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A Framework for Additive Manufacturing Technology Selection:
A Case for the Rail Industry

Rumbidzai Muvunzi, Tshwane University of Technology, South Africa
Khumbulani Mpofu, Tshwane University of Technology, South Africa
Malika Khodja, University of Pretoria, South Africa
Ilesanmi Daniyan, Tshwane University of Technology, South Africa*

ABSTRACT

Additive manufacturing is a popular emerging technology of producing parts directly from digital models. This technology has presented benefits such as freedom of design, the ability to customise, and shortened process chains. Presently, there are different additive manufacturing (AM) processes that are available in the market. Often, transport equipment manufacturing companies are faced with challenges while selecting the AM processes that are suited to their needs. Decision-makers need to consider all the underlining factors before a conclusion is reached. This paper proposes an approach that can be used by companies in the rail sector to select AM technologies that are suited to their applications. The approach involves identifying suitable parts, comparing applicable AM technologies, and selecting the most suitable technology. The next stage involves re-designing the parts based on the selected technology. The approach is applied to benchmark parts from the industry. The study provides enlightenment on how AM can be applied in the rail industry.

KEYWORDS

Additive Manufacturing, Rail Sector, Transport Equipment

INTRODUCTION

Many companies in the transport-manufacturing sector (i.e., rail, automotive, and aerospace) are interested in adopting additive manufacturing (AM) because of its benefits, such as freedom of design and shortened process chains. Traditionally, AM was mainly applied to produce prototypes as part of the product development process; however, this has shifted to producing fully functional parts (Kumar, 2016). Most manufacturing companies in Africa use conventional manufacturing methods; this limits the range of parts manufactured. AM technologies can enable these companies to produce parts that they previously could not due to the high costs and inflexibility of their manufacturing methods (Khorram Niaki et al., 2019). This is a sustainable drive for creating employment and improving manufacturing competitiveness. The companies need to select the most suitable AM technologies

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*Corresponding Author

that can satisfy their needs. Although some of the applications of various AM technologies can overlap, there are significant differences in terms of accuracy, speed, and materials (Bikas et al., 2019). Most of the methods for selecting AM processes developed in literature are mainly focused on specific part designs or groups of processes that use the same form of technology. Mançanares et al. (2015) developed a method for selecting AM processes depending on the characteristics of the parts. However, the method was limited to the fused deposition modelling (FDM) technology and is not applicable to other AM technologies. Papakostas et al. (2020) proposed an agent-based decision support system that can be used by companies to select AM service providers, equipment, and process configuration. In principle, the proposed approach could be used with 3D equipment, with the interfacing of the CAM software, except for the metal AM equipment. Wang et al. (2017) gave a review of process selection methods and proposed a new method based on the nonsequential decision-making method. In their argument, they pointed out that other sequential decision-making methods do not give the opportunities to modify the design of parts based on the design for AM (DfAM) perspective. The DfAM is an important approach to ensure full utilization of AM capabilities. The designer needs to choose the most suitable AM processes during the design stage. Whilst knowledge on conventional processes is available in literature, it is important to understand the capabilities of the AM processes, since they are free from the limitations of conventional methods. Although more than one AM technologies can be used for a specific application, the technologies differ in terms of size, materials, and quality (Bikas et al., 2019). Most companies that are interested in adopting AM technologies do not have the required knowledge to make the right decisions. Although knowledge of design rules is available in literature, the guidelines do not provide enough information on the capabilities of AM technologies (Vaneker et al., 2020). Gokuldoss et al. (2017) developed guidelines for selecting suitable AM processes among binder jetting, selective laser melting, and electron beam melting processes. Other AM approaches and their novelties are presented in Table 6 in the Appendix. Although the above-mentioned efforts were made to guide process selection, many AM processes have been recently developed. There is still a dearth of information regarding the development of a suitable framework for part selection for the transport industry. Most of the research done on the application of AM in transport manufacturing is on the aerospace and automotive sector, and there is limited information on the rail industry. This paper aims to propose an approach that companies in the rail sector can use to select AM technologies that are suited to their application. Hence, this study will add to the understanding of AM opportunities for the transport industry while presenting them with the parameters for comparative analysis of the AM technologies. The paper is structured in four sections. The following section provides a literature review. Then, the authors explains the proposed approach. Subsequently, the authors evaluate the proposed approach using typical case study parts. The last section gives a concluding summary.

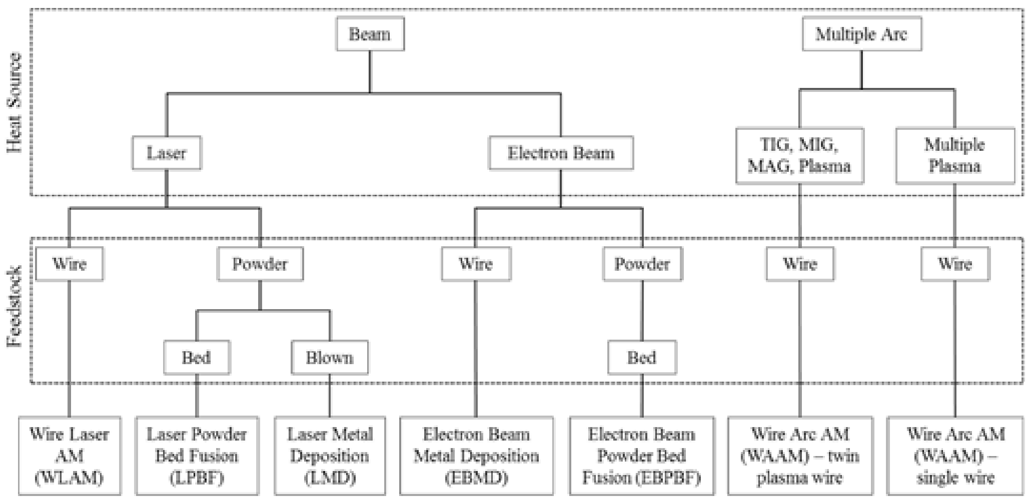
LITERATURE REVIEW

ISO/ASTM (ASTM, 2010) defines AM as the process of joining materials to manufacture parts directly from 3D model data, usually layer by layer . Metal AM technologies can be classified according to the heat source and the raw material type (Figure 1).

Metal AM presents many opportunities in the transport equipment manufacturing sector. Table 1 gives a summary of literature on the application of metal AM in the transport equipment manufacturing sector.

Based on the literature, the authors depicted in Table 1, AM has been mainly applied to produce functional parts in the aerospace and automotive industries. In the rail industry, much of the works involved using AM are to produce prototypes rather than functional parts. Farahani et al. (2019) used AM to develop a prototype model for a railway tunnel as a tool for evaluating the performance of a 3D-scanning system for inspection. Chen et al. (2021) investigated the use of fused deposition modelling, a polymer-based AM process to produce prototype railroad tracks for micropeople movers.

Figure 1. Classification of metal additive manufacturing technologies (Colomo et al., 2020)



Hoosainn et al. (2020) produced a weight-optimized prototype for a knuckle that is part of a system for connecting rail-cars.

Additive Manufacturing Opportunities in the Rail Industry

Although there has been limited application of AM in the rail industry, opportunities still exist. The next section explains some of these opportunities.

Optimizing Spare Parts Production

One of the major challenges rail equipment manufacturers face is the availability of spare parts. The demand for spare parts is volatile and often difficult to predict (Frandsen et al., 2020). As a result, downtime is experienced while waiting to replace a broken spare part. In other instances, much capital is tied up in spare-part inventory stock, which might not be useful at that particular time (Knofius et al., 2016). Also, considering the current trends in technological evolution, the designs of parts are continuously changing. Some spare parts become obsolete and it becomes difficult to replace them. AM can resolve the above-mentioned challenges by printing the spare parts on-demand, thereby eliminating the waiting time associated with procuring the parts elsewhere or the tooling costs of producing the parts in-house using conventional methods (Sgarbossa et al., 2021). In addition, reverse engineering can be conducted for parts with designs that have been lost. Thus, physical inventory can be converted to digital inventory, thereby resulting in cost savings. Europe is currently pursuing a project called Runtorail, which involves the use of composite materials to produce spare parts for the rail industry (Killen et al., 2018). Dubai's road transport authority is currently working towards the use of AM to produce spare parts (Rizvi, 2020). Webtech, an international railway company, is also using AM to produce spare parts (Colyer, 2019). Deutsche Bahn, a Germany rail company, is partnering with AM companies such as Siemens and Garfertech in producing space parts for their old fleet (Bahn, 2022).

Producing High-Value Components With Optimized Designs

AM gives the opportunity to develop designs with increased flexibility, thereby overcoming the restrictions of conventional manufacturing processes (Orme et al., 2017a; Zhu et al., 2018). This opens up opportunities for coming up with modular designs with increased adaptability

Table 1. Application of metal additive manufacturing in the transport equipment manufacturing sector

Author	Application	Sector	Technology
Abdi et al. (2018)	Design optimization and manufacture of a titanium brake pedal with improved functionality.	Automotive	LPBF
Hoosen et al. (2020)	Investigating the potential use of AM to produce a weight-optimized prototype with the support of simulation and topology optimization.	Rail	LPBF
Torres- Carrillo (2020)	Investigating the environmental impact of applying AM to manufacture turbine blades.	Aerospace	LPBF
Liu et al. (2017)	Investigating the application of AM to manufacture parts for the rail industry. Parts considered for AM include turbine housing, engine combustion chamber, exhaust duct, and airfoils.	Aerospace	LMD LPBF
Walton & Moztarzadeh (2017)	The study is focused on the use of topology optimization to produce a car suspension with an optimized design. The resultant AM part achieved a 36% weight reduction.	Automotive	EBMD
Shi et al. (2020)	Application of topology optimization to redesign an aerospace bracket with improved design.	Aerospace	LPBF
Kim et al. (2020)	Design optimization and manufacture of an automotive knuckle component using AM.	Automotive	LPBF
Orme et al. (2017a)	Design and manufacture of spacecraft components.	Spacecraft	LPBF
Uhlmann et al. (2015)	Research on the manufacture of engine components using titanium.	Aerospace	LPBF
Dimitrov et al. (2018)	Investigating process chains for manufacturing turbine blades.	Aerospace	LPBF
Gebauer et al. (2015)	Investigating the manufacture of a high-performance sheet metal forming tool for stamping a gear pan component.	Automotive	LPBF
Leal et al. (2017)	Investigating processes for manufacturing tool inserts for producing a body panel.	Automotive	LPBF
Juechter et al. (2018)	Investigating the use of Ti-45Al-4Nb-C to manufacture automotive components with improved functionality.	Automotive	LPBF
Reddy et al. (2016)	Design optimization and manufacture of a component for a formula race-car.	Automotive	LPBF
Santoliquido et al. (2017)	Design of novel ceramic structures for catalyst supports.	Automotive	LPBF
Caba et al. (2020)	Investigating the application of aluminum alloys for manufacturing crash relevant of crash-relevant application.	Automotive	LPBF
Suárez et al. (2021)	Investigation on the manufacture of an aeronautic fitting with different metal alloys using WAAM for improved efficiency.	Aerospace	WAAM
Orme et al. (2017b)	Design optimization and manufacture of camera brackets and a satellite panel insert.	Spacecraft	LPBF
General Electric (2018)	AM of fuel nozzle tip.	Aerospace	LPBF
Donath (2019)	AM of a thrust chamber of a rocket engine.	Aerospace	LPBF
Jia et al. (2020)	AM of a lettuce compressor impeller.	Aerospace	LPBF
Liu et al. (2020)	Design and manufacture of an upper stage cabin component.	Aerospace	LPBF
Berrocal et al. (2019)	Design optimization and manufacture of components: ● Connector support. ● Lever component.	Aerospace	LPBF
Guanghui et al. (2020)	Aerospace bracket		SLM

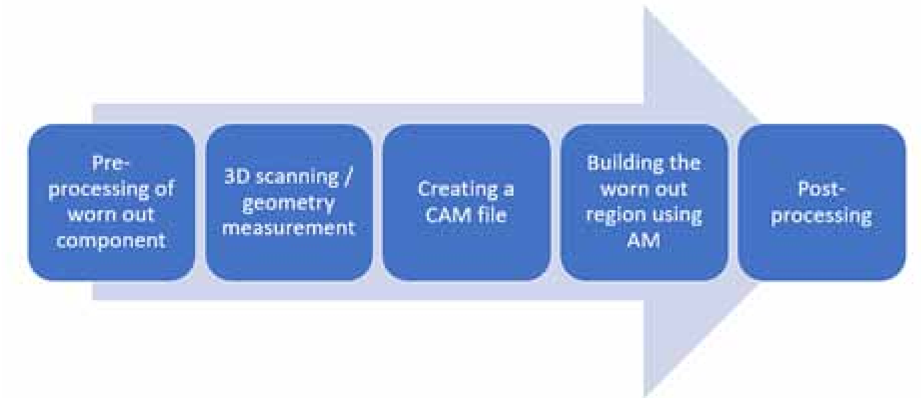
Note: LPBF-Laser Power Bed Fusion, WAAM-Wire Arc Additive Manufacturing, EBMD-Electron-Beam Additive Manufacturing, LMD-Laser Metal Deposition, SLM- Selective Laser Melting and upgradability, thus responding to the changing trends in design and customer preferences. With AM, the design of parts can be optimized to suit the needs of a particular application. Typical examples include consolidation of parts to limit the number of assemblies, removal of unnecessary material which does not contribute to the functionality, and the use of high-performance materials (Knofius et al., 2019). Consolidation of parts helps to reduce the costs, time, and resources used to assemble the parts (Yang et al., 2019). AM gives the freedom to allow placement of material only in regions that allow the functionality of the part (Orme et al., 2017b). This allows the production of railway components with reduced weight, thereby improving fuel efficiency. Figure 2 captures the methods that are necessary for achieving improvement in the DfAM. These include the change of existing material to a high-performing one, additional features for improving a product's efficiency, reduction in the number of components during assembly, topology optimization as well as the lightweight design of components.

Remanufacturing of Damaged Components

In the railway industry, AM presents an opportunity to remanufacture high-value worn-out components. Remanufacturing is the process of returning a part to its original state or performance before deterioration (Wahab & Azman, 2019). This is a sustainable approach to eliminate the costs and environmental burden associated with producing parts from scratch (Zhong & Liu, 2010). It is regarded as the best recovery method in terms of economic and environmental implications (Kurilova-Palisaitiene et al., 2018). Most of the work in literature on component repair using AM technologies was in the aerospace industry (Cavaliere & Silvello, 2017). Although a few cases were presented for the railway industry, this is a cost-effective measure of unlocking value. Taking advantage of the digital workflows in AM, 3D models of the damaged components can be created using reverse engineering. The models can then be used to produce the necessary CAM file. Figure 3 shows a proposed remanufacturing process chain. The European infrastructure project involved the use of LMD to repair the railroad head using a reinforced layer. This was done to increase fatigue performance and reduce the noise of wheel and rail contact (Hiensch et al., 2005). Lewis et al., (2015) investigated the application of LMD to repair rail tracks. Different materials such as maraging steel, stainless steel, and Hadfield were tested for the rail application. Aladesanmi et al. (2019) used LMD to coat rail tracks with titanium to reduce wear of rail wheel flanges during motion.

Figure 2. Design optimization options

Figure 3. Remanufacturing process chain



Manufacture of Complex Production Tools

The current global trends of technological advancement cause a continuous change in the train designs, thus the part designs also change. New tools are therefore required to keep up with the changes. In tool making, only a single or few components are produced. AM becomes a cost-effective method as compared to conventional processes (Lindemann et al., 2015). The initial cost of including AM in the tool manufacturing process may be higher than using conventional methods. However, the costs of producing the part are reduced due to the improved performance or reduced cycle time caused by using the tool produced using AM (Dimitrov & Moammer, 2010). Typical examples of production tools include jigs, fixtures, and stamping dies. AM creates opportunities for producing reconfigurable modular tools with increased flexibility (Scholz et al., 2016). Also, complex tools with added features for improved functionality can be produced. Typical examples include tools with embedded sensors to monitor the operating environment, dies with lubricating channels or conformal cooling features (Müller et al., 2016). AM has been used to produce sand moulds for making rail-clip fasteners. This helped to reduce the overall manufacturing lead time. Also, the moulds were designed with adaptive cooling channels for increased cooling efficiency (Fu & Kaewunruen, 2022).

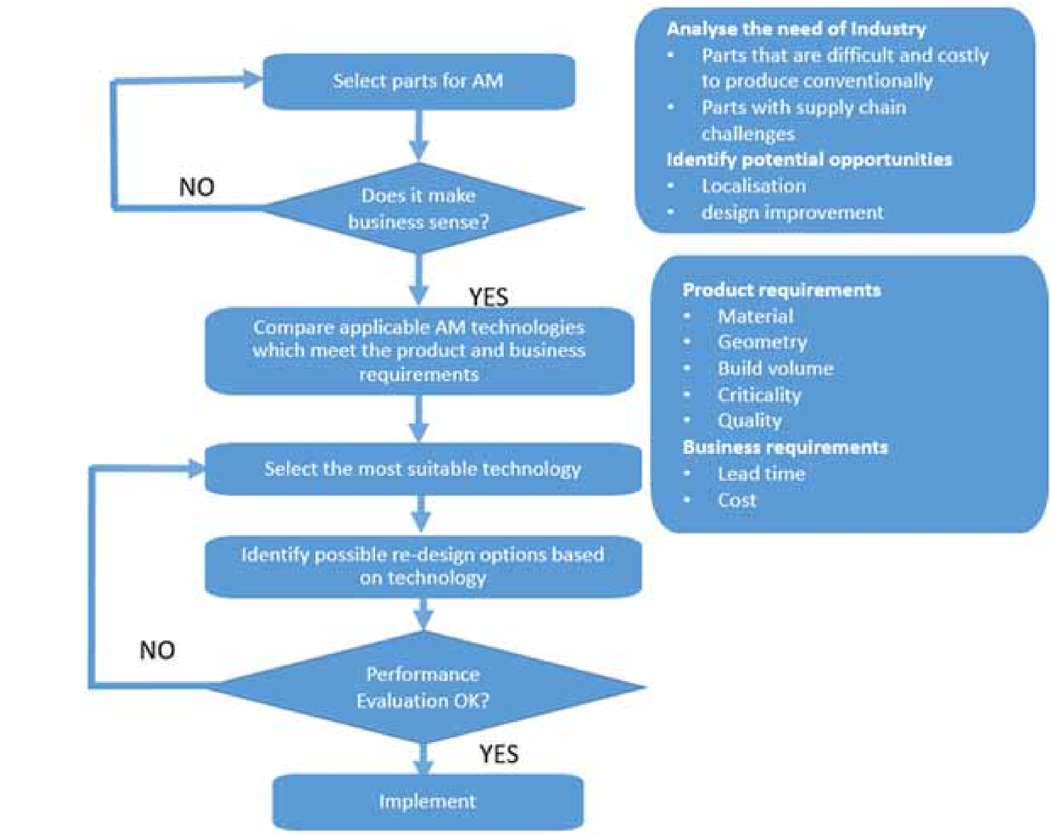
PROPOSED FRAMEWORK

Process selection is regarded as an important aspect of the DfAM (Kadkhoda-Ahmadi et al., 2019). The designer needs to be fully aware of the manufacturing constraints and capabilities before the design stage (Lopez Taborda et al., 2021). This will ensure that the parts are fully designed based on the achievable capabilities and constraints of the AM technology. Figure 4 shows the proposed approach for selecting the AM technologies. In addition, the following section details each of the steps.

Select Parts for Additive Manufacturing Application

It is important to fully analyse the industry needs and identify situations in which there are viable reasons to replace conventional processes with AM. The advantages and limitations of AM technologies, when compared to conventional methods, should be clear. AM has the potential to impact the manufacturing sector by reducing production costs for low-volume parts, reducing time to market and reducing inventory costs (Ghiasian et al., 2018). In this case, one of the most important needs is to ensure local production of parts that are imported because of lacking the required conventional technologies to produce them locally. With AM, the parts can be redesigned to suit the needs of the local customers. Another reason is to reduce supply chain costs. Considering the lifespan of railcars,

Figure 4. Approach for additive manufacturing technologies selection



some of the components become obsolete with time as technology evolves (Killen et al., 2018). Hence, producing parts with AM would be more cost-effective. Furthermore, it may be necessary to switch to lightweight and smart designs that are useful for increasing efficiency and lowering the carbon footprint (Blanco et al., 2022). The flexibility of AM allows for complex designs to be accommodated. In summary, the decision to switch to AM can be due to any of the following reasons:

- Ensuring local content.
- Reducing manufacturing costs and lead time.
- Reducing supply chain costs.
- Reducing inventory costs.
- Reducing carbon footprint and energy consumption through a lightweight and smart design.
- Increasing functionality through a high-performance design.

Compare Possible Additive Manufacturing Technologies

Several AM technologies are available on the market. Each of the AM processes has its advantages and limitations (Negi et al., 2012). At this stage, the parameters for comparing the alternative technologies are identified depending on the suggested application areas. The parameters can be classified under technical, economic, and environmental. A comprehensive comparison of the AM processes will help to expose the capabilities of the different AM technologies, allowing the designers to make a concrete decision. The technical parameters are focused on the capabilities and constraints of the technologies. The economic parameters assess the initial costs of investment and operating the equipment (Sgarbossa et al., 2021). The environmental parameters are used to evaluate the environmental impact of the technologies (Javaid et al., 2021). Table 2 gives parameters that can be used to compare the technologies.

Table 5 in the Appendix gives a more detailed comparison of the most common AM processes currently in use in industry.

Select the Most Suitable Additive Manufacturing Technology

In the process of selecting the most applicable technology, the following product and business requirements need to be considered.

Material Applicability

Certain AM processes are associated with specific processes, thus it is necessary to select AM processes which can process the required materials (Alghamdy et al., 2019). In addition, the material type affects the quality and product performance of a product (Gibson et al., 2021). By selecting the most suitable technology based on the materials, engineers can achieve optimized designs that suit their needs. Ngo et al. (2018) discussed different AM materials associated with different technologies. Materials such as titanium alloys, nickel alloys, aluminum alloys, stainless steels, tool steels, and maraging steels can be processed using PBF technology (Gibson et al., 2021). As Table 5 shows, different materials are suited for specific technologies. On the other hand, an alternative material with properties matching the initial material can be used. This is applicable if the initial material is not suited for the specific technologies or if there is a need to use a high-performance material for improving functionality. For example, Concept Laser was involved in a project in which they replaced aluminum with titanium in the manufacture of a cabin bracket with an optimized design (Liu et al., 2017). This was done to reduce weight and improve performance

Geometric Complexity

Although AM provides more design freedom, when compared to conventional processes such as machining, the level of complexity varies across different technologies (Abdulhameed et al., 2019). The powder bed fusion processes can produce highly complex parts as compared to other direct energy deposition processes such as LDMD and WAAM (Bandyopadhyay et al., 2020). Thus, a process can be selected depending on the level of complexity of the parts required. Due to the capability to achieve high complexity, PBFP can be used to produce parts with lattice structures and intricate features (Bandyopadhyay et al., 2020). On the other hand, WAAM can be used to produce larger parts with medium complexity (Satish Kumar et al., 2020).

Table 2. Parameters for comparing applicable technologies

Technical Parameters	Economic Parameters	Environmental Parameters
Material applicability	Initial investment cost	Environmental impact
Mechanical properties	Cost of raw materials	Material waste
Complexity	Build rate (speed)	Carbon emission
Accuracy	Lead time	
Surface finish		
Capability to repair damaged parts		

Build Volume

The build volume of the AM machines varies with the type of technology. Powder-bed fusion technologies have more limited build space, when compared to direct energy deposition processes (Singh & Khanna, 2021). Table 5 in the Appendix shows the average build volumes for different technologies. It is important to ensure that the size of the part can be accommodated into the machine build volume. If possible, larger parts can be converted into subcomponents which can be built separately and assembled afterward (Abdulhameed et al., 2019). Muvunzi et al. (2020) conducted a study in which a forming tool was divided into subassemblies to accommodate the size of the AM machine. The study proposed a practical process chain for manufacturing a large hybrid tool using milling and selective laser melting processes.

Quality

The quality characteristics associated with the different technologies are also an important factor during selection. This includes the mechanical properties, surface properties, and fatigue properties (Ngo et al., 2018). PBF LMD, and WAAM processes are cable of manufacturing parts with mechanical properties that are comparable to those produced conventionally (Kumar et al., 2020; Schmidt et al., 2017; Zhong & Liu, 2010). PBFP yields more dimensional accuracy, when compared to WAAM and LMD processes. However, it is prone to residual stresses which can lead to distortion, shrinkage, and cracking (Kruth et al., 2010). This can, however, be minimized through post-processing (Schmidt et al., 2017). For WAAM, the quality issues are mainly associated with poor resolution, residual stresses, and porosity depending on the process parameters (Cunningham et al., 2018). Williams et al. (2016) explained the strategies that can be employed to minimize the defects, such as in-process machining.

Criticality of Part

The high costs associated with producing parts with metal-based AM processes make them suitable for high-value parts. The value of a part can be characterized in terms of its costs and functionality. Churcher (2017) defined value as a ratio of cost and function. If the part functionality is of high importance and the part is required to have specific properties, then it can be adopted for AM application. In terms of functionality, some parts are exposed to extreme conditions, such as heavy mechanical loads or high-temperature applications, which require high-performance designs which are not achievable with specific AM processes. Thus, the value of the part must be considered when selecting the most appropriate technology

Lead Time

It is important to compare the manufacturing lead time associated with the different technologies. Each of the technologies has a different speed or build rate (Kumar et al., 2021). WAAM processes have a higher build rate, when compared to powder-bed fusion processes, although the accuracy is less (Williams et al., 2016). The preprocessing and postprocessing time should also be considered. Depending on the desired part characteristics, it is important to have a trade-off between the speed and the desired part quality. The production rate can also be affected by the material and design of parts (Kumar et al., 2021). According to Kumar et al. (2021), a time-cost-quality triangle is a key tool that can be used in analyzing the capability of the AM processes.

Cost

The costs associated with different potential AM technologies need to be compared. The reason for doing this is to identify the most cost-effective AM process which can be used to produce the part with the required quality characteristics. This includes the raw material, energy, and processing costs (Costabile et al., 2016). If the AM technology can increase the functionality of a product through a high-performance design, it is important to track the utility gained from the new design along with the production costs (Thomas & Gilbert, 2015). For example, the use of lighter parts can help to reduce fuel consumption or engine components with improved cooling capabilities. In the event of shifting to local manufacturing, it is important to consider the supply chain costs and risks associated with importing the part as compared to local manufacturing with AM (Kunovjanek et al., 2020). The manufacturing time also contributes to the cost of producing the part (Kumar et al., 2021).

Identifying Possible Redesign Options Based on Technology

At this stage, it is necessary to identify opportunities for modifying the design of the parts to reduce cost and improve functionality. This involves identifying the design rules and constraints associated with selected AM technologies and using them to redesign the parts to fully utilize the design freedom and opportunities offered by the AM technology (Thompson et al., 2016a). Hällgren et al. (2016) explained two methods for redesigning parts for AM, namely process-driven and design-driven methods. In their study, they suggested a cost prediction model for choosing parts for redesign from an economic point of view. The DfAM can be defined as the practice of designing and optimizing a product and the manufacturing process to reduce costs and time to manufacture, as well as to enhance performance, quality, and profitability (Thompson et al., 2016b). The following redesign options can be considered:

- Modifying existing design to ensure minimum usage of material while fulfilling the functional requirements.
- Modifying existing design to improve functionality.
- Replacing existing material with a high-performance material type.
- Modifying existing design to ensure an efficient process chain.
- Redesigning components for part consolidation.
- Modifying the design to ensure minimum usage of material while fulfilling the manufacturing requirements.
- Modifying existing design for optimized build orientation and support.

CASE STUDIES

The proposed framework is evaluated using industrial case study applications of AM in the rail industry. This includes a wheelset cover and a secondary roll stop which were manufactured additively for Deutsch Bann. Table 3 gives more information on the parts and the challenges (Gefertec, 2020).

As Table 3 shows, the challenges associated with the parts include the long delivery time which translates to downtime and the parts being costly to produce using conventional methods because of the tooling costs. The wheelset cover is an obsolete part that is difficult to outsource. As a result, AM was considered a cost-effective approach for producing the components. Table 4 shows a comparison of potential AM processes. WAAM was considered for manufacturing the parts. When compared to other processes, WAAM has a wider material application, and there are no challenges experienced when switching from one material to another. In addition, there is ongoing research to increase the material envelope. Shen et al. (2021) designed and developed a novel cablewire with multielement composition for improved energy savings and deposition rates. The developed wire constituted an Al-Co-Cr-Fe-Ni with high-performance properties. WAAM is capable of producing large and medium complex parts hence suiting the requirements of the benchmark parts. It also allows the parts to be produced quickly in a cost-effective manner. However, the major challenge with WAAM is the poor resolution and residual stresses, which can be rectified through post-processing. Table 4 presents the comparative analysis of AM technologies.

Table 3. Case study applications

	Component A- Wheelset Cover (Gefertec, 2020)	Component B- Secondary Roll Stop (Gefertec, 2020)
Part		
Description of part	Part is a wheelset bearing cover for a locomotive that was put in service in the 1960's. The absence of the part causes leakage to occur, leading to damage of the bearing and derailing of the locomotive. The time frame needed to replace the component is nine months while the locomotive is out of service (Inovar Communications, 2019.).	Part is a safety component whose function is to limit the interplay of components on the underside of a passenger rail car. The part was rarely available in stock since it is not a regular service item. The time frame needed to replace the component is 10 months (3D Printing Media Network, 2020).
Challenges	• Long delivery time (nine months), which leads to downtime. • Part is obsolete and costly to manufacture with conventional processes due to the tooling costs.	• Long delivery time (10 months), which leads to downtime. • The component is a spare part associated with inventory management costs and challenges. • The part was not readily available in stock.
Reasons for selecting a part for AM	• AM is a cost-effective and faster approach to producing the part. • High tooling costs associated with manufacturing the part conventionally.	• AM is a cost-effective and faster approach to producing the part. • High tooling costs associated with manufacturing the part conventionally.
The conventional process used to initially produce part	Casting	Casting
AM technology used to replace conventional process	WAAM	WAAM
Process chain steps	• Reverse engineering and creation of CAD model. • Printing of part to near shape (seven hours). • 3D scanning and geometry measurement. • Machining of finished part.	• Reverse engineering and creation of CAD model. • Printing of part to near shape (36 hours). • 3D scanning and geometry measurement. • Machining of finished part.
Justification for using selected technology	• Large part size (382 mm). • Reduction delivery time by seven months. • Cost savings. • Material savings.	• Large part size (250*216*312 mm). • Reduction delivery time by five months. • Cost savings. • Material savings.
Redesign options adopted	None	None

Table 4. Comparison of additive manufacturing technologies

Technology	WAAM	LPBF	LMD
Material applicability.	Yes	Yes	Yes
Does the technology cater for the complexity of the part?	Yes	Yes	Yes
Does the build volume of the technology accommodate the part size?	Yes	No	Yes
Cost (material and processing costs).	More affordable than LPBF and LMD.	More costly when compared to WAAM and LMD.	More affordable when compare to LPBF, but more costly than WAAM.
Manufacturing lead time (build rate).	Less than LPBF and LMD due to fast build rate.	More than WAAM and LMD.	More than WAAM but less than LPBF.
Potential defects associated with technology.	Residual stresses, distortion, and poor resolution (Wu *et al.*, 2018).	Porosity, residual stresses (Dass & Moridi, 2019).	Residual stresses thermal cracking (Schmidt et al., 2017).

CONCLUSION

The paper aimed to propose an approach that can be used by companies in the rail sector to select AM technologies that are suited to their operations. The proposed approach begins with identifying potential parts suitable for AM application. These includes parts that are costly and difficult to produce using conventional methods. Also, low-volume spare parts with supply chain challenges or those that have become obsolete due to the long service life of rail cars. The second stage involves identifying and comparing potential AM technologies that can be used to manufacture the parts. The comparison can be done from an economic, quality, technical or environmental point of view, depending on the needs of the industry. This is followed by a detailed evaluation of the possible technologies. Based on the evaluation, the authors selected suitable technologies. The next stage involves redesigning the parts for AM, if necessary. This is followed by performance evaluation and implementation. Based on the study, the following conclusions can be drawn:

- In the study, the authors proposed a framework for AM technology selection. The authors evaluated the framework using two industrial benchmark components that were manufactured using AM. For both parts, WAAM was the most cost-effective process yielding the required results. The authors presented a comparison of the WAAM process with other technologies. In both cases, the application of AM led to a reduction in the delivery lead time and cost savings.
- In the rail industry, AM has the potential to positively affect maintenance through the provision of spare parts on-demand. This is a cost-effective approach, especially considering the lifespan of rail cars and the rapid changes taking place in the design of trains. Other opportunities include remanufacturing of damaged components, producing high-value parts, and manufacture of tools with innovative features for improved functionality.
- It is important to fully analyze the industry needs and identify cases in which there are viable economic reasons to replace conventional processes with AM.
- Parameters such as part size, geometric complexity, and material should be analyzed when selecting a suitable AM process.

The practical and managerial significance of this study is that it can assist the transport equipment manufacturing companies in the rail sector make effective decision making regarding the selection of the AM processes that are suited to their needs in a cost-effective manner.

Future studies involve using the proposed framework to manufacture other components for the rail industry. The study lays a foundation for the application of AM in the rail industry. Most of the academic work in literature is mainly focused on the aerospace and automotive sectors and offers limited information focusing on the rail industry. The next stage of the study involves redesigning the selected parts to improve functionality based on the capabilities of the selected technologies.

In the Appendix, Table 5 presents the comparative analysis of the different Metal AM processes, while Table 6 shows the AM processes and the suitable materials. Other AM approaches and their novelties are captured in Table 7.

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APPENDIX: ADDITIONAL TABLES

Table 5. Comparison of different metal additive manufacturing processes

Parameters	LPBF	EBMPBF	LDM	WAAM
Material applicability (common materials)	316L, 1.2709, AlSi10Mg, IN718, Ti, Al, Ti6Al4V (Schmidt et al., 2017).	TiAl, Co-Cr-Mo, Fe, H13, IN718, Ti6Al4V (Körner, 2016)	316L, H13, IN718, Ti, Ti6Al4V, Ni-based alloys (Schmidt et al., 2017)	All materials that are weldable and available in wire form (Wu et al., 2018).
Mechanical Properties	Superior mechanical properties (Ti6Al4V UTS) 1250 MPa (Schmidt et al., 2017).	Superior mechanical properties (Ti6Al4V UTS) 1200 MPa (Schmidt et al., 2017).	Superior mechanical properties (Ti6Al4V UTS) 1163 MPa (Dutta & Froes, 2017).	Superior mechanical properties (Ti6Al4V UTS) 1033 MPa (Wang et al., 2013).
The complexity of parts produced	Very high	High	Medium to high	Low to medium
Accuracy	±0.04 (Ding et al., 2015)	±0.05 (Ding et al., 2015)	±0.13 (Ding et al., 2015)	±0.12 (Ding et al., 2015)
Surface finish (Ti6Al4V)	Fine Ra 9/12 µm (Dutta & Froes, 2017)	Fine Ra 25/35 µm (Dutta & Froes, 2017)	Course Ra 20–50 µm (Dutta & Froes, 2017)	Rough Ra 500 µm (Williams et al., 2016)
Capability to repair damaged engineering components	No	No	Yes	Yes
Build rate/ Speed	2 – 93×10^{-6} m^3/hr (General Electric, 2020)	5×10^{-4} m^3/hr (General Electric, 2020)	1-1.41×10^{-4} m^3/hr (Dutta & Froes, 2017)	0.5-4×10^{-3} m^3 (Williams et al., 2016)
Size of parts built	The average build volume 250 x 250 x 300 mm (Schmidt et al., 2017).	Limited by build envelope of the machine 350 x 430 mm (D x H) (General Electric, 2020).	Unlimited	Unlimited
Cost of raw materials (Digital Alloys, 2020)	\$300-\$500/kg	\$300-\$500/kg	\$150-\$250/kg	\$125-75/kg.
Environmental impact	Toxic powder requires precautionary measures to handle.	Toxic powder requires precautionary measures to handle.	Toxic powder requires precautionary measures to handle.	Relatively clean environment.
Capability to switch from one material to another	Possible. Risk of cross-contamination (Montazeri et al., 2018).	Possible. Risk of cross-contamination (Kravtsov & Chikvaidze, 2021).	Possible	Possible
Cost of Equipment (\$)	\$100 000- 400 000 (Cherdo, 2022)	\$ 720 000 (General Electric, 2020)	\$90 000-720 000 (Cherdo, 2022)	Gerfetech \$420 00 -720 000

Table 6. Additive manufacturing processes and the suitable materials

Process	Materials
PBFP	Stainless steel GPI, PHI and 17-4, Titanium Ti6Al4V, Ti6Al4V ELI, TiCP, IN718, maraging steel MSI, AlSi20Mg, Cobalt chrome MPI, Tool steel 1.2709 (Guo & Leu, 2013).
LMD	H13 tool steel, 17-4 PH, PH 13-8 Mo, 304, 316 and 420, Aluminium 4047, Titanium TiCP, Ti-6-4, Ti-6-2-4-2, Ti6-2-4-6, IN625, IN617, Cu-Ni alloy, cobalt Satelite 21 (Guo & Leu, 2013).
EBMPBF	Ti6Al4V, Ti6Al4V ELI, TiAl, Co-Cr-Mo, Fe, IN718 (Schmidt et al., 2017)
WAAM	Any weldable material is available in wire form. This includes steel, aluminum, titanium, and nickel-based alloys (Singh & Khanna, 2021).

Table 7. Other additive manufacturing approaches and their novelties

Approach	Novelty
Integrated design methodology model for AM	Capable of analysing a product or product family, either new or existing, with respect to their functional and physical architecture (Oyesola et al., 2019).
Interactive approach for product development via AM	Enables the ceation of products which combines optimal product performance with effective users' interaction (Daniyan et al., 2020a).
Computer-aided approach	Geared towards product innovation as well as reduction in the manufacturing lead time and cost (Daniyan et al., 2020b).
Hybrid-–AM cost model	It establishes a cost model derived from time-driven activity-based costing for technological integration of hybrid system to improve economic competitiveness ((Oyesola et al., 2020).

Rumbidzai Muvunzi is a Postdoctoral Research Fellow at the Department of Industrial Engineering, Tshwane University of Technology, Pretoria, South Africa. Her research includes advanced manufacturing technologies and additive manufacturing.

Ilesanmi Daniyan is a Postdoctoral Research Fellow at the Department of Industrial Engineering, Tshwane University of Technology, Pretoria, South Africa. His research interests include Production Engineering and Advanced Manufacturing.