Industry Taking up On-demand Additive Manufacturing of Spare Parts

***Abstract*—The adoption of Additive manufacturing (AM) in South Africa has grown significantly, with more industries investing and investigating the possibility of adoption to their operations. Some of these industries are the railway and mining industries, following the wider demands in the aerospace markets. This paper demonstrates some of the developments that has happened recently, what these industries are investigating, how they go about it, and how they can possibly benefit from adopting the technology.**

Keywords— Additive Manufacturing, On-demand supply, Industry case studies

I. Introduction

The early adopters of Additive Manufacturing (AM) technology have been the medical and aerospace industries sector. Centres such as the CRPM at Central University of Technology in Free State, began commercializing medical prototypes in plastics and metals. The focus is finally starting to shift from research to implementation in other industries such as the railway and mining industries [1, 2, 3, 4]. These industries are enormous and their adoption of the technology could begin to revolutionize the demand and manufacturing capabilities of South Africa.

Many aircraft manufacturers are already using AM technology to produce high-cost, long lead-time, metallic components. AM has begun to change the conventional configuration of the aircraft spare parts supply chain to achieve safety inventory reduction; thus cutting inventory holding cost across the entire supply chain [5]. Literature has demonstrated that the centralized AM supply chain is however more suitable for parts with low average demand, relatively high demand fluctuation and longer manufacturing lead time.

Globally, adaptability has typically been slow in sectors such as rail and mining maintenance systems with advances in design and technology delayed in filtering through to operators. Research, however, continues to grow on how the introduction of alternative manufacturing methods such as AM might assist these industries with design and production optimization, as well as the maintenance of various internal components. Companies such as Alstom are adopting light rail and heavy rail compatible assets that can be interchanged, in order to better adapt to changing demands [4, 6]. Deutsche Bahn have 3D printed parts for their older fleets, the first generations of ICE high-speed trains, which are no longer in large-scale production [6].

Companies want to understand the quantitative impact to understand what it means for their business, and make decisions to improve their operational efficiency and provide better service offerings. They are looking at a different approach in using AM, to minimize maintenance costs, down-time and to increase efficiency. AM has also proved to be beneficial in the production of spare parts, with opportunities for increasing localization of production and consumption goods to create employment. In the case of the mines, the reasoning is not necessarily to produce the parts at a cheaper price, but rather to, for instance, possibly empower and benefit the communities around them.

Since 2014, market research continue to project that adoption of 3D Printing would dramatically alter the supply chains, but most provide qualitative and quantitative descriptions of what that impact may be. Analyses suggest that 3D Printing will reduce the total supply chains cost by 50-90% as production will move from make-to-stock in offshore/low-cost locations to make-on-demand closer to the final customer with major reductions coming from transportation and inventory costs [7].

In this paper, the multiple case study was used to generate the framework for implementation of AM for on-demand manufacturing of spare parts, especially those in metallic materials such as steels.

II. Methodology

This research studies a holistic view on the impacts of AM across different phases, the structure illustrated in Fig. 1 will be exploited. The adopted framework encompasses the main processes that a given manufacturing company deals with across the various stages of AM technology impact evaluation.

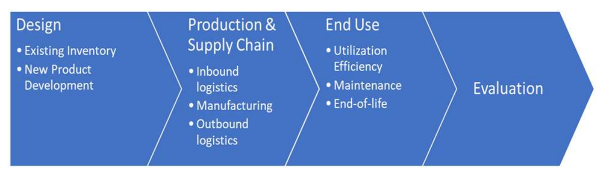


Fig. 1: Holistic view of AM technology impact [7]

Two case studies were carried out in companies operating in different industrial sectors. The first case study, in the rail context, shows the potential of AM, especially in the design phase, allowing for product customization. The second one, performed in the mining sector, shows the use of different techniques to demonstrate the impact of production and supply chain phase, on inbound logistics. The approach is to cover some of the opportunities and barriers towards the implementation of AM to South African industries.

Two different approaches were taken in each case study. The one used in case study 1 was to do a complete redesign,

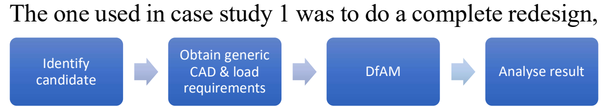


Fig. 2: Process flow of case study 1 - Railway industry approach

using Design for Additive Manufacturing (DfAM) tools, of an identified component. The other approach use in case study 2 was candidate identification from data collection and analysis. The candidates were then taken through the DfAM process. The DfAM process was done to obtain CAD models of the components, which was then used to determine cost and the correct method to additively manufacture.

A. *Case study 1*

In this case study, the knuckle in the coupler system was identified as the potential candidate. The coupler is used in the railway industry, where it is used to link the locomotive and carriages to one another. The knuckle (grey part in **Error! Reference source not found.**) is the part that interlocks and bears most of the load.

A comparison was then made between the topology optimized and the original organic CAD model with regards to strength and weight. The comparison was made to determine if the topology-optimized part would be able to handle the required loads, while being significantly lighter than the original part.

B. *Case study 2*

The second case study describes an approach taken towards AM by a company operating in the mining sector. The study includes an analysis of company's inventory of spare parts, such as impellers for pumps, shaft sleeves, gasket bonnet valves, and mining rock drill bits, exploring the impact of adopting a digitally distributed supply chain, and then digitizing, locally producing and testing these parts for operations in South Africa.

This case study took a much different approach to case study 1 and forms part of the first phase of the project, which is to investigate the use of AM in the production of

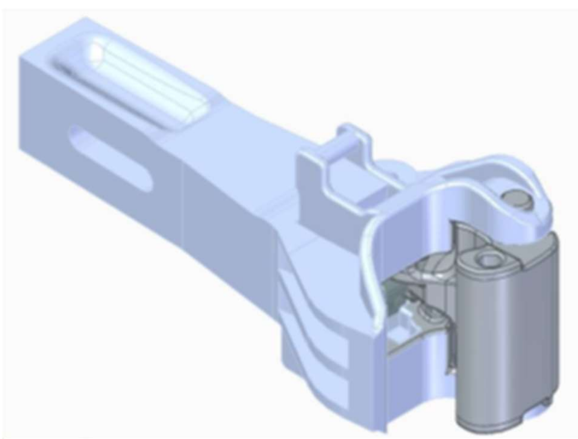


Fig. 3: Coupler system [1]

Fig. 4: Process flow of case study 2 - Mining industry approach

on-demand spare parts. Data was collected from the company's Supply Chain department on the inventory that can be candidates for digital distribution and local on-demand manufacturing model. The data consisted of stock count, lead-time, minimum order quantity, material price, etc.

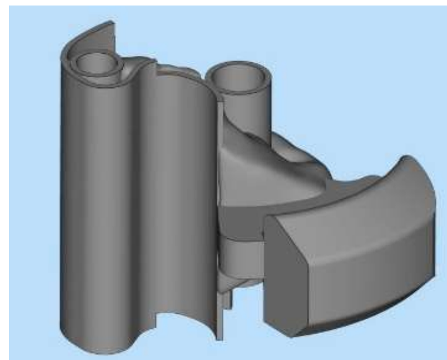
The candidate impellers were identified, procured and sent for reverse engineering to obtain their CAD models. The reverse engineering consisted of 3D scanning the impellers, importing the point cloud data into a CAD package and creating a model that fits the point cloud data exactly. Possible methods of manufacturing each impeller were identified, as well as the estimated costs for each method.

III. Results

A. *Case study 1*

The topology-optimized part is shown in Fig. 5. When analyzing the results shown in

TABLE I, it seems that the optimized design's stresses are much higher than the original design and that the optimized design will not be suitable for the application. **Error! Reference source not found.**, however show high



stress can be attributed to stress concentration in the part.

Fig. 5: Topology-optimized part

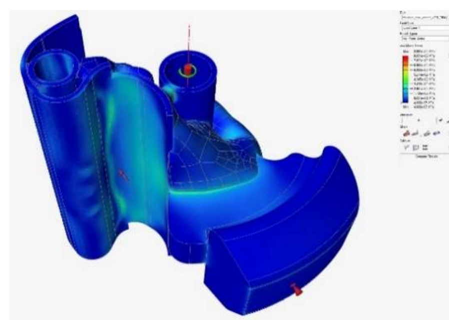


Fig. 6: Von Mises stress analysis of optimized part

TABLE I: Original Part vs Optimized Design

	Original part	**Optimized design**
Design weigh (Kg)	44.967	24.876
Part volume (cm^3)	5728	3169
Von mises stress (Mpa)	±246	±870

According to information received, the cost of one of these knuckles is R6,000.00, excluding Value Added Tax (VAT) and the freight charges, which significantly increases the cost. The major bottleneck has been the lead-time of up to six months and replacement happens every 4 to 5 years. The next step for this case study would be to determine a manufacturing process that would make the on-demand supply of these knuckles viable. The company has been inclined to invest in AM for several reasons among which, the following common goals can be mentioned:

- redesigning their products to fully exploit novel concepts introduced by AM,
- improving the production processes by cutting back on wastes and optimizing their resources,
- enhancing performance of their final products in the use phase.

By avoiding time-consuming steps spent for creating molds or tools, companies could test multiple working prototypes in just a few days; something that would otherwise take a couple of weeks (or even months) to be delivered by their external suppliers. Thus, for those products and sectors where high performance is not a key competence, the main aim behind introducing AM is not related to the possibility to customize products and increase their functionalities, but rather to the opportunity to reach their target market faster and reply to market changes with higher agility [7].

B. *Case study 2*

The preliminary investigation provided data from supply chain of three business units within the South African mining company. The data categorized items and the total spent for the year 2020 as presented in Fig. 7. The components identified as candidate parts were impellers that account to over $ 4 million of the total spent for 2020. The following are the reasons why impellers were chosen as the candidate parts over pumps and valves:

- They can be quite expensive, which would make AM a good option.
- Their geometry is complex enough to eliminate many traditional manufacturing methods.
- They need to be replaced after a certain amount of working hours or if wear is observed during a maintenance check.
- They are used in pumps and compressors, and along with bearings is the most commonly replaced in these systems.
- Valves do not have complex components that need replacing.

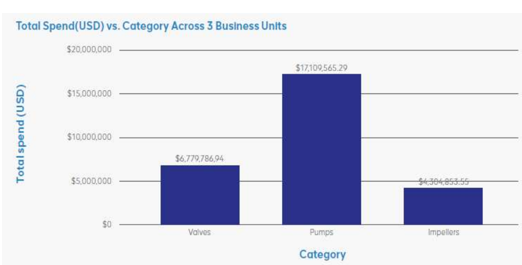


Fig. 7: Total spend on spare parts

The CAD model and build simulation result for one of the sampled impellers is shown in Fig. 8 and Fig. 9 to illustrate the design features. There were a few design and manufacturing challenges with this impeller. Firstly, the internal cavities made reverse engineering difficult. A mold had to be created of the internal and then the mold had to be 3D scanned so the CAD model could be completed. For manufacturing, the internal cavities need to be smooth as to not affect the performance of the impeller. With manufacturing through Laser Powder Bed Fusion (LPBF), as an example, support structures are required in order to anchor a part to the build plate and to conduct heat away from the processing area. Removal of these structures leave behind small features that affects the surface roughness. Thus, these structures need to be kept to a minimum and the only way to do this is to manufacture the impeller in the upright position, as illustrated in Fig. 9. However, this greatly increases the cost.

The research explored many possible methods of manufacturing the impeller and is shown in *TABLE II*. For the purpose of this case study, only methods that utilize AM where considered. The table also shows the estimated costs and the costs when following the normal procurement route.

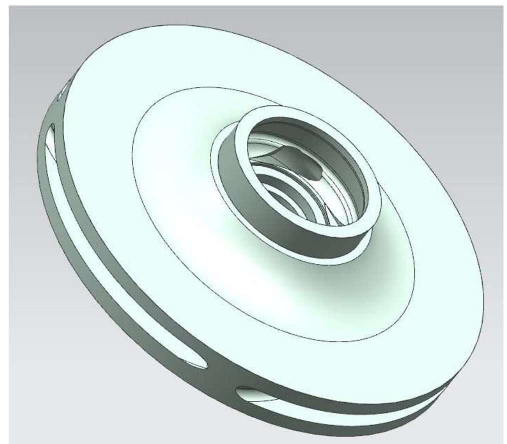


Fig. 8: Reverse engineered CAD model of Stainless Steel impeller

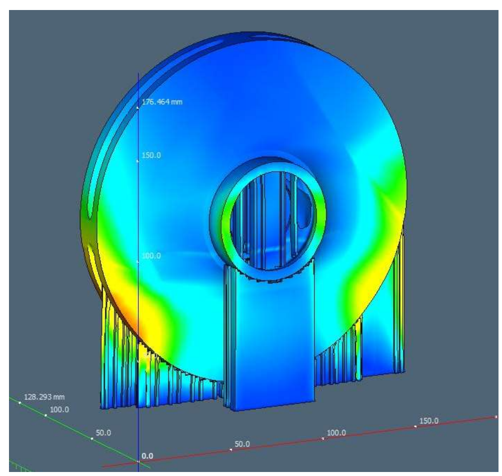


Fig. 9: Build simulation results for Stainless Steel impeller

TABLE II: CANDIDATE STEEL IMPELLERS

	Traditional Manufacturing	**Additive Manufacturing**
Method	Sand Casting	- Laser Powder Bed Fusion (LPBF) - AM assisted investment casting
Part Cost	R 17 875.45 $ 1 179.78	R 32 791.00 (LPBF) $ 2 164.18
Lead time (Days)	21	5

The two identified manufacturing processes for this impeller was LPBF and AM assisted investment casting. LPBF is a process that utilizes a laser to melt the cross-sections of a part, layer-by-layer. AM assisted investment casting is where a sacrificial model of the part is manufactured through an AM process, like binder jetting, in order to create an investment casting mold for the part. When looking at the costs presented in TABLE II, it seems that LPBF is much more expensive than the current method of procurement. However, the cost could be reduced by for instance doing a batch build of the impeller instead of just one at a time. Even though the cost of AM assisted investment casting is not shown, early predictions show that it might be a more viable option.

IV. Discussion

The results from the case studies presented in *TABLE II* presents a resume of the framework for a holistic view of the impact/change across supply chain processes and stages. AM impact the rail industry in the design phase, while leaving no significant impacts in the final use phase. The increases in unit production costs, and reduction of lead times in the production phase amount to conflicting results in the overall evaluation especially for the parts selected for the mining industry. However, if the final production cost is the only criterion for making a decision, it can be said that AM in this case may perform worse than the conventional process.

It can be argued that AM shows a dual impact in this case. On one hand, there is a positive impact on inbound logistics and pre-production phase, resulting in reduction of inventory level, lowering tool utilizations, and shortening the lead time from 4 weeks to 1 week.

TABLE III: Holistic framework

Holistic supply chain framework		Rail	Mining
Design	Product Development (concept, functionality development and prototyping)	Changing	No change
Production & Supply Chain	Inbound logistics (Transpotation, distribution & inventory)	Changing	Changing
	Production (Manufacturing, post-production & QC)	Changing	Changing
	Outbound logistics (Transpotation, distribution & inventory)	No change	No change
End Use	Utilization Efficiency	No change	No change
	Maintenance	No change	No change
	End-of-life	No change	No change

V. Conclusion

A. Case study 1

As mentioned in the results, the high stress results are caused by stress concentrations. These stress concentrations can be eliminated by redesigning these areas, which will not have a major effect on the part's volume. It can be concluded that the topology-optimized part could help achieve the goal of increasing payload, by achieving a weight saving of 45%.

B. Case study 2

The research in the mining sector continues through interviews and literature searches, a "top-down" approach was applied to a develop cost-benefit model to identify and evaluate potential spare parts for AM from the current spare parts portfolio. The results were evaluated as promising for several of the spare parts in terms of reduced manufacturing, procurement, tool cost, and lead-time reduction, which results in increased uptime for mining business units. There is also great potential for reducing the costs for warehousing, where spare parts of low demand can have their stocks reduced or eliminated by securing supply through on-demand manufacturing.

C. Overall conclusion

Exciting times lay ahead for AM in South Africa now that large industries such as the mining and railway industry are investigating the use of AM in their operations. When weighing the different options, one has to look at the bigger picture and not just at the cost. Some of the aspects, that also has to play a role in the decision-making, are as follows:

- Local investment and economy growth
- Storage costs/space
- Carbon footprint (e.g. shipping vs. locally manufactured)

The supply chain managers can reduce their inventories to virtually zero while still maintain 100% item fill rate from OEM manufacturers. While they are projected to lose revenue on the freight business this can be an opportunity to transform their service offerings and forge partnerships with end-users to provide integrated manufacturing and supply chain services.

The holistic assessment of the two industry sectors on the implementation of AM technologies demonstrate would have to cut across the manufacturing supply chain. Businesses have to go collect qualitative and quantitative data derived from real industrial cases. This preliminary study showed that industrial applications are beyond the limited number of cost related aspects that companies usually investigate. A series of changes and disruptive concepts across supply chain would consequently imply that AM adoption could be accelerated though digitized on-demand manufacturing using advanced AM technologies.

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