

Exploring the use of Additive Manufacturing in Providing an Alternative Approach to the Design, Manufacture and Maintenance of Interior Rail Components

Amy Killen^{1,2*}, Lisa Fu^{1,2*}, Selby Coxon¹, Robbie Napper¹

* These authors contributed equally to the work.

¹ Mobility Design Lab, Faculty of Art, Design and Architecture,
Monash University, Melbourne, Australia.

² Sustainable and Effective Public Transport: Graduate Research Industry Project (SEPT-GRIP), Monash
University, Melbourne, Australia.

Email for correspondence: amy.killen@monash.edu

Abstract

There is currently limited research on how the introduction of alternative manufacturing methods such as additive manufacturing (AM) might assist rail operators in optimising the design, production and maintenance of various internal and customer-facing components. However, questions also surround the economic viability and production cycle times of AM which may act as a barrier to the adoption of this technology by the rail industry. A review of existing literature and industry sources explore current best practice for AM applications within the rail industry. The areas of design, manufacture and maintenance are explored as potential methods of applying AM to the design of rail carriage customer-facing parts. Outcomes with regards to how costs, production times and labour may be reduced when using this technology are described with a focus on the Australian rail environment. Social considerations such as the usability, comfort and aesthetics of components have also been analysed, while further opportunities for AM's use in the rail environment are also outlined.

1. Introduction

The use of additive manufacturing (AM), commonly known as “3D printing”, has significantly increased in various industries over previous years. The steadily decreasing cost of AM provides new opportunities for areas such as those within the public transport sector where this approach can facilitate the introduction of customised production methods. In particular, AM techniques may assist with the refurbishment, replacement or redesign of rail components. Using this technology to trial new designs also enables operators to become more agile and user-centred when updating existing components. Traditional maintenance methods pose a number of issues for operators, such as the reliance on external manufacturers and the inability to provide flexible, customised parts on demand. Questions, therefore, surround how the introduction of alternative manufacturing methods such as AM might assist rail operators with design and production optimisation as well as the maintenance of various internal components. However, there are also potential issues regarding AM techniques such as those regarding economic viability and production cycle times, which may act as a barrier to the adoption of this technology by the rail industry. This paper, therefore, reviews current industry applications to assess whether additive manufacturing is a viable option for rail operators and in which areas it might best be implemented. An investigation is also undertaken into how this approach could be adopted alongside traditional manufacturing measures in order to provide tighter coupling of design and production whilst having the added benefit of reducing manufacture cycle times,

increasing the autonomy of fabrication and providing a more user-centric experience through faster deployment of design updates.

This paper analyses information presented in a wide range of studies on additive manufacturing techniques and their application within various industries. Firstly, terminology in reference to additive manufacturing is defined, with possible advantages and limitations of this process then explored. A review of current industry AM applications is then undertaken, with further investigation completed in the areas of rail design and manufacturing. With a focus on potential applications within the Australian rail industry, the areas of maintenance and redesign are explored as potential areas of suitability to the application of AM for customer-facing parts within rail. Outcomes with regards to how costs, production times and labour may be reduced when using this technology are described, with social considerations such as the usability, comfort and aesthetics also analysed. Strategies emphasising future directions for incorporating additive manufacturing in the rail environment has then been evaluated with the strengths and limitations of the approach and findings critically reviewed.

2. Background

When discussing traditional design and manufacturing processes, Wits, Garcia & Becker (2016, p. 694) contend that “product-in-use and operational knowledge (production statistics) are well-known by the end-user; however, product and part fabrication knowledge usually not so much.” Limited manufacturing knowledge leads to end-users often relying on the Original Equipment Manufacturer (OEM) to address maintenance, repair and overhaul (MRO) processes. Although rail operators may have dedicated maintenance crews, the manufacture of components is often outsourced, resulting in dependencies surrounding design and supply. However, disruptive technologies such as AM provide the potential to eliminate some of these obstacles and streamline maintenance processes. While a large variety of products can be manufactured using additive manufacturing, there are many factors that will determine the likelihood and extent of adoption by certain industries. When viewing the possible procurement of new technology, decisions are often determined using profit forecasting, with the net benefit resulting from introducing a new technology proving to be the main driver behind implementation (Foster and Rosenzweig, 2010; Stoneman, 2001). To influence the application of AM techniques over traditional methods, Bourell, Leu, and Rosen (2009), speculate that an increase of at least 30% to 40% in revenue must be projected by businesses. Such conservative figures may help explain the slow implementation of new technologies within industry settings. In the context of public transport organisations, such as those within the rail sector, greater emphasis may be placed upon easing the maintenance burden via more centralised and autonomous processes, ensuring the ability to meet service demands. When considering the potential widespread adoption of AM in future and its ability to disrupt the traditional “technological status quo”, Keitzmann, Pitt & Berthon (2015) contend that trends suggest a reduction in prices, with printer features continuing to improve and becoming more sophisticated with time. Such improvements may, therefore, help speed up the implementation of this process by industry and change existing models of product design development.

3. Additive Manufacturing

3.1 Definition

Additive manufacturing is a manufacturing process whereby typically a material is deposited layer by layer in order to create a three-dimension part (See Figure 1 for a full list of techniques). These parts are determined by dimensions specified in a computer file created with the use of 3D CAD (computer-aided design) software (Conner et al 2014, Berman 2012, Achillas et al 2015). Moreover, if a CAD file format is unavailable, there is the possibility to digitise the part through 3D scanning of the original. This differs from traditional manufacturing techniques which often involves the forming, joining or removal of material, as well as the creation of new tooling for parts that are no longer produced. As noted by Conner et al (2014), there are a variety of different AM technologies that create parts using this layer by layer material depositing technique. These are outlined in Figure 1, which describes the types of commonly used AM technologies as well as their suitability towards the rail industry. Each technology has its own processing capabilities with varying strengths and limitations surrounding “materials, build volume, processing speed, part quality...and the amount of post-processing required to improve the material properties, surface finish, and/or dimensional accuracy”. During the last decade, there have been significant technological advancements in the field of AM, prompting many industries to consider the use of this process in place of conventional manufacturing methods. However, such processes can also be the source of divisive opinions, with the reaction to its potential application varied among business leaders (Conner et al., 2014). Such contending views of additive manufacturing justify an analysis of this technology within industry and how it might best be applied to the rail sector.

Figure 1. Types of 3D printing technologies and their applicability towards customer-facing parts and prototyping parts suitability within the rail sector (Duchêne et al., 2016; Geissbauer & Wunderlin, 2017)

3D printing technologies

	Electron beam (EBM) / Direct Metal Printing (DMP)	Laser sintering (SLS) and melting (SLM)	Fused deposition modelling (FDM) and extrusion (FFF)	Stereo lithography (SLA)
Principles	Electron beams are used to melt and deposit powder material.	Lasers are used to melt/sinter powder material in bulk (like a laser printer).	Molten polymers or ceramics are precisely deposited layer by layer.	A UV laser initiates photopolymerization, usually with resin liquids.
Applications	Functional metal parts that need to be quick and accurate.	Producing durable, functional parts which are heat/chemical resistant.	Conceptual models, as well as mockup or prototype testing.	Producing high surface quality parts for demonstration purposes
Materials	Pure metals and alloys.	Metal alloys and polymers.	Polymers or ceramics.	Polymers (resins).
Resolution	Highly durable parts, strong structure, very high res material finish. Up to .0012" res.	Durable parts with strong structure and high res material finish. Up to .004" res.	Durable parts with strong structure and medium res material finish. Typically .01" res.	Very High resolution material finish and capable of fit and form testing. Up to .002" resolution.
Suitability for customer facing functional parts	Able to be used for testing and final customer facing parts purposes.	Highly suitable parts with strong structure and high resolution material finish.	Suitable for testing and trial purposes. Less so for functional customer facing parts.	Suitable for producing parts for presentation and display purposes rather than functional.

3.2 Potential Advantages

3.2.1 Economic

Additive manufacturing processes pose a number of operational and financial benefits when compared to traditional techniques. One significant economic advantage of AM includes the ability to explore various iterations of designs through prototypes without the commitment to expensive tooling. As explained by Kruth, Leu and Nakagawa, the early application of AM to plastic prototypes was due to its ability to produce “net shaped plastic products without need for expensive and time consuming special tools, like injection moulds” (1998, p. 528). Petrick and Simpson (2015) add to this narrative by stating that the traditional economy-of-scale model of manufacturing is not relevant to AM, but rather leads to an “economy-of-one” model, asserting that standard practices associated with design for manufacturing and assembly (DFMA) may not directly apply. As noted by Thilmany, “it’s cheap to do this stuff. . . it costs the same to produce two different variants as two identical ones. The economies-of-scale rationale of serial production does not apply” (2009, p. 39). United Pacific Railroad, a freight company, also contends that de-globalised, de-externalised, in-house AM prototypes accelerate their rate of change, allowing them to make multiple modifications using an iterative design process for product and parts development (Inside Track, 2018). From a supply chain perspective, costs can also be minimised by replicating components on-demand rather than stockpiling items in anticipation of future requirements (Keitzmann, Pitt & Berthon, 2015). When discussing economic feasibility in this context, many advocates of AM argue that the technology is financially competitive when applied to small, complicated or customised parts as well as low to medium production volumes (Campbell et al., 2011).

When considering specific production numbers where AM techniques become no longer economically viable, there are varying opinions among researchers. While discussing competitiveness with plastics injection moulding methods, Sedacca (2011) contends that 3D printing is cost-effective on production runs of 50 to 5,000 units, whereas other sources argue that 3D printing is competitive with runs of around 1,000 parts (‘Print me a Stradivarius’ 2011). While it is clear that both AM and traditional manufacturing techniques can profitably produce products in limited quantities as well during the development of prototypes, economic viability becomes uncertain when applied to large-scale production runs. However, in ‘The Printed World’ (2011), Terry Wohlers, a specialist in 3D printing, reports that over 20% of products produced using this technology are final products rather than prototypes. He also predicts that this number will rise to 50% by the year 2020. Conner et al. (2014) further contends that “more high-volume product opportunities will be realized as additive processes evolve to have higher production rates through larger build volumes, faster build speeds, or continuous processes” (2014, p.75).

3.2.2 Production

Beyond economic advantages, AM technology also includes a significant reduction in development and prototype wait time due to no tooling or other set-up requirements as previously discussed. At present, one common application where AM proves beneficial in larger quantities is that of bridge manufacturing. This process includes “bridging” the time span between the completion of a part’s design and when it is ready for mass production. Manufacturing in this form is utilised when tooling is expensive and time-consuming or when several thousand parts are required prior to tooling creation (Berman, 2012). This process of fabrication may also be used for test marketing whereby a variety of prototypes are created

with varying characteristics and then tested by members of the public. When creating and testing various version of a design, any desired complexities are free, proving another significant benefit of AM. As explained by Campbell et al. (2011), “AM is a “single tool” process...This, in effect, makes shape complexity free—there is no additional cost or lead time between making an object complex or simple.”

Considerable time savings are also possible when revising or updating the designs of products currently in use. When comparing AM to mass customization using conventional methods, there are significant differences in logistic and supply chain requirements. Berman highlights that “since the component parts that are used in mass customization typically come from multiple suppliers, mass customization requires a high degree of supply chain integration to ensure that the right parts are available in the right quantities at the right times” (2012, p. 156). However, with AM, supplies are readily available, with the manufacturing process automated due to its basis in CAD software files. This reduces attention required by operators or large teams of people working on different stages of production. As asserted by Alpern, “all you have to do is load a file and you can replicate shapes that are not manufacturable through traditional methods...I call it a flexible factory in a box” (2010, p. 47). The in-house production nature of AM also eliminates the risk of security and privacy issues, further simplifying design and manufacture processes.

Advances in AM have also enabled the application of a wide range of materials such as metals, polymers, ceramics and composite materials, which may be difficult and/or expensive to produce using conventional machining methods (Berman, 2012). Moreover, improvements in material development have resulted in the ability to create more sophisticated prototypes with additive manufacturing. As stated by Kruth, Leu and Nakagawa, the capabilities of prototypes developed with AM has developed from “visual or look-at prototypes to more functional prototypes” (1998, p. 529). When discussing materiality capabilities, it is also worth noting the significant reduction in waste material when using AM technology. In certain applications, especially within the metal sector, a 40% reduction in waste material is possible with 3D printing techniques when compared to traditional subtractive machining technologies (Reeves, 2008). The ability to save on material requirements during the design and manufacturing stages can significantly reduce development costs for organisations. Factors such as production quantity, size and complexity of the part will also assist in determining the economic feasibility of additive manufacturing. Structural competency of parts produced using AM techniques is often noted as a potential barrier to the application of such technology. However, recent advancements in AM processes have enabled production with high tensile strength materials, helping to negate these structural concerns (Berman, 2012). Although the cost associated with using such materials still proves a limitation of AM, continual advancements in technology will allow AM to better compete with traditional manufacturing processes.

4. The Rail Industry

As demand for urban transport systems continues to grow, continual improvements are required in design, manufacturing and maintenance (Prieto Moneo, 2016; Vuchic, 2007). As adaptability is typically slow within rail maintenance systems, advances in design and technology can be delayed in filtering through to operators. This, therefore, increases difficulty when attempting to rapidly implement design changes or introduce customised parts in response to unexpected problems. At present, there is currently limited research on how the introduction of alternative manufacturing methods such as AM might assist rail operators with design and production optimisation as well as the maintenance of various internal components.

As noted by Tzanakakis (2013), the responsiveness in maintenance and upkeep of trains will only need to be more streamlined as rail networks begin to adopt a 24/7 availability. In particular, traditional maintenance of internal components poses a number of issues for rail operators, such as the heavy reliance on external manufacturers. This reliance can result in a number of bottlenecks detrimental to the effective operation of maintenance procedures. For example, bulk orders from external suppliers require large storage facilities and may result in slow delivery times. Tooling, storage and transportation requirements also contribute to increased expenditure by rail operators. Questions and opportunities, therefore, surround how costs, production times and labour may be reduced by such operators when using AM technology.

4.1 Current AM Applications

The growing demand for adaptability and modularity in rail carriage designs can be observed as having a significant influence on how AM techniques are currently being implemented. This is reflected in industry changes to product development, such as Alstom adopting light rail and heavy rail compatible assets that can be interchanged, in order to better adapt to changing demands. The European Commission has also financed a project called ‘MODTRAIN’, which explored the standardization of parts to reduce maintenance, manufacturing and reliability costs associated with intercity and freight trains. This has been further explored in a £2.7m project called ‘Run2Rail’ in Europe, investigating 3D printing and composite material applications within rail (Iwnicki 2018; Demadonna 2018; Zschiedrich, 2008; Duchêne et al., 2016). Additive manufacturing is also already being utilised by various rail operators to reduce maintenance times and refurbishment/replacement cycles. One such example includes the initiatives undertaken by Dubai’s Road Transport Authority’s maintenance team in 2016. These initiatives included investment and application of additive manufacturing with respects to various metro assets within the network, such as printing parts for ticketing machines and ticket gates (Government of Dubai, 2016).

Similar approaches are those observed by Deutsche Bahn. In collaboration with Siemens (Breuer, 2016; Rutsch, 2018). 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 (Breuer, 2016). Replacement of parts within older fleets can prove to be an expensive and complicated process, as they may no longer be manufactured and therefore expensive to reproduce using traditional manufacturing techniques. AM can also negate the upfront cost of producing tooling or moulds for parts which are no longer being produced. The use of AM is a growing investment in rail companies such as Dubai’s RTA and Deutsche Bahn, with 2000 parts being printed by Deutsche bahn in 2017 and a planned 15,000 parts by 2018 (Government of Dubai, 2016; Rutsch, 2018). The use of AM has also been used to prototype and trial design updates across Deutsche Bahn’s network and fleet. Engineering parts such as ventilation grills and transverse damper consoles have been printed using AM. Design parts that involve customer interaction have also been printed, such as new headrests for their regional rail fleet seats, as well as vision impaired braille signage on handrails (Deutsche Bahn AG, 2017). The use of AM by Deutsche Bahn demonstrates the potential to prototype and update rail carriage fleet designs outside of traditional mid-life refits, providing a more flexible and iterative operational production method.

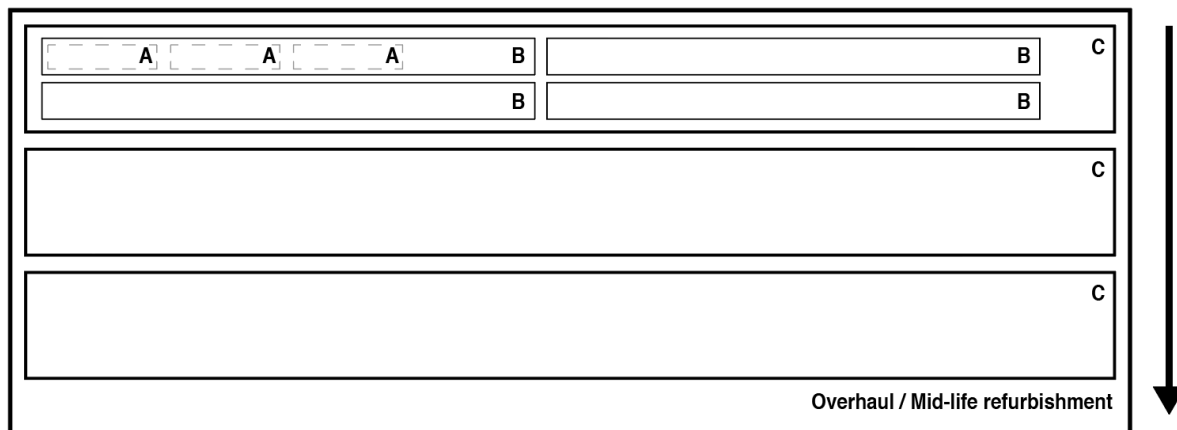
4.2. Maintenance and Manufacture

4.2.1. Maintenance Optimisation for better coupling with design

When examining potential applications within refurbishment or replacement processes, it is essential to explore the maintenance frameworks in which such applications will be implemented. The rolling stock as a physical design typically goes through one formal mid-life review for refurbishment, allowing it to adapt and stay up-to-date or play catch-up to how the world has changed in a decade (Vuchic, 2007). Routine maintenance occurs on a shorter timeline, typically including cleaning, general overhaul and dismantling or rebuilding of parts. The maintenance procedure typically consists of series of ‘A’, ‘B’, ‘C’ and so on services undertaken at increasing frequencies (see Figure 2), where every four ‘A’ service is a ‘B’ service and every four ‘B’ services is a ‘C’ service (Vuchic, 2017). The rail industry uses a combination of predictive, preventative and reactive maintenance to complement their services (Vuchic, 2017). However, more proactive approaches to maintenance are also emerging within industry, such as condition-based maintenance, where the use of sensors monitor the vehicle/asset during normal operating conditions (‘Think Act’ 2016). There is also an emergence of modular maintenance techniques (ibid; Vuchic, 2017), which involves replacing components during light maintenance (i.e. an ‘A’ service) in order to reduce the need and resources for periodic maintenance of the whole vehicle at once (i.e. a ‘C’ service, which may run less often). Technologies such as AM have the potential to streamline the efficiencies of processes such as modular maintenance by producing parts that are on-demand and highly customised, which can allow more immediate implementation of updates and improvements to the design of customer facing parts. AM can provide a tighter coupling between design decisions and updates and maintenance procedures and processes, and may allow for the types of design variation seen in regional european trains where designs vary based on cold and warm weather seasons (Cerny & Daggers, 2016).

Figure 2. Typical rail vehicle maintenance service procedure (adapted from Vuchic, 2017)

An ‘A’ service can either be on the frequency of time, such as every 7 days, or be determined by distance travelled, such as every 12,500km. ‘A’ services will generally include additional elements of maintenance and repair cleaning. ‘B’ services can include general overhaul and some vehicle dismantling and rebuilding. ‘C’ services and so on include more major maintenance, such as major cleans or a mid-life refurbishment and design update.



4.2.2. Maintenance and cost optimisation of spare production parts

Due to the long service life of trains, typically 35 years to 45 years, operators need to ensure the regular maintenance of their ageing stock as discussed previously (Vuchic, 2007). However, this process often requires the obtainment and storage of spare parts. The tradeoff between the availability of spare parts and stock level optimisation continues to be an area for development (Sleptchenko, van der Heijden & van Harten, 2003). This is still an issue with a

significant potential for cost savings, as innovative ideas or product offerings are missing or not yet well implemented.”. There are also circumstances where rail operators are required to procure replacement parts which are considered obsolete by current standards or requirements. Remanufacturing legacy components using the same materials and processes may be too cost restrictive due to the original specifications and production equipment no longer available. Furthermore, producing such parts in small and sporadic runs is not cost effective and can make planning for manufacture difficult. Additive manufacturing helps reduce these issues by providing the ability to commission small batch runs quickly and without the need for expensive tooling. This process also provides opportunities in replacing only the damaged area, rather than the entire component. Allowing for the types of general overhaul, vehicle dismantling and rebuilding undertaken in longer period vehicle maintenance service procedures, such as during a ‘B’ or ‘C’ service, by providing parts on-demand and that are able to be customised to specific repair needs. Therefore, the ability to utilise AM for spare parts manufacturing has the opportunity to reduce supply chain cost by reducing off-shore part production and increasing the opportunity for on-demand local AM. Outdated or legacy components can also be reverse engineered using AM techniques, reducing the need for external suppliers and easing the maintenance burden of operators.

4.3 Design Optimisation

As mentioned previously, AM provides the opportunity for a tighter coupling between design updates and the manufacture of components. AM can allow for the development of designs with increased adaptability, modularization, upgradeability and flexibility, which are some ways to respond to designing for changing environments and future uncertainty (Bischof, 2010; Umeda et al., 2005). When discussing the advantages of AM within MRO processes, Wits, Garcia & Becker (2016) highlight that this technique provides the ability to easily and efficiently replace or restore damaged components as discussed. However, AM also provides the added benefit of allowing end-users and operators to optimise parts via the editing of the CAD file in order to meet specific needs. This, therefore, assists in optimizing the redesign stage of components which, “goes along well with liberalization and digitization, because it can easily be contracted out to independent specialists” (‘Think Act’ 2016, p.10). Wits, Garcia & Becker (2016) further emphasise that redesign optimisation using AM can be focused on four different goals, including:

1. Adaption of parts to end-user
2. Merging parts to avoid unnecessary assemblies
3. Update parts for new applications
4. Combination of aforementioned strategies

The first optimization goal refers to the capability of the end-user to quickly modify the CAD file in order to change elements such as size, shape and textures. This, therefore, does not require the intervention of the OEM or other external suppliers, decreasing the cost of customisation. Customisation accessibility can lead consumers to take on a more “prosumer” role, which refers to the ability of consumers to take a more active role in design development and outcomes (Kotler, 1986; Ritzer, Dean & Jurgenson, 2012). This attitude is becoming increasingly common within the experience economy and has the ability to create a better customer experience and relationship between operators, manufacturers and travellers of rail. Operators such as Deutsche Bahn are leading the way in prototyping and iterating new designs and updates on their system in this respect, such as catering to vision impaired public transit passengers by better adapting handrails to assist them in wayfinding (Rutsch, 2018). The adaption of parts towards different end-user groups traditionally can be seen under-executed within the aims of inclusive design practices. Iteration of parts can enable operators and

manufacturers to increase their rate of design updates, with shorter lead times and use of CAD model modifications. It is currently uncertain as to how rail operators and manufacturers will manage the opportunity to close customer feedback loops more quickly through iterative design updates made possible through AM. However, AM allows the potential for a much more cost-effective, customised design outcome in this respect, and has the potential to change the way operators respond to customer needs in the experience economy.

Allowing MRO technicians to merge parts, as outlined in goal number two, can also save manufacturing time, material and costs. By merging parts, unnecessary assembly steps, as well as the need for additional resources such as screws and fasteners, is eliminated. In a similar vein, additive manufacturing also allows for a reduction in material quantities while still achieving the required product characteristics as previously discussed. As explained by Klahn, Leutenecker & Meboldt (2014, p139), “AM’s geometrical freedom of design allows placing material only in locations where it is needed for the function of the part. This increases the complexity, but reduces material and weight.” This design optimisation feature has significant implications for rail components, with lighter parts helping to lower the overall vehicle weight and improve efficiency. A significant example of this ability can be seen in Geissbauer et al.’s (2017) case study on GE Aviation, where 18 different parts sourced from different vendors was consolidated into one part, with a 25% weight reduction and increased overall performance. The compounding of parts can be potentially utilised in the streamlining of parts within the rail interior, where modular parts are typically separated. Additionally, parts which can be streamlined through material reduction may have greater flexibility in their design outcomes.

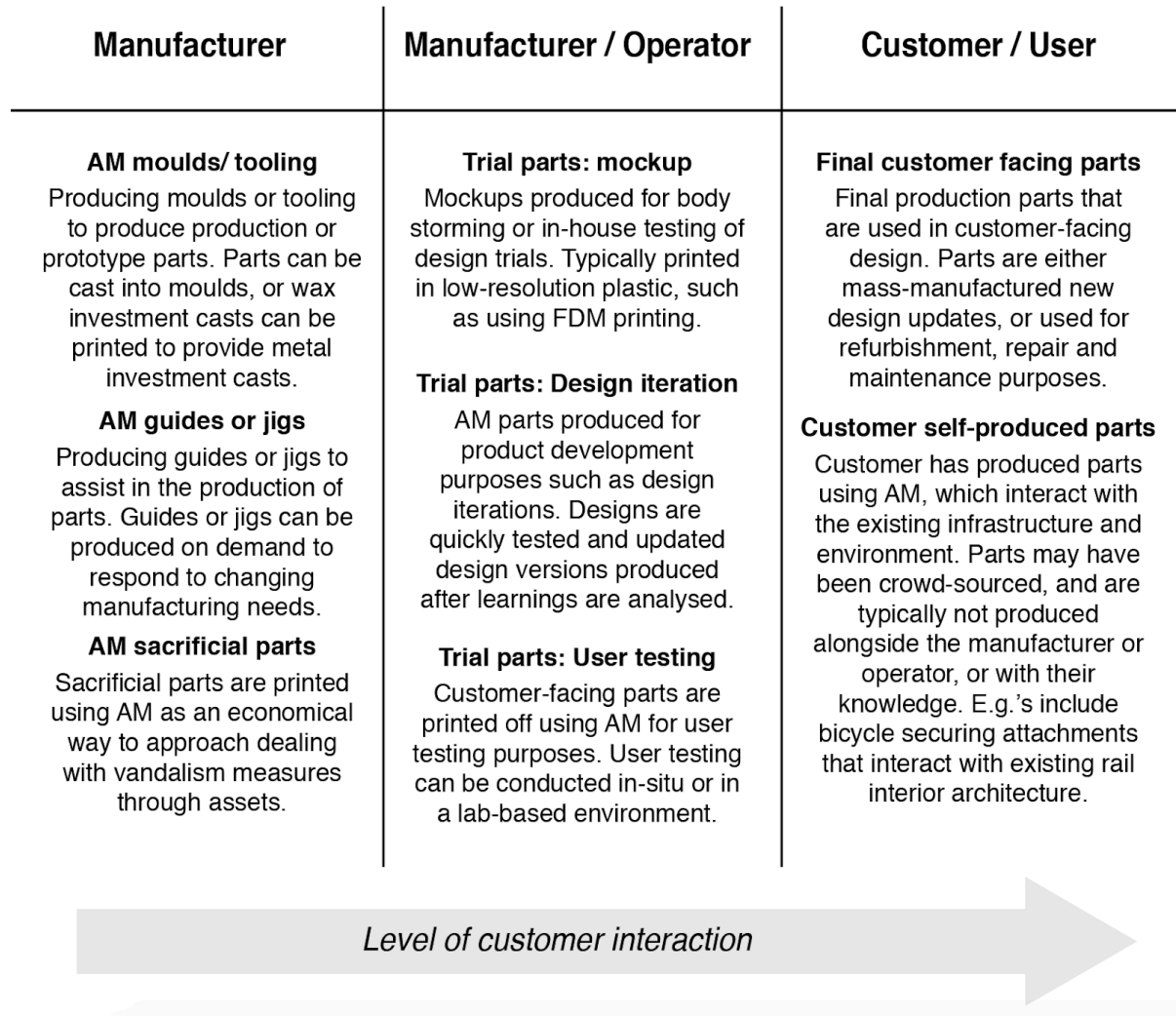
The third strategy outlined refers to modifying existing components to allow for new applications. As explained by Wits, Garcia & Becker, “the original part will be the base of the new part and the design begins from the 3D file of the original part” (2016, p. 696). This process allows for a more streamlined and cost-efficient process when designing and manufacturing new components. In a similar vein, AM applications provide the opportunity to develop “retrofitted” solutions which refers to the addition of new features or technology to existing systems. In the context of rail, this may include applications such as sacrificial or modular components to ease maintenance procedures. This application may also allow consumers to produce their own components to assist with various travel related hindrances (refer to figure 3 below). Modification of existing components does not necessarily rely solely on rigid functional parts printed in polymer or metal. Advances in technical textile AM and smart textiles introduces the possibilities for specific fastening systems to be printed onto textiles according to relevant needs, as well as printing of electronics onto textiles which are able to sense, compute, communicate and actuate (Duchêne et al., 2016). Possibilities for textiles has also been shown in the incorporation of textiles with AM structures, such as in the BMW concept “EDAG Light Cocoon”, allowing for the construction of lightweight structures where an AM structure is covered by textile (EDAG, 2018).

5. Discussion

Additive manufacturing has the opportunity to relieve cost for manufacturers and operators, while also allowing added agility in the design process to provide better value travel experience for end users. AM can be applied in a number of ways from a manufacturer level through to the end user level. Rail operators serve to also mediate the product development between manufacturers and end users. These applications, outlined throughout the paper, have been comprehensively summarised in figure 3. Particular attention is focussed towards how AM might affect the travel experience of customers and end users, with discussion concluding on

some of the underdeveloped and opportunity areas in AM. The review of potential AM applications within rail maintenance, manufacture and design processes, therefore, form the contribution of the paper.

Figure 3. Summary of AM opportunities within rail (Author's own image)



5.1 The User Experience

Beyond providing various advantages for rail manufacturers and operators, AM also presents opportunities in creating a meaningful impact on the experience of travelling by improving usability, comfort, as well as emotional and aesthetic appeal. AM allows for form language and designs that traditional manufacturing may not allow for, or may be too expensive to achieve through traditional means. These areas can often be qualitatively defined and as such, have yet to receive the same focus within traditional transport planning research as the automotive industry has a history of doing so (Napper, 2010; Coxon, 2015; Schiefelbusch, 2010). In the design of rolling stock, there is often less sculptural freedom due to the carrying capacity-driven form, long life cycle and traditional need for durability (Coxon, 2015). However, improvements to the design of physical touchpoints such as the rail carriage interior can improve the hedonic value of travel, as has been shown in improvements towards rail station quality (Cascetta & Carteni, 2014; Edwards, 2013; Kiddo, 2005). As retail becomes increasingly mobile with connectivity on-board improving, as well as changes such as the job-tech movement taking place, the design and experience of the customer-facing experience

onboard will become increasingly important. Designs have the opportunity to even become seasonally changed, when coupled and optimised with maintenance schedules and services mentioned in section 4.2.1.

Consumers are beginning to play a more active role in an increasingly experience-driven economy (Pine & Gilmore, 2011), and are now beginning to have a more crucial and active role in the creation and production of their own experiences (Ritzer et al., 2012). AM means that consumers can begin to act more like “prosumers”, helping to co-create new ideas, designs and finished articles (Ritzer et al., 2012; Rauch et al., 2016). Co-creation activities within the literature generally refer to consumer goods, often involving crowd-sourcing or open innovation platforms where consumers might choose from options that the manufacturers give them. Many of these co-creation methods involve the company or manufacturer in an integrated manner. However, differentiated forms of co-creation, such as crowd-customisation, which involves the modification of goods post-purchase, can mean that users can print their own parts and bring them into the rail carriage. Although travellers currently utilise their own parts to some extent, this is not currently observed with parts created using AM techniques. For example, many cyclists currently bring their own bungee cords to better secure their bicycles while travelling by rail. As the use of AM continues to grow (Jiang et al., 2017), there is the opportunity for consumers to begin to mediate their own experience of travel through the use of open source networks and co-creation platforms (Rayna et al., 2015), such as on sites such as thingiverse and instructables where product ideas can be developed open source (MakerBot Industries, 2018; Autodesk, 2018).

5.2. Australian Metro Rail

The incorporation and possibilities of AM within international rail networks are just beginning, with potential applications in the context of Australia’s metro rail and transport infrastructure yet to be explored. As Deutsche Bahn’s use of 3D printing shows, the use of rapid prototyping can be used to more readily provide iterative updates to the design of rail carriage interiors, moving to a more proactive approach compared to the traditional mid-life refit of rail carriages, while also updating the travel experience within public transport stations as well. Rail operators within Australia are beginning to become more user-centred in their approach through user testing, such as seen in the High Capacity Metro Trains user-testing in Melbourne (State of Victoria, 2018). However, opportunities for more low fidelity mockup testing and trialling of customer-facing parts in-situ on the current network through AM reinforced capabilities remains to be developed and standardised within product development of rolling stock. Low fidelity testing would involve utilising AM technologies which are fast and economical to produce parts from (such as FDM printing), in a way that is not dissimilar to design testing methods in traditional industrial design product development as well as digital product design development. Within a ‘turn up and go’ metro-style system that cities in Australia hope to aim for and achieve, customisation of experience and user-centred design are key. Thus AM can provide a more responsive way to continuously improve on travel experience, compared to traditional means of maintenance and service operation.

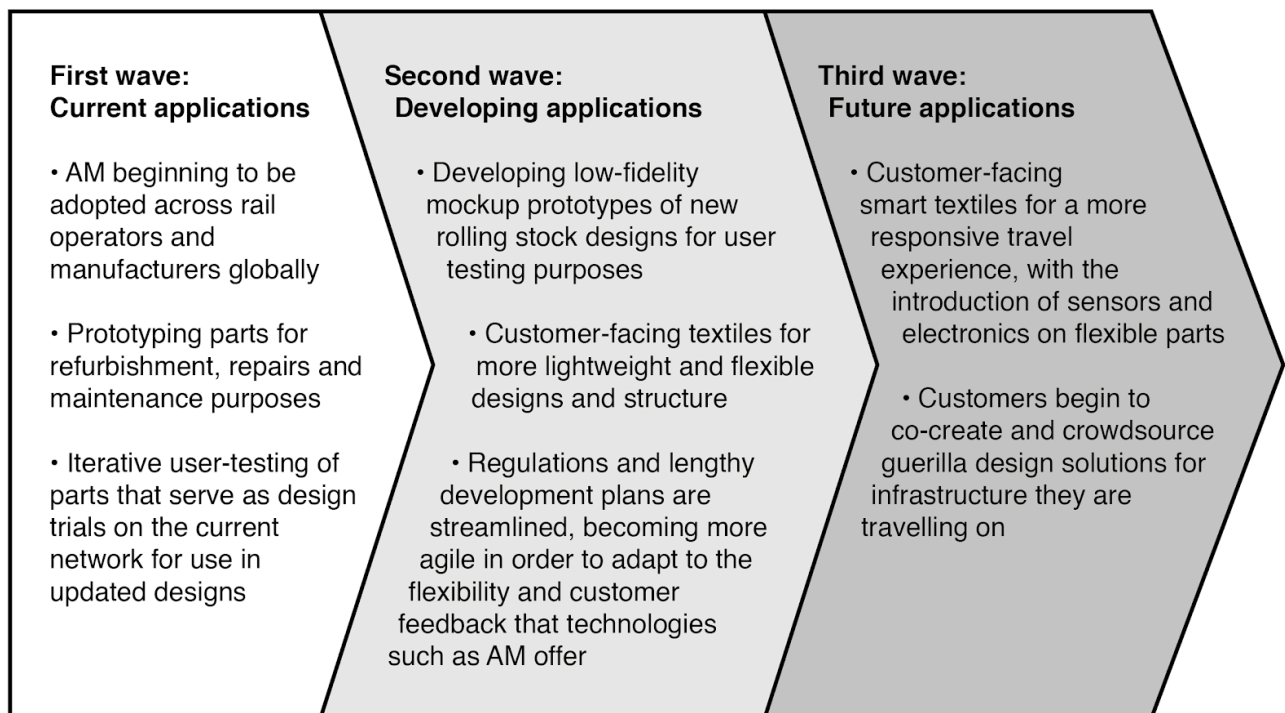
A more proactive approach to catering to a more user-centred travel experience will require an update of product design specifications regarding the design of rolling stock, as well as a re-evaluation of traditional vehicle service maintenance procedures. These changes will not only impact the delivery phase of the commission of rolling stock, where operational readiness activities may include a more user-centred focus, but also the maintenance and operational phase of the commission, where various standards set out may include more proactive and

iterative user-centred approaches discussed within this paper. As transport agencies and operators move to become more user-centred, a re-evaluation of the commission components mentioned will be required in order to continue improving on the experience of rail for an innovative service experience that continues to remain relevant in the future (State of Victoria, 2017).

5.3 Implementing AM Within the Australian Rail Industry

Transport areas such as rail and aircrafts can often have lengthy development processes. For example, the delivery of new rolling stock can often take 1-2 years in the tendering process, and another 2-3 years in product development (State of Victoria, 2017). As AM begins to become incorporated in these areas, further characterisation of materials and processes will aid in the security and safety implications of using AM for production parts. Such as the requirement of finished parts to meet a certain safety standard rating in order to be properly incorporated into the running and operation of an asset. AM also still needs to grapple with production costs in terms of high-end materials such as titanium and aluminium parts, which can have an impact on the scalability of mass manufactured production parts. Surface quality and finish is yet to reach quality expectations and will generally require post-processing in order to achieve a high-quality finish. There are many areas within AM yet to be explored such as the use of textiles in conjunction with AM for the design of assets, as well as how prototyping, user-testing and feedback can be better incorporated into the product development and maintenance of rolling stock. Strategies for refurbishment, repair and maintenance have only begun to be explored within AM on a global scale and have yet to be fully explored within Australian rail. It is also important to critically consider the hype surrounding AM in order to implement it in areas that will actually add value for the manufacturer, operator and end users. Figure 3 provides a roadmap for addressing some of the potential changes and applications that AM could impact on metro rail in Australia.

Figure 4. A Roadmap of AM Applications Within Metro Rail in Australia (Author's own image)



6. Conclusion

This paper has sought to analyse the potential advantages and limitations of additive manufacturing when applied to the design, production and maintenance of interior rail components. When observing AM's applications within the rail industry, applications can be observed in the areas of prototyping of carriage internal components for iterative user-testing, serving as design trials on the current network. However, there is currently limited information with regards to how AM might impact on the experience of travelling by improving usability, comfort, as well as emotional and aesthetic appeal. In creating a user-centred travel experience, a more proactive approach is needed from rail operators and will, therefore, require an update of rolling stock interior components as well as a re-evaluation of traditional maintenance procedures, as well as product development cycles. When designing for future rail interior environments, creating a design with adaptability, modularization, upgradeability and flexibility will assist with allowing rail operators to remain competitive as transport providers within an experience economy landscape with increasingly selective and mobile consumers.

Ultimately, additive manufacturing techniques prove a viable alternative and complementary approach to the design and maintenance of interior rail components when adopted alongside traditional manufacturing methods. Within the development phase of rail projects, economic advantages lie in AM's ability to explore various iterations of prototypes without the commitment to expensive tooling. Eliminating tooling or other set-up requirements also results in a significant reduction in development wait time. This reduction allows for more fine tuning of designs and, in turn, serves a more competitive transport service and experience for end users. When considering potential applications of AM within rail maintenance processes, significant operational advantages can also be observed. As supplies are readily available, fabrication becomes autonomous due to its basis in CAD software. This, therefore, reduces labour requirements throughout various stages of production. Ultimately, AM must overcome limitations regarding materiality capabilities, costs and cycles times if it is to compete with traditional mass manufacturing methods. However, current AM capabilities provide rail operators with increasing levels of opportunity to optimise their design, maintenance and manufacturing methods by allowing for customisable, on-demand components that can be quickly and effectively repaired or replaced. From a supply chain perspective, the ability to replicate components on-demand eliminates the involvement of OEMs, transportation requirements and storage facilities. Coupling AM alongside traditional design, maintenance and manufacturing techniques also provide further areas of opportunity for rail operators. When considering the continuous technological advancements occurring within the AM field, the future of such technology will ultimately benefit operations within an increasingly competitive and experience focused rail industry.

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