. Due to the low response rate, the data was first analysed by looking at the respondents as a whole, then by splitting the respondents into those with experience working in this specific area for less than 10 years, hereafter referred to as Group 1, and engineers with more than 10 years' work experience, hereafter referred to as Group 2. This was done based on the observation that engineers in this research area with more years of work experience have a more senior role in system development. Project duration was not considered as a control variable as 11 out of 12 respondents work on projects that last 2 to 4 years.

Table 1 below displays results for questions where the consensus (level of agreement) is higher than 0.6 for at least one group. The cells that are greyed out indicate a result where the consensus is less than 0.6. A value of 0.6 was chosen as it indicates a clear majority in terms of level of agreement (a value of 1 indicates complete agreement in a category as previously explained).

Table 1: Overview of Quantitative results (greyed out cells, consensus < 0.6)

General Systems Engineering Awareness	Overall	Group 1	Group 2
Systems engineering methods are applied during system development in your research area.	Neither agree nor disagree	Mostly Disagree	Mostly Agree
There is a well-documented systems engineering process that is widely communicated in the research area.	Mostly Disagree	Mostly Disagree	Somewhat Disagree
Systems Engineering Technical Category	Overall	Group 1	Group 2
Requirements are clearly defined and analysed after stakeholder engagements and before development begin.	Somewhat Disagree	Mostly Disagree	Neither Agree nor Disagree
The requirements documentation of system and system elements can be accessed by all members of the development team.	Neither Agree nor Disagree	Mostly Disagree	Mostly Agree
The requirements do not change significantly during a project life-cycle.	Mostly Disagree	Neither agree nor disagree	Mostly Disagree
There is a defined and documented guideline to choosing Commercial-Off-The-Shelf (COTS) components that meet specifications.	Mostly Disagree	Mostly Disagree	Mostly Disagree
Systems Engineering Management Category	Overall	Group 1	Group 2
Risks are identified and assessed during the concept exploration stage of a system life cycle and risk mitigation plans are put in place and documented.	Somewhat Disagree	Mostly Disagree	Neither Agree nor Disagree
There are accurate and up-to-date descriptions defining interfaces of a system in detail using interface control documents or the like.	Mostly Agree	Neither agree nor disagree	Mostly Agree
Task progress is regularly tracked and reported by those who develop and update the project plan.	Mostly Agree	Mostly Agree	Mostly Agree
There are design reviews at significant milestones at various project life-cycle phases which are well documented.	Somewhat Agree	Neither agree nor disagree	Mostly Agree
Project Success Criteria	Overall	Group 1	Group 2
Projects in this research area are completed on schedule.	Mostly Disagree	Mostly Disagree	Mostly Disagree
Projects in this research area are completed within budget.	Mostly Disagree	Mostly Disagree	Mostly Disagree
Projects in this research area fulfil all customer requirements on completion.	Neither Agree nor Disagree	Mostly Disagree	Mostly Agree

The Fisher Exact Test analysis was done on the results of the online survey to determine if there was any significance in the results between Group 1 and 2 engineers. The format displayed in Table 2 was used to test for significance in the quantitative results.

Table 2: Fisher Test Format

	Number who Agree	Number who Disagree	Marginal Row Total
Group 1 (< than 10 yrs)	a	b	a + b
Group 2 (> than 10 yrs)	c	d	c + d
Marginal Column Total	a + c	b + d	a + b + c + d

The results of the Fisher Exact indicated significance at $p<0.05$ for only one question, which was ***"Systems engineering methods are applied during system development in your research area."*** This indicates evidence of a statistically significant difference in the agreement of engineers in Group 1 and Group 2 on whether systems engineering methods are applied in this research area. Group 1 engineers were most likely to disagree with the statement while Group 2 engineers were most likely to agree with it.

Qualitative Data Results

The written comments in the online survey were considered for qualitative analysis. Semi-structured interviews were conducted with two senior engineers in the research area. The interviews were transcribed and the data analysed for themes.

Summary of Written comments. A common theme in the comments was that systems engineering methods are not consistently applied, even though in principle it should be applied in system development in this research area. Although requirements analysis is done some participants felt that it is not done to the right level and proves to be insufficient for the later phases of the project. Some of the reasons offered for this include a lack of meaningful involvement of the client in this process as well as constraints on time and resources in refining requirements. Some participants feel that due to the experimental nature of the work, requirements cannot be finalised upfront, a changing requirements base is needed. Other comments regarding requirements include that the requirements are not documented and communicated to the wider team, which can hamper the verification and validation process.

Trade-off studies are done but not all participants are involved in this process. There was a contradiction between two participants' comments on the execution of this process. One felt that although the studies are done, the selection of solutions is based on incorrect criteria. The other participant felt that the trade-off studies performed are done in depth according to a defined value system although not documented as standardised criteria across projects.

In the question regarding risk management, some participants stated that risk mitigation plans were not documented up front and mostly done ad hoc. This contradicted another participant's comment that risk registers are maintained and consulted throughout system development. Participants felt that integration plans are often not documented but verbally discussed. A reason given for this approach is that the nature of work results in circumstances changing so frequently, it would be a waste of time documenting plans that won't be followed.

Design reviews are performed in this research area however it primarily involves senior engineers. Here again there was a contradiction in the comments from participants regarding the quality of documentation generated as well as the consistency of the process. The final comments were regarding whether customer requirements were met on project completion. There was no definitive answer but the general feeling was that some requirements were exceeded while others were not met. Due to the experimental nature of the work, clients may be more flexible regarding the changing nature of requirements.

Summary of Semi-structured Interviews. After the analysis of the transcribed interviews, the following important themes could be identified. When defining requirements for a system in this research area, either the client has a base set of requirements that are then further refined or the system engineers will engage with the client to understand their needs and define the requirements. Scope creep that changes requirements can affect system development, therefore changes in contractually defined requirements must be agreed upon with the client. The impact of the changes in terms of financial and scheduling must be analysed to truly understand how it will affect the development. When factoring in sustainability in system design, this research area focuses primarily on the longevity of the system, the cost of maintenance and the type of technology, the technology chosen must not be obsolete in the near future.

The verification and validation of the system requirements is done either formally, during project reviews where the system is demonstrated to clients, or informally where the client works more closely with the development team and it is done more frequently. Verification and validation was also explained as something to be demonstrated on multiple levels, from component to system level. Therefore during requirements definition, there must be an agreement on how the various requirements will be demonstrated or measured as not everything can be measured in the same way.

Project management is considered as a key factor in facilitating the systems engineering process as it controls scheduling of resources and tasks, the budgeting of the project and the assessment of risk and other factors that will impact the delivery of the final system.

A successfully developed system is one that is completed on time, on budget and, most importantly, that meets client requirements. The key challenges to meeting these criteria in this research area are poorly defined requirements as well as constraints such as availability of resources. Requirements need to be defined in a realistic manner taking into consideration resource and budget constraints.

The overall feeling is that there needs to be some form of formalization of the systems engineering process in this research area as it will help define processes and lead to some conformity across projects.

Conclusion and Recommendations

The objective of this study was to analyse the development of radar systems in a research and development environment from a systems engineering perspective and identify which, if any, systems engineering tools and methods are used.

Research conclusions

Based on the results from the data gathering process, common factors and issues in the design, development and integration of radar systems were extracted.

The online questionnaire asked participants to rate their agreement with statements relating to the application of systems engineering in areas such as the definition of stakeholder and system level requirements, verification and validation of system specifications, assessment and selection of solutions, monitoring and controlling resources, integration of disciplines, risk management, data and configuration management, and ensuring quality.

In principle systems engineering methods are supposed to be applied in this research area. However when analysing the quantitative data, there was only consensus regarding a certain aspects.

In the systems engineering technical category, most participants disagreed with the statement that requirements do not change significantly during the project life-cycle. This corresponded with the qualitative data results where participants stated that due to the experimental nature of the work, systems are developed that try to answer vaguely defined research questions and therefore some requirements may not be properly defined before system development begins. Overall, participants did not agree that requirements are clearly defined before system development begins. Most participants also disagreed that there is a defined and documented guideline when choosing COTS components that meet specifications.

From the systems engineering management category, it could be gathered that processes such as risk mitigation, integration, design reviews and engineering design are not consistently documented across projects and if they are, the documentation is not sufficient or made available to the entire team. A positive in this category was that most participants agreed that task progress is tracked and reported so that the project plan can be updated.

The Fisher Exact Test was done on the results of the online survey and a statistically significant difference was found for one result. Participants with less than 10 years' work experience (Group 1) were most likely to disagree with the statement, "Systems engineering methods are applied during system development in your research area". Participants with more than 10 years' experience (Group 2) were most likely to agree with the statement. When looking in totality at the data gathered, there could be a few reasons behind this discrepancy. Some possible reasons are listed below:

1. Systems engineering methods are applied primarily by senior/lead engineers, sometimes tacitly. These processes are not documented or the documentation is not made widely available, therefore engineers not directly involved in these processes are not aware of these methods, the decisions made during these processes and consequently the impact thereof on system design and development decisions.
2. Senior/lead engineers have knowledge of systems engineering methods and tools, but due to a lack of defined processes, documentation and terminologies in this research area, the methods used are dependent on the lead engineer/s and are not applied consistently across projects.
3. Senior/lead engineers do not have the requisite amount of expertise and experience in systems engineering and are therefore not consistently applying these principles in system development.
4. Systems engineering methods are being applied in this research area but less experienced engineers are not cognisant of it due to a lack of communication, inclusivity or awareness of systems engineering.

Many of the key themes gathered from the semi-structured interviews corresponded with that of the data gathered from the online survey. Unclear requirements and resource constraints were some of the key challenges in this research area. The participants were in agreement that a requirements baseline must be contractually agreed on with the client and changes introduced during system development must be analysed with an impact study and changes to budget and schedule agreed upon with the client. Interviewees also agreed that project management plays a key role in facilitating systems engineering and that a formalised systems engineering process could assist in establishing processes and consistency across projects.

As stated by the interviewees, the key components in evaluating a successfully developed system was completion on time, on budget and on brief, with the most important being the fulfilment of requirements. These three criteria were also used in the online survey as project success criteria. Overall, participants of the online survey disagreed that projects are completed on time or budget. A clear answer was not obtained regarding fulfilment of customer requirements, overall the result indicated that participants neither agreed nor disagreed with the statement. However Group 2 engineers mostly agreed with the statement. The written comments expanded on this result by explaining that some system requirements are exceeded while others are not met. However, clients may be flexible regarding certain requirements considering the experimental nature of the work and at times there is renegotiation of these requirements during the development phase.

Based on the data, the main research questions were addressed below.

What are the primary systems engineering tools and methods used in radar system development? Based on the results of the quantitative and qualitative data gathering, systems engineering tools used include requirements analysis and definition with the client, concept development which entails trade study analysis of various solutions, risk analysis and feasibility studies and cost modelling. This is followed by detailed engineering design and development, with design reviews at significant milestones, implementing an integration plan, and verification and validation of requirements. In the conceptual development phase, based on the trade-off studies and risk analysis, decisions have to be made on whether to "make or buy" system elements. The system elements must have a long life cycle, have high availability and be low maintenance. Important documentation includes requirements documentation, risk registers, engineering design documentation such as interface control documents, integration plans and project plans with monitoring of task progress.

Is the systems engineering process being used effectively along with project management to deliver successful radar systems? From the results of the survey, participants did not agree that projects were completed on time or on budget. Although project management is primarily responsible for these criteria being met, systems engineering can assist in estimating these parameters. Systems engineering plays a huge role in meeting systems requirements by guiding the technical effort, but there was not a conclusive answer on whether all customer requirements were met on project completion. Based on the data it can be concluded that systems engineering and project management are not being used together effectively in this research area.

What barriers exist to using systems engineering methods in a research and development environment? As discussed, the primary challenges include poorly defined requirements as well as resource constraints. The experimental nature of the work, where several unknowns exist, and a lack of meaningful client interaction lead to the requirements definition process being short-changed. Poor requirements definition which influences technical design decisions leads to unforeseen technical challenges during development and ultimately schedule and budget overruns. Delays introduced by constrained resources and other internal processes also lead to projects going over time and budget.

Does a use of systems engineering tools and methods lead to successful radar system development? This question cannot be conclusively answered in the context of this case study. The data shows that although senior engineers in this research area are aware of various systems engineering tools and methods, some participants state that these methods are not consistently applied in projects. This is supported by the data gathered from the survey, where participants disagree on whether several key systems engineering methods are applied. Systems engineering primarily plays a role in the quality of the final system, however here again it cannot be conclusively said that, in this research area, the system meets all customer requirements on project completion. Therefore, based on this case study, a relationship between the use of systems engineering methods and successful radar system development cannot be established.

Recommendations

A key challenge in system development in this research area is the lack of properly defined requirements. Requirements engineering is a key component of systems engineering, therefore it can play an important role in the requirements definition process and must be applied diligently. Systems engineering is an iterative process and the objective is to meet requirements, the system design process is a step by step lessening of abstraction with each step coming closer to the final system (Maier 1996).

Considering resource constraints in this research area, a base set of realisable requirements must be defined as early as possible in the development cycle and agreed upon with the client. Changeability must be built into the system requirements to cater for current and future requirements as more information is provided by clients (Ross, Rhodes & Hastings 2008). Additional requirements must be renegotiated with the client after considering budget and schedule impact. Systems engineering is about solving problems with clients and they must be engaged in the development process (Shenhar 1994).

Project management and systems engineering need to work together in order to successfully develop a system. The data from this case study suggests that several of project management activities are not being consistently driven and therefore it is recommended that project management plays a more interactive role in system development along with systems engineers.

System development is a team effort and although not all team members have the same level of responsibility, they must have an understanding of system and sub-system level specifications in the context of customer requirements. This can be communicated via clear and up to date documentation. It is recommended that systems engineering documentation templates be provided across projects and the location of the documents accessible to all team members. This will also make it easier when resources move across projects to have a base set of documentation to familiarise themselves with the system.

Integration is a vital component of systems development as many issues may arise when sub-systems are integrated that need to be resolved as quickly as possible. Therefore it is recommended that an integration plan is discussed up-front, documented and updated, and that there is sufficient project control so that the plan is implemented.

In many projects, systems engineering is not a segregated task, it may even form part of project management (Elm et al. 2008). If there is not an agreement on what is categorised as a systems engineering task, the effectiveness of the methods can be hard to evaluate and it can be difficult to make a case for dedicated systems engineering activities.

Therefore it is important to establish some form of process in order to measure the effectiveness of it. As stated previously, the data collected in this study could either help analyse the effect of using best practice systems engineering methods on project performance, or build a business case for using these methods Based on the results of this case study, it is recommended that this research area formalises its systems engineering process. The intensity of the application of processes may vary across projects, as explained by Emes, Smith, James, Whyndham, Leal & Jackson (2012), there should not be an over-dependence on processes, especially where it does not apply, engineers must understand the principle behind a process rather than mindlessly enforce it.

Future ResearchAlthough this case study touched on aspects of project management, it was not explored in detail. Therefore the relationship between project management and how it can facilitate and also benefit from systems engineering can be explored in more detail in future research.

As can be gathered from this case study, properly defined requirements have an impact on system design and development. Requirements engineering in the context of an experimental research and development environment with funding restrictions is also a topic that can be further researched.

This study used certain categories of the SECM EIA/IS 731 model to measure the capability of systems engineering processes, future research can also use models such as Capability Maturity Model Integration (CMMI) and Software Process Improvement and Capability Evaluation (SPICE) that are used to assess and improve both software and systems engineering processes.

References

Adrian, O, Ferrier, J.M & Ricci, Y 2007, *A combination of NLOS radar technology and LOS optical technology for Defence & Security*, Thales Air Systems.

Bar-Yam, Y 2003, 'When Systems Engineering Fails---Toward Complex Systems Engineering. Exchange', 16, pp. 1990-1993.

Blanchard, B. & Blyler, J. 2016. *Introduction to System Engineering. System Engineering Management*, pp 1-52.

Borrego, M, Douglas, EP & Amelink, CT 2009, 'Quantitative, qualitative, and mixed research methods in engineering education', *Journal of Engineering education*, 98(1), pp. 53-66.

Botha, BW 2016. 'Systems Engineering as integrator between engineering and business', 2016 *IEEE Frontiers in Education Conference (FIE)*, 2016. IEEE, 1-7.

Brayman, A & Cramer, D 2011, *Quantitative Data Analysis with IBM SPSS 17, 18 and 19: A Guide for Social Scientists (First Published)*, NewYork: Psychology Press.

Emes, MR, Smith, A, James, AM, Whyndham, MW, Leal, R & Jackson, SC, 2012, 'Principles of Systems Engineering Management: Reflections from 45 years of spacecraft technology research and development at the Mullard Space Science Laboratory', *INCOSE International Symposium, 2012*. Wiley Online Library, pp. 1069-1084.

Elm, J. P, Goldenson, D, El Emam, K, Donatelli, N & Neisa, A 2008, *A Survey of Systems Engineering Effectiveness-Initial Results*, Carnegie Mellon University.

INCOSE Measurement Working Group, 2010, *Systems Engineering Measurement Primer: A basic introduction to measurement concepts and use for systems engineering*, 2010, INCOSE.

Hamid, U, Raza, MK & Naqvi, RF 2013, 'Impact of System Engineering Practices on the Performance of R&D Projects-Initial Results', *International Journal of Computer Theory and Engineering*, 5(1), pp. 158.

Harding, T & Whitehead, D 2013, *Analysing data in qualitative research*, Elsevier-Mosby, Marrickville, Sydney.

Hill, RT, 2001, 'Considerations in radar system engineering', *Radar, 2001 CIE International Conference on, Proceedings*, IEEE, pp. 25-28.

Kossiakoff, A, Sweet, WN, Seymour, SJ & Biemer, SM 2011, *Systems engineering principles and practice*, John Wiley & Sons.

Mabelo, PB & Sunjka, BP 2017, 'Application of systems engineering concepts to enhance project lifecycle methodologies', *South African Journal of Industrial Engineering*, 28(3), pp. 40-55.

Maier, MW 1996. 'Integrated modeling: A unified approach to system engineering'. *Journal of Systems and Software*, 32(2), pp. 101-119.

Malik, HH, Erasmus, L & Pretorius, JHC 2017, 'Qualitative exploration into the application of Systems Engineering within a South African science council', *2017 IEEE Technology & Engineering Management Conference (TEMSCON)*, IEEE, pp. 221-226.

Nahum, CE, 'Requirements of RADAR techniques for defence activities 2015', *Signal Processing Symposium (SPSympo), 2015*. IEEE, pp. 1-5.

O'Cathain, A & Thomas, KJ 2004, '"Any other comments?" Open questions on questionnaires–a bane or a bonus to research?' *BMC medical research methodology*, 4(1), pp. 25.

Ross, AM, Rhodes, DH & Hastings, DE 2008, 'Defining changeability: Reconciling flexibility, adaptability, scalability, modifiability, and robustness for maintaining system lifecycle value', *Systems Engineering*, 11(3), pp 246-262.

Saunders, M N 2016, *Research methods for business students*, 7th ed., Pearson Education India.

Shenhar, A 1994, 'Systems engineering management: A framework for the development of a multidisciplinary discipline,' *IEEE Transactions on Systems, Man, and Cybernetics*, 24(2), pp. 327-332.

Smartt, C & Ferreira, S 2013, 'Applying systems engineering to survey research', *Procedia Computer Science*, 16, pp. 1102-1111.

StatisticsSolutions 2019, *Fisher Exact test* [Online], Available: https://www.statisticssolutions.com/fisher-exact-test/ [Accessed 24 June 2019 2019].

Tastle, WJ & Wierman, MJ 2007, 'Consensus and dissention: A measure of ordinal dispersion'. *International Journal of Approximate Reasoning*, 45(3), pp. 531-545.

Weber, P, Premji, A, Nohara, TJ & Krasnor, C 2004, 'Low-cost radar surveillance of inland waterways for homeland security applications', *Radar Conference, Proceedings of the IEEE, 2004*, IEEE, pp. 134-139.

Widmann, E, Anderson, G, Hudak, G & Hudak, T 1999, 'The taxonomy of systems engineering competency for the new millennium', *Proceedings of the ninth annual international symposium of the INCOSE*, 1999, Citeseer.

Wohlin, C & Aurum, A 2015, 'Towards a decision-making structure for selecting a research design in empirical software engineering', *Empirical Software Engineering*, 20(6), pp. 1427-1455.

Zahle, J 2018. *Data, epistemic values, and multiple methods in case study research*. Studies in History and Philosophy of Science Part A.

Biography

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Louwrence D. Erasmus worked for more than 25 years in academia, national and international industries. He holds appointments as Principal Systems Engineer at the Council for Scientific and Industrial Research (CSIR) and part-time senior lecturer at the Graduate School for Technology Management (GSTM), University of Pretoria. He held various positions as engineer in various industries. His research interest is the underlying formal structures in systems engineering using constructivist philosophy of science and their implications in practice. He graduated from the Potchefstroom University with B.Sc., B.Ing., M.Sc. degrees in 1989, 1991 and 1993 and a Ph.D. in 2008 from North West University, Potchefstroom. He is a registered professional engineer with Engineering Council of South Africa (ECSA) and a senior member of the IEEE and South African Institute of Electrical Engineering (SAIEE) and a member of the International Council on Systems Engineering (INCOSE).