A conceptual evaluation and benefit of additive manufacturing technology to improve maintenance tasks in the railway industry

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ABSTRACT: The railway industry relies on frequent preventative and corrective maintenance tasks to ensure asset life is at its highest. In order to conduct these maintenance tasks, track personnel use different measuring systems to comply with maintenance standards. Some of these systems include; wayside lubricators, thermite gap gauges, welding & grinding templates, rail break detectors and many more. One major challenge experienced is the shortage of measuring gauges and availability of spare parts for a variety of wayside assets. This is usually a result of uneasily available parts or breakage which leads to backlogs and inconsistency in maintenance execution. The purpose of this paper is to determine the feasibility of additive manufacturing in the railway environment, to reduce lead times for procuring measuring gauges and fabrication of spare parts. A framework has been developed based on case studies which assist with the implementation of additive manufacturing within the railway environment. Added to this framework process, is the method of implementation proposed to be undertaken by Transnet Freight Rail to realise the full benefit of additive manufacturing across all maintenance depots. Other factors relating to prototyping, rapid product development and design optimisation will also be investigated.

1 INTRODUCTION

The intent of this paper is to conceptually evaluate the current state-of-the-art techniques available in additive manufacturing and determine benefits to assist in the improvement of maintenance tasks at Transnet Freight Rail. These benefits include reducing lead times to replace measuring tools and replenish spare parts for wayside assets as a method of as-and-when-needed approach. A framework model has been developed for Transnet Freight Rail to effectively utilize additive manufacturing techniques to assist with maintenance tasks. Proper maintenance philosophies govern any railway infrastructure's asset life and are determined through reliability, availability, maintainability and safety (RAMS) for railway operations and are extensively covered in the European standard EN 50126 (EN B. 50126, 1999). Transnet's focus on increasing its Gross Million Tonnages (GMT) transported results in an increased traffic loading and rail utilization on the infrastructure. Challenges in the domain of maintenance cycles are more evident. Due to the increased levels of maintenance required, factors with regard to spare parts and measuring tools are becoming scarce, which then results in delayed maintenance execution. Figure 1 illustrates a map of the railway tracks owned by Transnet Freight Rail.

Figure 1. Transnet Railway Network

2 BACKGROUND

2.1 *Additive manufacturing technologies*

Additive Manufacturing (AM), commonly known as 3D printing is a manufacturing process used to create a component by depositing material in a layer-by-layer fashion until the final product is complete. Compared to conventional manufacturing methods used in industry, (subtractive, formative and joining processes), parts created using the AM method include all of the conventional manufacturing processes at its design phase (the model created using computer-aided design software) before physically printing the part. In cases where an existing component needs to be replicated, reverse engineering methods using 3D scanning techniques to generate computer models for 3D printing is available (Conner, et al., 2014). It is this reason, compounded with many other positive factors associated with this method of manufacturing that AM is rapidly being adopted into the industrial sector. It is therefore critical to identify a suitable place for AM in the railway environment.

A survey conducted in 2018 by (Wohlers, 2018), looked at the current trends and uses for 3D printing. The survey covered responses from industry manufacturers, 3D printing service providers and 3D printer makers to help identify the current use of this technology. Figure 2 illustrates a bar graph adapted from (Wohlers, 2018).

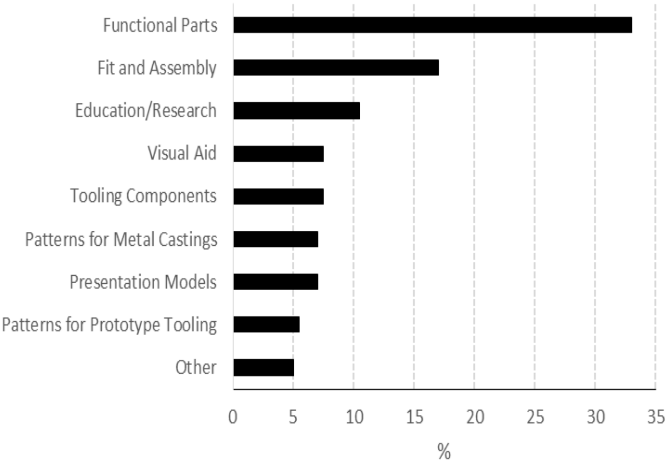

Figure 2. How Organisations are Utilizing Industrial Additive Manufacturing Systems in 2018

It can be seen that the highest percentage of AM in the industry contributes to printing functional parts. This implies the capabilities associated with the technology.

The general process involved in creating a physical part using 3D printing techniques starts with a computer-aided design (CAD) which is converted into a Stereolithography (STL) file - Stage 1. Once the model is converted, the file is sent to the 3D printer software to prepare it for printing - Stage 2. After selecting the appropriate settings for the print, the model may be 3D printed - Stage 3. Depending on the type of printer used, the post-processing method may vary. The final stage of the process involves cleaning and in some cases assembling the final product - Stage 4. Figure 3 is a visual illustration of the flow process specific to the polymer Fused Filament Fabrication (FFF) method of 3D printing.

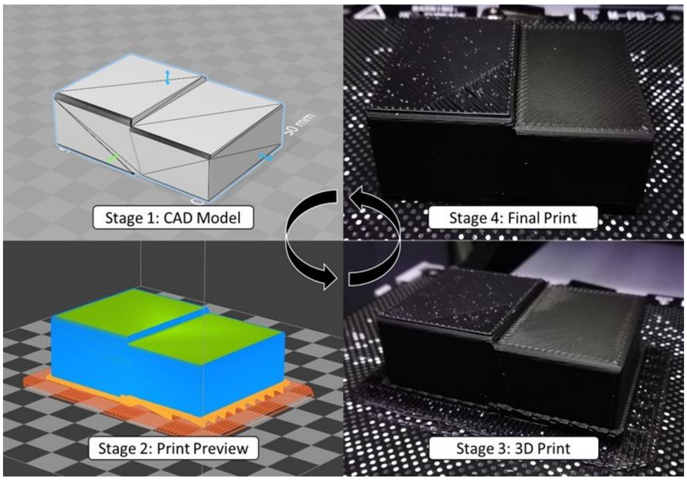

Figure 3. Additive Manufacturing Flow Diagram

3D printers are usually restricted by its design. Factors related to its design restriction include; build volume, print speed, material type, printer type, feed rate and so forth. Numerous 3D printing machines are available commercially, with different printing techniques and technologies. These include; material extrusion, powder fusion, material jetting, binder jetting, vat Photo-polymerization, sheet lamination and energy deposition (Strickland, 2016). Table 1 is a summarized table adapted from (killen, et al., 2018) with the most common 3D printing technologies currently used in industry, their respective capabilities and recommended use. For the purpose of this research, the FFF printing method using polymers will be used to 3D print parts. The printing method and material used is due to it being cost-effective, flexible and accessible.

Table 1. Common 3D Printing Technologies

	Electron beam (EBM)/ Direct Metal Printing (DMP)	Laser sintering (SLS) and melting (SLM)	Fused deposition modelling (FDM) & Extrusion (FFF)	Stereo lithography (SLA)
Principles	Powered material is welded together using an electron beam	Powered material is welded together using a laser	Melted polymers or ceramics are deposited layer by layer.	Photopoly merization, of resin liquids using UV light
Use	Functional metal parts.	Bulk parts, heat & chemical resistant.	Conceptual and mock-up models.	Demonstration purposes
Materials	Pure metals and alloys	Metal alloys and polymers.	Polymers or ceramics.	Polymer resins
Resolution	Up to .0012”	Up to .004”	Up to 0.01”	Up to 0.002”
Suitability	Testing and final parts.	High detailed & strong parts.	Prototyping	Parts for presentation & display

2.2 *Benefits associated with additive manufacturing*

This outlines the advantages that could be seen with AM in the railway environment through existing industry implementation. It considers the economic advantage, lead times due to the production of printed components and prototyping benefits with design optimisations.

2.2.1 *Economic Advantage*

There are numerous financial and operational benefits associated with AM used in industry, as compared to conventional manufacturing methods. The most significant cost-benefit of 3D printing is the ability to conduct complex rapid product development with numerous iterations without the need to invest in expensive tooling or specialised equipment (killen, et al., 2018). Previously, multiple design iterations for product development could only be done on very rare occasions, due to the high costs needed when using conventional manufacturing processes (Onuh & Yusuf, 1999). A comparative study of 3D printing methods and conventional manufacturing processes was conducted by researchers in Italy. They discovered that 93.5 % of the current manufacturing cost structure is associated with the tooling stage which includes manufacture, maintenance, storage and tracking of these tools (Lindemann, et al., 2012).

With the implementation of 3D printing methods, the result reduced material wastage and reduced material costs. This is clearly seen when machining a block of steel into a specific component. Large amounts of steel are wasted in order to create the final part. This differs in the case of 3D printing technology, where only material to create the end product is used with little wastage from support material being produced (Boubekri & Alqahtani, 2015).

As a by-product of unspecialised tooling required for product development when using 3D printing technologies, large scale customisations can be realised. This means that a large variety and increased complexity of parts and components can be manufactured faster and cheaper, implying the benefit of design iterations (Boubekri & Alqahtani, 2015). Anderson (2013) determined that the manufacturing costs associated with producing complex and customised products through AM were the same for producing identical products through conventional methods of equal quantity. This proves the economic benefit associated with additive manufacturing.

2.2.2 *Lead times for production*

Anderson (2013) also determined that 3D printing provides the best solution for smaller production manufacturing quantities. This is supported by the technology which provides manufacturing solutions to niche markets that were impossible in the past. As a result, lead times for part manufacture were eliminated since no retooling was required with AM in comparison to conventional methods (Lipson & Kurman, 2013). Other benefits were seen with no retooling and setup requirements with the use of AM technology, which includes a significant reduction in lead times for rapid product development and prototyping concepts (killen, et al., 2018).

In the long run, the benefits of using 3D printing for product development will allow small businesses to enter the market space and disrupt the traditional supply chain processes. Benefits for large companies also exist and allows them to bring new and existing products to market in-house, reducing the need to store parts in warehouses and have extended logistics in procurement. As a result, reduces lead times even further (The Economist Intelligence Unit, 2018).

This is true for the German railway company, Deutsche Bahn (DB) who began implementing 3D printing technology in 2015. The company elected to utilize this method of manufacturing in order to generate spare parts for older rolling stock and wayside systems in the infrastructure domain. This occurred, primarily due to two reasons. The first reason being that the suppliers no longer provided the required parts for older systems. The second reason is that the lead time for replacement was too long. To date, the company is believed to have successfully produced 15 000 3D printed products ranging from ventilation grilles, headrests, coat hooks and cable boxes (Rutch, 2019).

Siemens Mobility, another giant in the railway industry, highlights that “The ability to 3D print customized tools and spare parts whenever we need them, with no minimum quantity, has transformed our supply chain” (Griffiths, 2018). The company has opened its first digital rail maintenance centre for the sole purpose of eliminating the inventory needed for spare parts. They are able to achieve this through the use of AM techniques. By implementing this technology, Siemens Mobility has been able to reduce manufacturing lead times by up to 95 % for select railway parts (Griffiths, 2018).

2.2.3 *Design Optimisation*

Additive manufacturing is able to capitalize on large scale customization and small batch manufacturing of parts and products. This is achieved by having a close relationship between rapid design updates and printed parts (killen, et al., 2018). With this advantage, rapid prototyping for product development can be executed efficiently and still be cost-effective. A new design methodology has been developed to include the benefits of 3D printing and its capabilities for rapid product development. The basic steps involved in the design cycle, adapted from (Wong & Hernandez, 2012), has been modified for our case which shows three distinct stages and is illustrated in Figure 4.

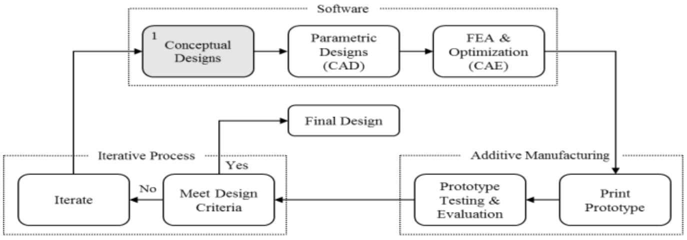

Figure 4. Design Cycle for Rapid Prototyping

Figure 4 illustrates that the initial design process occurs at the computer software level and once completed, the model can be printed. Multiple iterations of a design can be printed, tested and evaluated using this cycle to determine the most efficient component.

Research conducted by (Wits, et al., 2016) investigated strategies of design optimisation, using AM technology, in the fields of Maintenance, Repair and Overhaul (MRO) of spare parts. The study focuses on how end-users can utilize 3D printing technology to fabricate spare parts and remove the dependence on service providers. Four approaches to design optimisation, adapted from (Wits, et al., 2016), is illustrated in Figure 5.

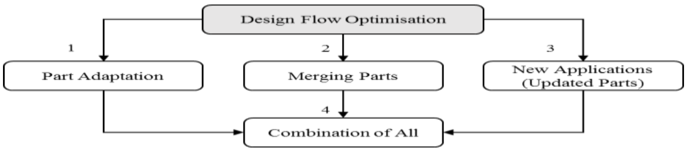

Figure 5. Design Optimisation: End-user Process Flow

With the advantages of 3D printing, the ability to modify a parts shape or size for part adaptation, merging components to reduce assembly size and weight and creating new designs from base components can be done with ease. This is done by changing the CAD files, to a specific end-users need, for a given application. This will be able to remove the barrier between internal manufacturing knowledge within the railway environment and reliance on Original Equipment Manufacturers (OEM) (Wits, et al., 2016). For design optimisation to be executed effectively and efficiently through AM techniques, combining all of the design flow processes together will transform 3D printed components (Wits, et al., 2016).

An important factor in design optimisation for AM is understanding the relationships between 3D printing methods and the mechanical properties associated with the printed part. This is an important factor for design engineers in the railway environment. By understanding the advantages of mechanical properties in relation to 3D printing techniques it will allow for better functional parts to be created. Research conducted by (Kim & Oh, 2008) investigated the relationships between printing techniques and mechanical properties. The properties focused includes; tensile and compressive strengths, hardness, impact strength, heat resistance, surface roughness, geometric and dimensional accuracy and manufacturing speed for all 3D printed parts for varied orientations. The final results of the study are summarized in Table 2.

Table 2. Summarised Results (Kim & Oh, 2008)

Printing Process	Advantageous
SL	Hardness, Accuracy, Surface roughness
Poly-Jet	Tensile Strength at room temp.
SLS	Compressive Strength & Manufacturing Speed
3DP	Speed & Material Cost
LOM	Heat Resistance
FFF/FDM	Impact Strength in the scanning direction*

*opposite to the build direction

3 RAILWAY INDUSTRY APPLICATIONS

This section of the paper will present various case studies of using 3D printing at Transnet Freight Rail for generation of spare parts, for integral maintenance activities and design optimisation of railway prototype.

3.1 *Case study 1: Generation of spare parts*

Focuses on how 3D printing is used to recreate spare parts and tools for track-related maintenance.

3.1.1 *Grease refill screwdrivers*

Current challenges in the wayside lubrication domain include tool availability and breakage of the grease refill screwdrivers. These screwdrivers allow operators to open the reservoir of the lubricator to fill it with grease. When these tools are not available, grease levels within the tank deplete and refilling becomes an issue. In severe cases where grease is needed, track maintenance teams are forced to refill grease from the reverse side of the reservoir. Figure 6 illustrates the result of this type of maintenance activity which usually results in failure of the entire mechanical system.

Figure 6. Incorrect Maintenance Practice for Grease Refill

A simple solution using 3D printing to print the tool within a few minutes will allow track personnel to correctly fill the tanks to capacity. Figure 7 illustrates the 3D printed tool and its use on site. Table 3 illustrates the print properties.

Figure 7. 3D Printed Grease Refill Screwdriver

Table 3. Print Properties

Material	Material Used	Print Time	Layer Height
ASB+	22.9 g	1.8 hours	0.2 mm

3.1.2 *Grease stoppers*

Another challenge within the wayside lubrication domain is the extended lead times needed to receive cork grease stoppers. These stoppers are used to contain grease between the rail web and the applicator bar. The proposed solution is to 3D print replicas of the cork stoppers for use or until new inventory arrives. This will prevent grease wastage, ballast contamination and allow continued effective rail lubrication. Figure 8 illustrates the cork stopper, a mechanical lubricator experiencing grease leakage as a result of not installing the stoppers and the 3D printed versions. Table 4 illustrates the print properties

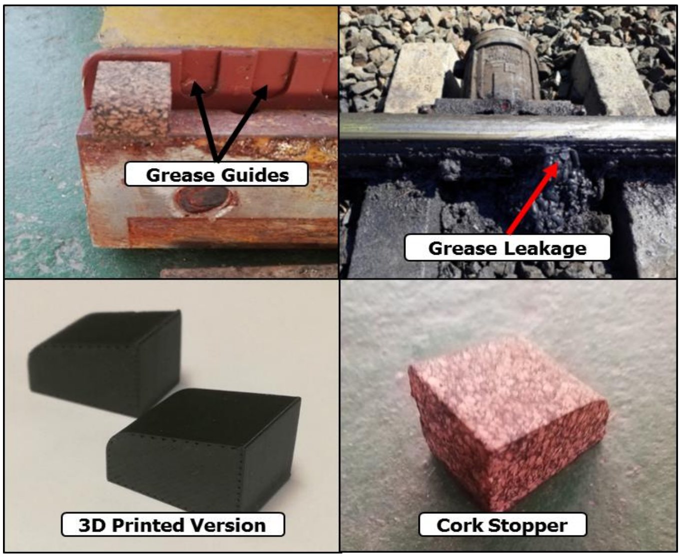

Figure 8. Grease Stopper & Leakage on the Mechanical Lubricators

Table 4. Print Properties for Two Stoppers

Material	Material Used	Print Time	Layer Height
Flexible	6.9 g	38.3 minutes	0.2 mm

3.2 *Case Study 2: Measuring equipment & tools for maintenance activities*

Focuses on how 3D printing is used to create simple measuring tools for maintenance activities.

3.2.1 *Thermite Weld-Gap Gauge*

A simple measuring gauge used to measure the gap between two rail ends to determine the required thermite mould size needed to join them together. AM techniques can be used to replicate this measuring tool and prevent any delays in rail welding maintenance. Both the existing gauge and the 3D printed gauge is illustrated in Figure 9. Through AM, these tools can be created within a few minutes, at a fraction of the original cost and allow continued maintenance activities to be done correctly. It was found that the 3D printed part was accurate to 0.05 mm of the recommended rail gap sizes. The print properties are illustrated in Table 5.

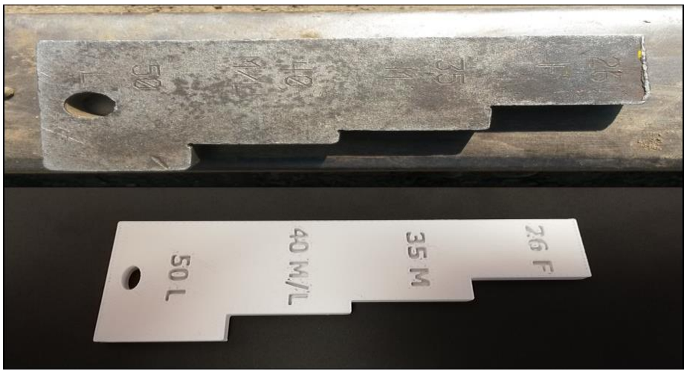

Figure 9. Thermite Weld Gap Gauge

Table 5. Print Properties for the Welding Gauge

Material	Material Used	Print Time	Layer Height
ASB+	14.1 g	1.3 hours	0.2 mm

3.2.2 *Lubricator plunger height gauge.*

The current challenge faced with these lubricator plunger height gauges is that they are difficult to source. A solution is presented to use 3D printing techniques to replicate the measuring tool so track personnel can print a new tool when needed. Figure 10 illustrates the conventional plunger height gauge and the 3D printed measuring tool.
Table 6 illustrates the print properties.

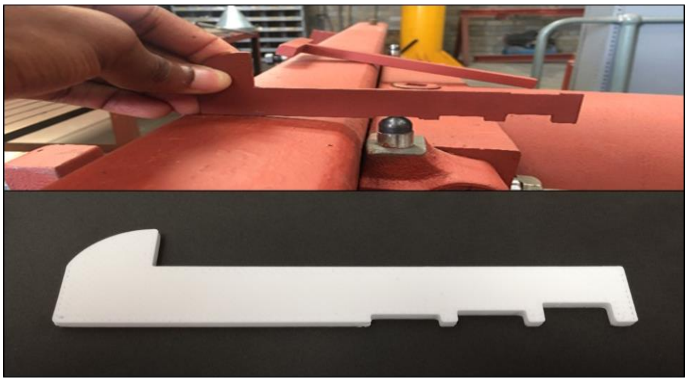

Figure 10. Plunger Nozzle Height Gauge

Table 6. Print Properties

Material	Material Used	Print Time	Layer Height
Flexible	5 g	30.8 minutes	0.2 mm

3.3 *Case Study 3: Design Optimisation & Prototypes*

The case studies presented below are based on prototyping and design optimised measuring systems using 3D printing for the railway environment.

3.3.1 *Wheel sensor measuring device*

This covers the process used to create a prototype wheel measuring device. A device was required to count passing rail wheels, bogies and wagons for the purpose of track testing. AM methods were used to create a custom housing - for the electronics - and mounting clamps specific to TFR's rail types (48 kg/m, 57 kg/m, and 60 kg/m). Figure 11 illustrates the design of the prototype process undertaken.

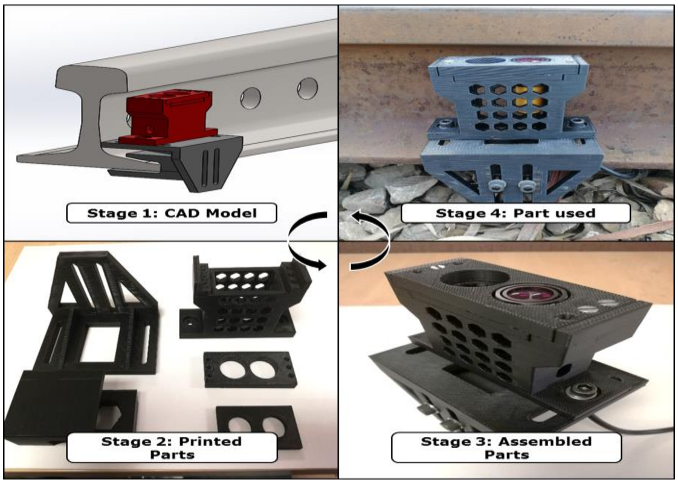

Figure 11. Smart Wheel Sensor

The prototype was tested and it was determined that the printed parts were rigid, stable and easy to attach to the rail. Further trials will be conducted to test how far 3D printed parts can be used. Table 7 illustrates the print properties for the prototype.

Table 7. Print Properties for the entire prototype

Material	Material Used	Print Time	Layer Height
ABS+	127 g	12 hours	0.3 mm

3.3.2 *Applicator Bar Supports*

The current challenges experienced with these supports include theft and vandalism due to it being made of steel. To solve this issue, 3D printing techniques can be used to recreate the support since plastic is not as valuable as steel. A disadvantage of plastic over steel is its strength. In order to make the 3D printed support stronger for the application, reinforced internal meshing will be required. A topology analysis is used to determine the internal stress locations due to the applied load on the support. Once the regions are located, reinforced internal mesh infills can be created to improve the structural capabilities of the support. Figure 12 illustrates the design optimisation process used to create a strong applicator bar support using 3D printing. Table 8 illustrates the print properties for two supports.

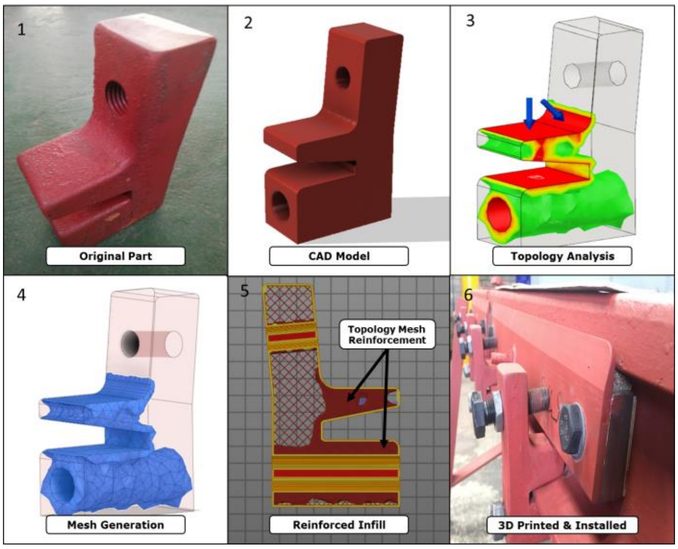

Figure 12 Design Optimisation Process

Table 8 Print Properties

Material	Material Used	Print Time	Layer Height
ABS+	243 g	15 hours	0.2 mm

The overall support was created to have two different internal mesh regions. With the aid of the topology analysis, internal stress locations were determined based on a 33.17 N force applied to it and a 30 % strength part factor. This stress profile is then converted into a separate mesh part and later merged with the 3D printable file. A 100 % infill for the stress profile mesh is used while a 20 % infill is used for the non-stressed locations. This method of optimisation allows the designer to increase the 3D printed part strength at specific locations which experiences high internal stresses while reducing infill in unstressed areas. This saves material costs and increases overall strength.

3.4 *Case Study 4: Other Additive Manufacturing Applications in the Railway Environment*

The track infrastructure is composed of different interacting disciplines. Within each discipline, various tools, machines and equipment are used to conduct maintenance and will require spare parts. These are areas in which AM could be incorporated. Table 9 illustrates a list of respective disciplines and possible uses for AM.

Table 9. Other Additive Manufacturing Applications in the Railway Environment

Disciplines	AM Possibilities
Perway	Spares on Inspection trolleys. Spares for wayside monitoring equipment.
Signals	Specialized enclosures for electronics. Circuitry & Custom PCB boards.
Electrical	Specialized electrical circuit enclosures. Spares on substations.
Telecoms	Complex connectors. Brackets & enclosures for high-sight equipment. Radio communication with trains.

4 ADDITIVE MANUFACTURING FRAMEWORK FOR TRANSNET FREIGHT RAIL

A conceptualised framework has been developed for Transnet Freight Rail to assist with the implementation and future development of AM. The framework provides an envisioned approach to improve internal fabrication of assets, thereby reducing the dependency on OEM's.

Guidelines for developing this specific framework is based on research conducted by (Mellor, et al., 2014) combined with the expected operation within Transnet Freight Rail. The framework of AM for Transnet Freight Rail is illustrated in Figure 13.

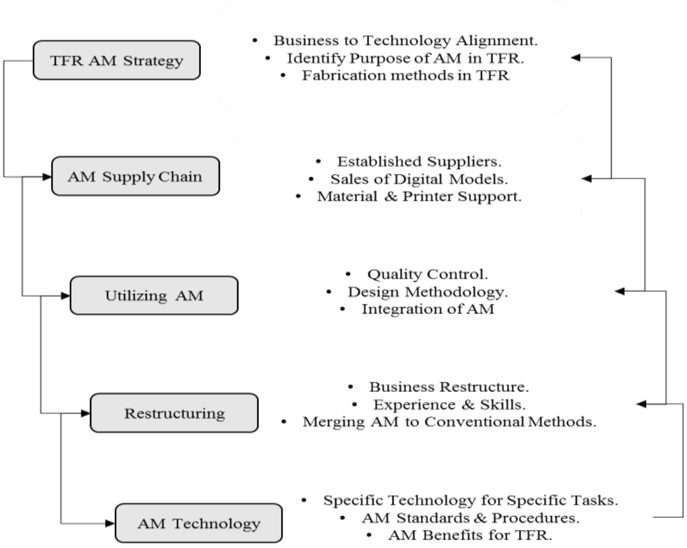

Figure 13. TFR Framework for AM Implementation

4.1 *Transnet Freight Rails Additive Manufacturing Strategy*

In order to effectively utilize the capabilities of AM at Transnet Freight Rail, distinct benefits need to be realised. The beneficial relationship between railway research and development of advanced systems and in-house fabrication of spare parts need to be optimal. In order to fulfil this relationship, suitable Transnet assets need to be identified for AM and merged with conventional strategies.

4.2 *Additive Manufacturing Supply Chain*

Moving into the age of digitization and fabrication through 3D printing, the conventional supply chain methods within Transnet will need to undergo change. With the implementation of AM, the supply of digital products – in the form of CAD models – will be a new requirement for suppliers. Added to this, established suppliers in the field of AM will need to be identified.

4.3 *Utilizing Additive Manufacturing at TFR*

Focuses on acceptable railway applications that AM can be fully incorporated and be in line with the operational capabilities of the available technologies. TFR will have to determine how AM can be seamlessly integrated into its current methods of maintenance operations. A specific design methodology for product development using 3D printing will also need to be created. This will have to factor in parts, tools and equipment that can be fabricated using AM techniques. Parts fabricated will also need to undergo a specific quality control methodology to identify suitability.

4.4 *Organizational Restructuring*

Focuses on the current organisational structure at Transnet Freight Rail and how to merge this new technology within its structure. These factors include printing technology, material types and the experience and skills needed to effectively capitalize on this new fabrication method.

4.5 *Additive Manufacturing Technology*

Due to the demands of the railway environment, production of additively manufactured spare parts and components needs to align with suitable technology and meet recommended standards and procedures. Transnet will need to develop new standards to incorporate AM for functional part creation and identify suitable printing techniques and printers that may be needed.

4.6 *Transnet Freight Rails Adoption to Additive Manufacturing for Track Related Maintenance*

The current approach for adopting AM at TFR for track follows three main stages. This includes; digitization, cloud-based interface and fabrication & maintenance execution. Figure 14 illustrates the proposed flow process in which TFR is using for spare part fabrication.

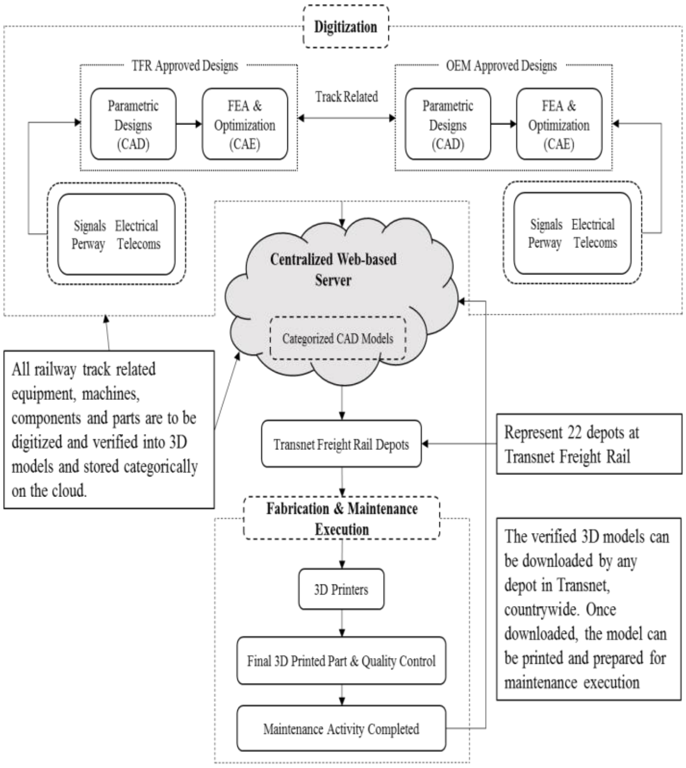

Figure 14. TFR Adoption of Additive Manufacturing

5 CONCLUSION

This paper presented the benefits of AM found in other manufacturing industries as well as other railway companies. This proved that 3D printing can be used to recreate spare parts for trackside equipment, reduce manufacturing and part replacement lead times and transform the current supply chain process. The case studies presented in this paper are based on solutions required to help assist with maintenance activities within Transnet Freight Rail. All components, parts and tools were printed using the FFF method using polymer materials as it is easily accessible and cost-effective for prototypes.

Valid points and simple case studies illustrate that AM does have a place within the railway industry, and most importantly it will assist with improving maintenance tasks. Further work will be required to investigate other critical components and spare parts that could benefit from this technology.

The conceptualised framework for implementing and adopting AM techniques to merge the technology with railway related maintenance has been proposed. The main challenge experienced with the framework is the digitization stage of AM adoption. These challenges are experienced with OEM's cooperation to share verified digital models and effective adaptation of the technology within the confines of respective Transnet Freight Rail depots. The end goal is to establish a sizeable digital database of 3D printable railway track components, spare parts and simple tooling for maintenance executions that will allow all depots to access from any location at any time. This will aid in reducing lead times, improve track maintenance, reduce part storage and reduce overall costs.

6 RECOMMENDATIONS

Further work is required in order to advance the proposed concepts. These include;

- Further refinement of the framework.
- Investigate other printing techniques and material types suitable for the railway environment.
- Cost comparison between AM & OEM reliance.
- Expanding and optimising the digitization process for future AM within the railway track environment.
- Determine the benefits of reinforced infill.

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