

Additive Manufacturing in the spare parts supply chain: Introducing FDM techniques into an established engine plant

By

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A Dissertation

Submitted to the School of Engineering, Manufacturing and Logistics

University of Wales, Trinity Saint David

In partial fulfilment of the requirements

For the degree of Bachelor of Engineering in Manufacturing Systems

May 2019

Declaration of Authenticity

This thesis is the result of the author's original research. It has been composed by the author and has not been previously submitted for examination which has led to the award of a degree.

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Acknowledgements

Firstly, I would like to thank my family and friends for their support in particular Kevin Fahey. I would like to thank my partner Rowan Dent for her unending support of me throughout the whole process of this dissertation and in all aspects.

Next, I would like to thank many employees of Ford Motor Company for their assistance in the implementation and data gathering for this paper and allowing me access to normally restricted areas to do so. All those who gave interviews and discussed these topics with me deserve recognition but I would especially like to extend my thanks to Phil Moreton and Garry Evans.

Finally, I would like to thank the lecturers in the University of Wales Trinity Saint David for providing me with the knowledge and tools required to perform an investigation like the one carried out here.

Abstract

This paper discusses and follows the implementation of Additive Manufacturing techniques through Fused Deposition Modelling into an engine plant's spare parts supply chain.

First an investigation into the published literature surrounding AM and its use in manufacturing both currently and in the future. The current gaps in the literature are also discussed as well as contemporary research that has been undertaken in the use of AM for spare parts.

The company's current relationship with AM is reviewed and then the implementation in this particular plant begins. The setup of the department is noted and the system in which spare parts are currently garnered is described. Case studies are put forward as evidence of the suitability of the resulting FDM parts and their ability to save significant sums of money. Further to this Value Stream Maps are created for the current systems in place and the suggested systems to demonstrate the potential for time savings that can be achieved by the techniques discussed. As well as the benefits and successes of AM implementation the drawbacks and challenges are also noted.

The future of AM within the engine plant are speculated on, with the author's recommendations for future work to be carried out also discussed.

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Acronyms and Abbreviations

3D	Three-Dimensional
ABS	Acrylonitrile Butadiene Styrene
AM	Additive Manufacturing
BEP	Bridgend Engine Plant
BPA	Bisphenol A
CAD	Computer Aided Design
DEP	Dagenham Engine Plant
ECS	Electrical Control Specialist
ET	Emerging Technologies
FDM	Fused Deposition Modelling
FFF	Fused Filament Fabrication
FMC	Ford Motor Company
MMC	Mechanical Maintenance Craftsman
MRF	Maintenance Request Form
PC	Polycarbonate
PLA	Polylactic Acid
PLC	Programmable Logic Controller
RP	Rapid Processes
SLA	Stereolithography
SLS	Selective Laser Sintering
SLM	Selective Laser Melting
VSM	Value Stream Mapping

Introduction

Ford Motor Company's engine plant in Bridgend has one of the largest value of non-product stores items across three continents, these items are considered 'spare parts'. Spare parts are integral to maintenance operations, allowing the process of fixing and maintaining equipment to occur as efficiently as possible. Without the stores items held on site the lead time of a repair would be hugely increased to the wait for delivery. However, the financial impact of the non-product stores is concerning to some (Moreton, 2018). Therefore, engineers at BEP have been searching for means of reducing the impact the non-product stores has on BEP's cash-flow. BEP also has a 'tool room' where skilled tool makers craft any bespoke parts, from nylon and steel, required by skilled employees to ensure that the assembly and machining lines are running to their expected level both in terms of quality and delivery. It has been suggested by some that the tool room sometimes struggles to keep up with the demand for their items and so backlogs happen fairly regularly (Phillips, 2019). One method that has potential to solve these concerns is the use of FDM techniques, a branch of Additive Manufacturing.

3D printing is the more colloquial name given to AM, especially FDM printing. For many years, 3D printing has primarily been believed to be the reserve of hobbyists and model makers. With newer literature focussing on design for AM and its scalability for larger operations there is a gap in the knowledge of practical implementation within the spare parts supply chain of a manufacturer.

Although the automotive industry is the third largest growth industry for additive manufacturing (Wohlers, 2017), this is not reflected in Ford Motor Company's (FMC) Bridgend Engine Plant (BEP). Until 2018 there were no 3D printed parts in BEP at all despite large scale investments from FMC in this industry (Goehrke, 2018). AM is also considered by many to be a 'disruptive technology' in assisting with the implementation of industry 4.0, a trend of automation that FMC is currently attempting to realize.

The purpose of this paper is to investigate the implementation of AM techniques into an established manufacturing environment, supplementing the already existing processes in the creation of spare parts. In doing so it is to be established whether AM is more suited to these uses in terms of cost and delivery.

The preliminary findings within this paper are discussed and assessed as to the future potential for this technology in an environment it has not yet been widely adopted in.

Literature review

The purpose of this section is to give the reader an overview of the current published literature in Additive Manufacturing's (AM) advances in the manufacturing industry, as well as introducing concepts that will be used later in the paper.

Additive Manufacturing

Additive Manufacturing (AM) is a process whereby new material is added to material that has already been placed, hence additive. This is in contrast to traditional machines found in a workshop which are subtractive in nature where a full block of material is cut away bit by bit to create the final part. Gibson, et al., (2010) explain that unlike subtractive methods, AM technologies are fabricated directly and don't require process planning such as determining which features should be fabricated first and what tools will be required.

AM is often referred to as 3D printing, due to it 'printing' a layer of material at a time giving the effect of a computer printer. The objects that are created by the 3D printer are initially created via a Computer Aided Design (CAD) package (Khajavi, et al., 2018).

AM Process

From initial concept to completed AM part there are four main stages to the AM process, as explained by Gibson, et al., (2010):

- CAD (Computer Aided Design) – Parts are created with computer-based design software.
- Slicing – These CAD designs are then “sliced” using slicing software to convert the solid object into a series of layers and pathways for the printer to follow as it extrudes the molten material. Support structures for the model are also added here, either manually by the designer or automatically by the software.
- Printing – The process of model fabrication on a printer.
- Post-processing – The removal of any support structures or excess material left by the printing process.

Uses of AM

Gibson, et al., (2010), explain that the initial use of AM was to create prototypes and models for visual representation of a part whilst in development. They go on to explain that as AM technologies became faster and more accurate and access to different materials increased, components can now be created to within the tolerances in the specification with no further processes required.

Wong & Hernandez, (2012) found that the most common use of AM was to create functional models, with direct part production coming second (Fig 1). Until recent years, AM wasn't often considered more than a prototype technology by publications (Zanardini, et al., 2016) (Ford & Despeisse, 2016) (Khajavi, et al., 2013).

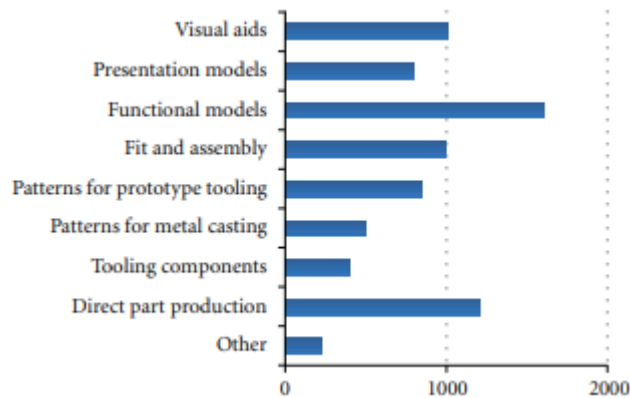


Figure 1: Use of AM processes (Wong & Hernandez, 2012)

Wong & Hernandez, (2012) also describe some of the applications used for AM at the time including:

- Weight reduction in machines
- Architectural modelling
- Medical applications
- Art
- Hobbyists
- Strength analysis

Types of AM

Whilst AM is often thought of as '3D printing', it can take multiple forms. There are several different methods of AM which are outlined in this section.

Fused Deposition Modelling

Fused Deposition Modelling (FDM), also known as Fused Filament Fabrication (FFF) is the most widespread types of AM currently used (Pitayachaval & Masnok, 2017). However, there are many different systems available at varying price points, ranging from inexpensive desk-top printers for hobbyists to costly large scale systems for high-level requirements.

FDM machines work by taking, most commonly, plastic material in filament form on a spool which is fed into a 'hot end', melting the material. The melted material then goes through the nozzle and onto the print bed (and later the previous layers) whilst the nozzle/bed moves to

create what is sometimes referred to as a 2D model. This is then built upon, creating the 3D part.

FDM models are often derided for their “prototype” looks (Gibson, et al., 2010), because of the visible layers that have been built up in their creation, visible in Fig. 2. These layers are often the weakest points in FDM prints due to the poorer material adhesion than in a process that creates parts from one ‘piece’ of material (Gibson, et al., 2010).



Figure 2: FDM product showing the layers that form during creation (Varotsis, 2019)

Powder bed fusion

Ngo, et al., (2018) explain that Powder Bed Fusion is where a print bed is layered with a very thin layer of powder, areas of which are then laser treated (or heated in another manner) to bind this layer with the previous ones. This repeats layer by layer creating a block of material which contains within it the desired components. Ngo, et al., (2018) go on to state that Powder Bed Fusion AM technology is divided into two main categories:

- Selective Layer Sintering (SLS) – Which can be used with many different plastic polymers and metal alloys. This process when performed on metals and alloys has also become known as Direct Metal Laser Sintering (DMLS) (Srivatsan, et al., 2016).
- Selective Laser Melting (SLM) – Which uses certain metals including aluminium and steel.

Models created by modern Powder Bed Fusion techniques are isotropic, meaning that they have consistent material properties from all directions, as opposed to FDM printing (Dilberoglu, et al., 2017).

Stereolithography

Stereolithography (SLA), as described by Ngo, et al., (2018), was one of the first AM methods developed. It consists of a bed of liquid resin which is then treated with UV light to

solidify. As with other AM technologies, this layer is then built upon by another until the product is completed. More and more resins are being created in recent years, making SLA more desirable again due to the range of properties offered by the various materials available (Latouche, 2019).

Design for AM

Design for AM is one of the most widely discussed and published topics related to AM. For example: Chung, et al., (2018) use a low-cost FDM printer commonly used by hobbyists to create a replica of a patient's abdominal aortic aneurysm geometry, and conclude that the process is sufficient for further investigation into creating these models for medical training purposes.

Most of the material regarding AM/FDM design is concerned with topology optimisation for maximum strength with minimum weight of optimisation for printing (Belhabib & Guessasma, 2017) (Qureshi, et al., 2015) (Strano, et al., 2012).

Since AM is a newer technology that has not yet been implemented to the point where its concept is factored in as a possible method for manufacture, engineers and designers often have little experience with optimising designs for these processes. However through newer topology optimisation software it is possible for this to be done automatically which can lead to better efficiency and productivity of AM processes (Dilberoglu, et al., 2017).

The research that has been conducted in this area is vast. As such further additions to the over-arching subject of 'design for AM' are not within the remit of this paper.

Materials

As BEP currently uses FDM printers, (as will be discussed in 'AM in BEP') the materials for this technology will be discussed. FDM printers use material that is called 'filament' rolled onto a spool. Filament is a small diameter (1.75mm) length.

The most common materials used in FDM printing, that can be printed on almost all standard FDM printers, by both hobbyists and industrial users as described by Ngo, et al., (2018) and Fischer, (2011) are:

- PLA (Polylactic Acid) – Known for its ease of printing, i.e. broad temperature ranges and minimal system requirements such as a heated bed or an enclosed printer. PLA has relatively meagre mechanical properties. However, it has been found that these same properties, when printed on a 3D printer, have been shown by Song, et al., (2017) to have improved qualities in both tension and compression. PLA is the ideal material for use in rapid prototyping due to its printing ease and low price.

- ABS (Acrylonitrile butadiene styrene) – Fischer (2011) explains that ABS was the most commonly used material used in FDM printing due to the fact that it is a ‘general purpose’ material and has a high level of strength. ABS requires an enclosure and the cooling fan of a printer to be turned off whilst creating a part.
- PC (Polycarbonate) – PC is the most widely used industrial thermoplastic, and as such has been available for use in FDM for multiple years. PC is very strong, very durable and also stable (Fischer, 2011). PC, like ABS, requires an enclosed FDM printer and no fan. PC typically contains ‘Bisphenol A’ (BPA) which is a chemical that has been shown to have a strong link to having negative effects on human health including: behavioural changes, altered growth, internal lesions and early sexual development (Erler & Novak, 2010) (McGovern, 2009).

Often there are materials not used by mainstream hobbyists that are very useful, especially in industrial settings. These materials can also be printed with most standard FDM printers:

- Polyurethane – Specifically, a material by the company NinjaTek called ‘Cheetah’. Cheetah material is flexible and has some comparable properties to rubber. NinjaTek, (2019) suggest that Cheetah is suitable for the creation of seals or plugs, meaning it has great potential for industrial designs. NinjaTek, (2019) go on to state that the shore hardness of Cheetah is 95A which is far greater than the shore hardness of PC that (Singh, et al., 2017) found to be around 70A when printed on a FDM printer. NinjaTek, (2019) also claim it has a 84% greater impact strength than ABS, which is used for its strength.
- Polymers for wear resistance – ‘igus’ have created a range of Tribo-Filament including ‘iglidur I150-PF’ (igludur). igus, (2019) explain that these materials can be used for applications such as bearings and jigs due to their very high abrasion resistance. These applications have the potential to have huge impacts on the supply chains of manufacturers due to the potential new method for acquiring these parts.

FDM filaments are sensitive to moisture in the air and so must be stored correctly once opened (Filamentive, 2019).

Settings

In FDM printing the following terms are used:

- Nozzle temperature – The temperature of the ‘hot-end’, where the filament is melted for extrusion.
- Bed temperature – The temperature maintained on the print bed during the printing process, to assist in material adhesion (Varotsis, 2019).

- Layer height – Layer height is the depth of each layer that the printer extrudes from the nozzle, the smaller the layer height, the higher the fidelity of the part to the original CAD design (Gibson, et al., 2010).
- Retraction – Relieves pressure of molten material in the hot end of the printer by withdrawing filament slightly (Landry, 2015).
- Print speed – The rate at which the motors move the frame that houses the print-head. This dictates the speed of the process as different materials can cope with being printed at different speeds (Varotsis, 2019).
- Infill density – When a solid part is sliced, the software recognizes where there is enough space to create a cavity and the infill dictates how much of this cavity is filled by a structure – if 100% density is selected then there will be no hollow channels, if 0% there will be hollow cavities. This infill affects the speed of a print drastically so favour is given to lower infill where possible, but this is also where the strength of the printed component is dictated (Ultimaker, 2019) Fig 3. shows how certain different infill densities look.



Figure 3: Different infill densities, 10% 25% and 50% respectively (Ultimaker, 2019)

While there are other settings used in FDM printing, the settings discussed above are the most commonly altered by printing operators (Cahoon, 2017) (Ngo, et al., 2018) (Varotsis, 2019).

Manufacturing spare parts for production

Since AM has the potential to create prototypes and usable models there is a large potential for the creation of a new spare parts supply chain within a manufacturer or the modification of an existing one. In 2013 Khajavi, et al., believed AM could be a disruptive system to supply chain management due to factors including: the lack of requirement for tooling; the quick design turnaround time, optimisation for function and the potential for minimising lead times and amount of stock.

The 8 wastes

The Toyota Production System (TPS) was created by Ōno Taiichi (Ōno, 1988) as a method for ensuring the efficient production of Toyota cars. Part of this system was concerned with what Ōno believed were considered the biggest wastes of most processes.

The types of waste as defined by (Ōno, 1988) in the TPS are:

1. Delay/waiting – Any point where nothing is being done to the product that relates to its creation or delivery, including waiting to be loaded onto a lorry or idle equipment.
2. Over production – The creation of too many parts for the demand, this happens often in manufacturing environments and can lead to poor work flow and larger costs due to the necessity for storage space. (Skhmot, 2017)
3. Over processing – Often when parts are created by hand, such as by a toolmaker, they will follow the brief that they have been given and sometimes to a further degree, such as giving a component a surface finish that isn't required. This constitutes a waste due to the time and effort taken to add these unnecessary touches.
4. Transportation – When anything related to the creation/delivery of a product is transported from one place to another, this includes both long distances (across country) and short distances (to a different part of a factory). Any tool, person or vehicle involved affects this. For example, if a forklift is required to move parts from one place to another, waste can be reduced by moving these locations closer together.
5. Unnecessary movement – Unnecessary movement is similar to the waste of transportation but is on a more personal scale. For example, if an operator on an assembly line needs to retrieve four engine components from containers located behind their backs they would need to turn around move to retrieve two components and return to fit them, then repeat again. If these boxes were instead located on either side of the operator with a feed-in system, the movement they were previously performing would be eliminated.
6. Inventory – It may appear that having extra inventory is a benefit, if there's a sudden increase in demand, for example, the extra inventory can make up for any shortfall for a little while. However, inventory that is stored, usually, cannot get the attention it requires to remain in the best shape possible. Whilst standing in storage the quality of the product has the potential to drop, through: damage, wear & tear etc. Storage space also incurs a cost that wouldn't exist otherwise.
7. Defects – Manufacturing processes typically have quality standards; these limit the errors or flaws of a manufactured part. Those that do not pass these tests typically

have defects. Depending on the process a defect may mean a part is immediately scrapped or, in cases such as engine assembly there may need to be a 'strip-back' where components are removed back to a certain point and re-inserted back on the line. This would mean that work has been put into stripping back the product and then the initial assembly was wasted since all of the processes are being repeated.

8. Underutilising staff skills – Often skilled employees do not use the full extent of their expertise on a regular basis, with most of their role comprising mundane routine jobs. Sometimes employees' skills are never put to use in their role – it is beneficial to both employees and the employer that these staff members move to a more suitable role or a modification to their existing one. An example: if a machine were to break down, requiring the attention of a tradesperson or engineer, the operators of said machine often know the cause because of their experience with the equipment. These individuals may have crucial information for the repair team and their expertise should not be overlooked.

Industry 4.0 - Disruptive Technologies

There is a recent movement in manufacturing in referring to the implementation of intelligent automation and associated disruptive technologies as the fourth industrial revolution or 'Industry 4.0' (Dilberoglu, et al., 2017).

One of these disruptive technologies is AM. Hannibal & Knight, (2018), explain that AM has the potential to revolutionise manufacturing supply chains at all levels. Vaidya, et al., (2018), agree with this and also state that AM has the potential to drastically reduce transport distances of parts by creating decentralized hubs of this type of manufacture. They go on to state that the complexity required by customers will be far more likely to be achieved through AM.

Value stream mapping

A value stream contains all major processes (both value adding and non-value adding) that are required to make a component or to provide a service to a customer (Kuhlang, et al., 2014).

Each stage of the process is represented on the diagram, with each station, or process, showing the time it takes to complete, other things in the process that take time (the non-value adding components), such as delivery lorries waiting to be dispatched/waiting to be loaded are included if known (Boonsthonsatit & Jungthawan, 2015). The value adding components are compared with the overall lead time to assess how much of an improvement is possible. An ideal system will have zero non-value adding time (Kuhlang, et al., 2014).

Value Stream Mapping (VSM) is described by Tyagi, et al., (2015), as a lean tool to help reduce the wastes in manufacturing that have previously been discussed. Tyagi, et al., (2015), go on to explain how valuable VSM has become to some companies due to it's ability to pinpoint wates and help improve process flow. It is often seen as a key component to lean thinking (Boonsthonsatit & Jungthawan, 2015) (Lin, et al., 2017).

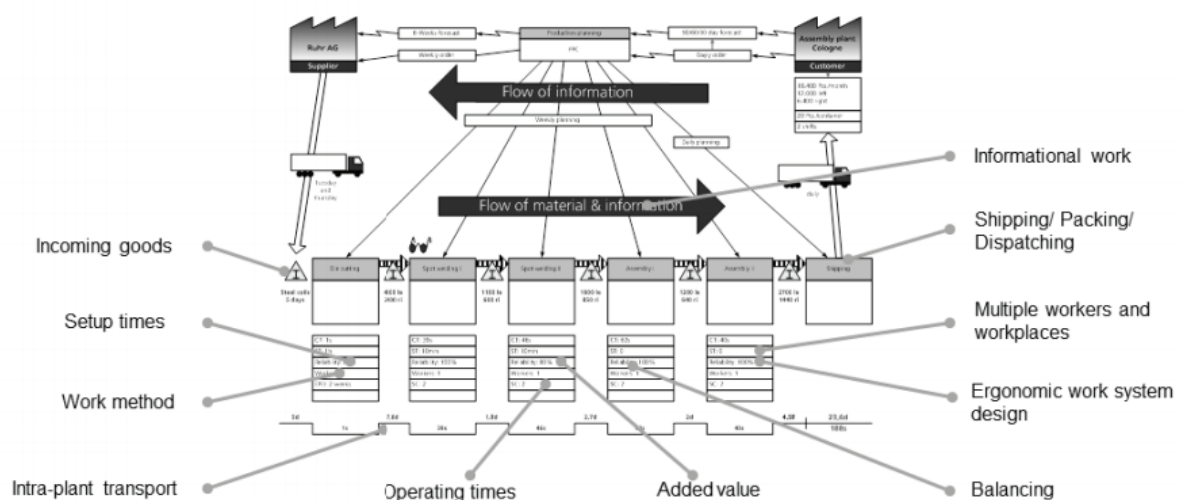


Figure 4: A labelled Value Stream Map template provided by Kuhlang, et al., (2014)

The future of AM

Whilst AM is being adopted more and more into stages of the manufacturing process, there are still concerns around many factors. Due to the relative newness of the technology compared to established and tried-and-tested methods such as CNC machining or injection moulding as well as general unfamiliarity with the process, resistance can be encountered when trying to adopt AM (Jiang, et al., 2017). This can be overcome through reassurance of the quality of parts such as the quality assurance tool developed by Crowell, et al., (2018),

where software was used to create a feedback loop. Once a component is made on a printer it is tested via scanners for accuracy and any inaccuracies are communicated to decision makers in order to improve the component on its next print.

Jiang, et al., (2017), found that AM technologies have already had a huge impact – not just on manufacturing industries but also on society, with the availability of an at-home manufacturing process. In the same paper Jiang, et al., (2017) performed a Delphi study, attempting to predict the implications of AM for the year 2030. They found that consensus of the experts was only found in one third of the proposed sections which they believed was likely due to the infancy of the technology and its adoption. Of the areas where a consensus was reached it is strongly believed that consumer behaviour would be altered, this is applicable to all types of consumers including those discussed in this paper. They also found that it was believed that the skills and knowledge required to perform AM techniques to a industry standard was equivalent to other production techniques and that this knowledge was likely to be taken up by more and more manufacturers. The experts in this Delphi study also took note that research must continue into the opportunities for introducing AM into manufacturing product flows. This study is based on qualitative inputs of experts in the field – as these inputs are based on qualitative factors and results they are likely trustworthy.

Tofail, et al., (2018), believe that AM as a technology is at the crossroads, at the tipping point of being adopted in many different industries. To achieve this they also believe that research needs to continue both academically and in industry.

Literature gaps

Currently the academic body of knowledge concerned with AM is almost entirely centred around materials, design, efficiencies in production volume and the processes involved (Balletti, et al., 2017) (Ngo, et al., 2018) (Pitayachaval & Masnok, 2017) (Schniederjans, 2016). AM does still have issues in these areas, expanding to: reliability of machines, topology optimisation for AM and repeatability of results, thus on-going research is crucial. Whilst this work is critical for the future success of AM technologies and their future adoption, the technology now available to almost all companies and researchers means that there can now be steps made to implement various AM tools within current, non-specialist facilities.

Whilst there are also papers published on the supply chains related to that parts that go on a product itself, there were very few that were focused on the spare parts supply chain with the notable exception of Holström, et al., (2010) who called for more research to be done into the AM of spare parts. However, since 2018 there has been an increase in these papers, for

example: Knofius, et al., (2019) found that parts consolidation through AM was likely to increase overall cost of replacing spare parts if a total cost perspective is not taken. Khajavi, et al., (2018) found that decentralised hubs with AM facilities may give the best cost efficiency as opposed to one main supplier of AM parts to various facilities. Whereas, in contrast, Zhang, et al., (2018), found that AM operations that they investigated could not offer the same cost efficiency as more traditional warehouse facilities supplying spare parts. Whilst the findings of the literature on spare parts is interesting, they are mostly concerned with a supply chain that always has spare parts coming in from an external source and not the manufacturing facility itself, so even though the results are not always promising they are likely not to be fully relevant when comparing the work that has been undertaken in BEP and this paper.

AM in Ford UK

Dunton Technical Centre

FMC UK has established a 'Technical Centre' in Dunton, Essex in order to research and develop a huge variety of aspects of a range of FMC's vehicles. They have roughly 3,000 engineers onsite with the capability to test and develop 100 engines and fifteen cars concurrently. The Technical Centre also looks for future opportunities for factories such as DEP and BEP.

In FMC's Technical Centre also hosts the Rapid Processes (RP) department. The Skilled Foreman of this department is Derek Banks, (2019) and this department has existed in this location for a number of years. The primary focus of this department is to ensure that new methods of manufacture are investigated to ascertain their suitability for any potential uses. Their facilities are extensive and they have a large amount of expertise in the department, AM, and relevant technology available to the RP department, as explained in a communication with Banks, (2019):

- FDM printers – Ideal for design aids, master models and semi-functional prototypes. Also used for creating one-off parts (in PC or ABS) for under-bonnet applications when prototype vehicles/engines are being assessed at the Technical Centre.
- SLA Printers – Used for high quality and high accuracy parts, commonly master models and design aids.
- Optical Measuring Machine (Fig 5) – a large-scale, high-detail scanner that can be used to reverse engineer parts or inspect created parts to compare to the original CAD data.
- SLS – These machines have many applications, each with positives and negatives to their usage.
 - EOS (Fig 6) – This system currently uses a nylon material which is

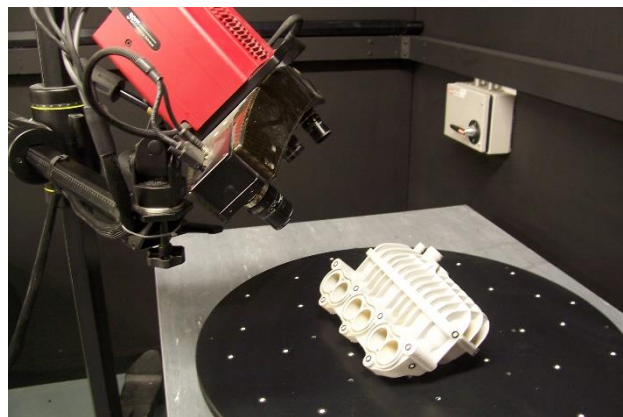


Figure 5: Dunton RP 3D scanner

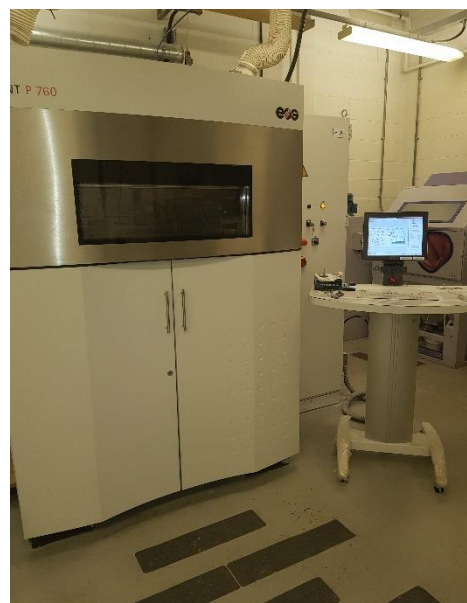


Figure 6: EOS SLS printer in Dunton RP

equivalent to PA66. This material can easily be glued so parts beyond the 740 x 380 x 560mm build envelope can still be created. The items made on this machine can be used in most engine related cold-side components. This is the most widely used Rapid process in the Technical Centre.

- HP (Fig 7) – This machine is similar to the EOS SLS machine, with a newer printing technique using black ink to fuse material layers together. The initial print material is PA12 nylon, with PA11 nylon soon to be trialled. The build envelope for this machine is 380 x 280 x 380mm and parts created in PA12 are more difficult to glue, meaning that it shouldn't be used for parts be larger than this volume.
- Renishaw SLM (Fig 8) – This machine works as described in the 'literature review' section. It uses an aluminium powder to additively create components. Sometimes machining is required, but this is unusual due to the fine layer thickness. The build envelope for this machine is 250 x 250 x 300mm. Parts created on this machine come out relatively rough but can be tumbled or shot-blasted to get the desired surface-finish.



Figure 7: HP SLS printer in Dunton RP



Figure 8: Renishaw SLM machine in Dunton RP

- Sand printing (Fig 9) – Creates items by layering sand and a binding agent, in a conceptually similar method to SLS. These can be used to create models for visual inspection as a design tool, an example can be seen in fig 10. They can also create one-off moulds for casting purposes. These are large scale machines which can create scale models for design engineers at a fraction of the cost and in a fraction of the time (Ford Motor Company, 2019) of traditional processes. There are two of these printers in the RP department.



Figure 9: Dunton RP's sand printer



Figure 10: Model created by Dunton RP's sand printer

Dagenham

Dagenham Engine Plant (DEP) is considered BEP's 'sister plant'. DEP builds diesel engines, whereas BEP builds petrol engines. DEP created an Emerging Technologies department at the same time as BEP, gaining similar initial funding to set up a department to investigate newer technologies to help the plant run at a more efficient or cost-effective level. Moreton, (2019) explained that the DEP Emerging Technology department focused its efforts more on other areas and thus has not progressed as successfully in introducing AM as BEP.

Moreton, (2019) went on to state that DEP's department only has a single FDM printer and a single employee to run it and work on other projects that the department is involved with.

AM in Bridgend Engine Plant

Emerging Technology department

As briefly mentioned in the previous 'Dagenham' section, in 2018 BEP was given funding to create a new onsite department, the Emerging Technologies (ET) department. The main goal of this department is to find savings and efficiencies through new technology. Other than AM the ET department is also investigating:

- Drones – Internal gantry inspections and external roof leak reconnaissance
- Collaborative robots – Cheaper than traditional manufacturing robots and can work alongside production operators without barriers
- Optical microphones – Quality testing during engine assembly to ensure components are fully mated when installed.

Initial setup

The department was initially only set up with one employee, Phil Moreton, the Senior Emerging Technologies Engineer. A 3D printer was researched by Moreton and purchased a Raise 3D - Pro2 Plus (Fig 11). This printer has a large build volume when compared to most FDM printers and has two hot ends – meaning that two materials or two colours of the same material can be printed with at a time (Moreton, 2019).

The author, an Electrical Apprentice at the time, was asked by Moreton to help set up the new Emerging Technologies department due to his experience with

3D printing. The author would initially design the parts, run the 3D printer and set up the systems surrounding it, including: settings, recommending materials and organising the work order or ordered parts (Moreton, 2019).



Figure 11 :Raise 3D - Pro 2 Plus 3D Printer (Raise 3D, 2018)

Current facilities

Since the inception of the ET department, Moreton (2019), decided to order two more Raise 3D - Pro2 Plus printers since it was determined that the parts created were deemed of sufficient quality and ample ease of use.



Figure 12: Einscan 3D scanner (Shining 3D, 2018)

To create the CAD models the ET department has acquired a high-specification PC that can process almost all computing applications that could potentially be required in the process of implementing AM in BEP.

The ET department has also invested in a 3D scanner with turntable (Fig 12), inspired by similar equipment in the Technical Centre's RP department. It can be used to reverse engineer parts that are difficult to assess via conventional hand tools.

Finally, the AM side of the ET department is run by a single skilled employee, who designs components and runs the printers.

Spare parts

When manufacturing almost anything, it must be expected that spare parts will be required for maintenance, no matter the maintenance strategy chosen (Huiskonen, 2001). On-hand spare parts ensure that a manufacturing operation can return to smooth running after a breakdown and ensure that planned maintenance can be carried out without any delay (Gopalakrishnan & Banerji, 2013).

Huiskonen, (2001) explains that the requirement of spare parts is difficult to predict with the cost of these parts often varying each time they are ordered from an external source. Spare parts are integral to the running of BEP but many believe that the current system is not up to the standard it needs to be to compete in the current global climate (Moreton, 2018) (Phillips, 2019).

Stores

BEP has the largest value of non-product stores of any of FMC's engine plants in Europe, Africa and Asia, with a total value of around £32,000,000 held at all times (Moreton, 2019). There is a vast array of spare parts kept onsite relating to anything that may be needed on short notice, including: tools, jigs, seals, bearings, handles, PLCs and many others.

Items are delivered straight to the stores department where they are catalogued and inventoried by FMC employees who then place the parts into bins within racks, seen in Figs 13 and 14

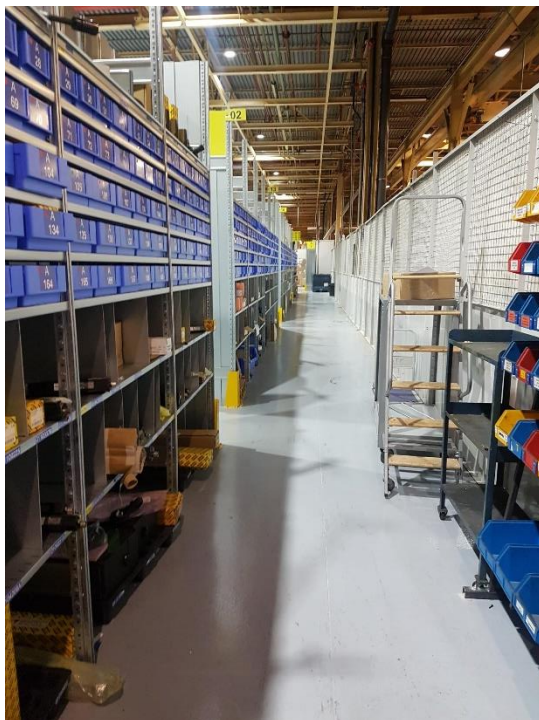


Figure 14: Aisle of BEP stores



Figure 13: Drawers of BEP stores

Many of these parts are deemed to be over-priced by the maintenance staff that order them (Evans, 2018) and the supervisors that approve them (Duckett, 2019). Moreton, (2019) has asked the ET department to investigate the stores and see if there are items that could potentially be replaced by 3D printed components. This is further discussed in the section 'Costs and savings'.

Parts are ordered from the stores via FMC's 'Maximo' system. When an order is placed through this system a skilled employee fills in a form that contains the manufacturing line they work on, the part they require, a description of the part and how many parts they require. This order is then sent on to the area supervisor who must approve the order to be collected from stores – collection from stores is immediately possible as long as the parts are in stock.

External suppliers

External suppliers are the source of parts located in the stores onsite in BEP. There are many suppliers in BEP's supply chain that cover many different areas of the manufacturing process (Duckett, 2019). There are many people in BEP whose jobs are solely focused on the supply chains that run in and out of the stores in BEP. These suppliers are worked with closely to ensure that BEP gets the required components on demand.

The items supplied by external companies are usually components that wear out and are replaced at least occasionally, however some suppliers provide one-off parts that are custom made. These custom made parts are not entered into the stores system but go instead directly to the engineer or skilled person who ordered them.

Tool room

The tool room in BEP is staffed by four shifts of skilled workers who are onsite twenty-four hours a day, seven days a week. They are tasked with creating working items of all manner to keep the various lines in BEP running consistently.

The BEP tool room works in various grades of steels and nylons, through the use of milling machines, lathes, pillar drills and many other pieces of equipment.

Components are ordered through the tool room by engineers or skilled employees, they must go down in person, usually with an already designed part for the tool makers to re-create. Once the tool maker has agreed to produce the part a Maintenance Request Form (MRF) is submitted with a priority given, for example a part might be urgently required to keep a line going or provide a modification that will implemented in the next few weeks.

Wastes of current processes

As discussed in the literature review there are considered to be eight wastes associated with manufacturing processes (Ōno, 1988). These eight considerations (in the order discussed in the literature review) have been applied to the current two processes that are currently implemented in BEP for the supply of spare parts suppliers and the tool room.

External Suppliers

1. Duckett, (2019) explained that when BEP order a new part from an external supplier there is usually a 2-4 week turnaround to receive the part that has been designed, manufactured and delivered. This can increase or decrease depending on many factors including: the type of process required; the backlog of work the supplier currently has; and the complexity of the design. This 2-4 week waiting period can have costly implications if the part is required immediately.

2. Over-production from an external supplier may cause issues with waste but it does not affect FMC directly.
3. Like over-production, over-processing is an issue that will not affect BEP in terms of waste. Suppliers may over-process to give FMC a better product in an attempt to secure future business (Duckett, 2019). This could affect BEP if the over-processing incurs a delay in delivery.
4. In BEP there is a delivery system whereby stores staff will take delivery and retain the item until it is collected by the designated person, however, there is no system in place to alert the engineer that their item has arrived. This is true in regards to unique one-off or prototype parts, in cases where a part is constantly stocked and replenished in the BEP stores the online inventory management will show when they are back in stock.
5. Wasted movement can occur in the case of external suppliers: if an engineer visits the stores but their item hasn't arrived this would be a waste of movement.
6. The stores system is managed to reduce the waste of inventory as much as possible whilst keeping the required quantity of spare parts on-hand to ensure there is enough time to order and take delivery of more before they are needed again (Duckett, 2019). Poor inventory management on the side of the external supplier doesn't affect BEP directly.
7. Defects incurred by an external supplier when not caught can have a large impact on BEP in that: they may be then put into use and break/be unusable earlier than they should causing more down time and needing to be replaced again. If they are caught by the external supplier however, then there can be delays in delivery to BEP.
8. BEP does not suffer directly if an external supplier has poor utilisation of their staff members.

Tool room

1. The tool room in BEP is often viewed as inefficient by skilled employees (Phillips, 2019) (Mayo, 2019). It is not uncommon for parts to take two weeks to be completed, for example due to back-logs and the shift patterns of tool makers. Whilst it is clearly the case that the tool room sometimes struggles to reduce the wait times for their customers, the estimated times that are given are likely inflated (Duckett, 2019).
2. Tool makers, by the nature of their work, are unlikely to over-produce any products due to the bespoke nature of the items they typically deal with.
3. Staff in the tool room are highly skilled tool makers and as such will follow any drawings to the specification given. There are times when a tolerance is not tight and

standard accuracy does not need to be adhered to, but still is. This over-processing can waste time and effort.

4. With three assembly lines and eight machining lines, BEP is a large site. The tool room is located in a corner of the site. While this works for the Dragon engine assembly line, all of the other lines are between five and fifteen minutes' walk away (Mayo, 2019). Because there is currently no system in place to notify trades people and engineers when their parts are complete they must physically go to the tool room to check. Often the part is not ready, meaning that a journey of between ten to thirty minutes is wasted – this is multiplied by how many times they check with no success. This waste of transport of people is large and would add up to an incredible loss of time overall (Moreton, 2019).
5. The tool room has various manual and automatic methods by which to create a work-piece at their disposal, including milling machines, lathes, CNC machines and pillar drills. All of these individual machines are located around a relatively large workshop, meaning that, if multiple machines are used there may be a lot of wasted movement in creating one part.
6. In terms of inventory, the tool room keep a large supply of nylon and metal of various sizes and specifications so that they are likely to be able to create most things whenever they are asked to. This requires a large amount of space for storage.
7. If a tool maker is creating a part and something goes wrong, e.g. they slip, miscalculate a measurement, the machine breaks, or the material cracks, then they will most likely need to start again, meaning a loss of the current accumulated work time. Even if after a defect occurs the piece can be repaired an amount of extra time will need to be put into the item that wasn't previously required (Ngo, et al., 2018).
8. Since tool makers have such a high level of training and expertise their skills are not being put to full use when they are asked to make simple pieces.

Materials

Common materials used in FDM printing were discussed in the literature review. BEP uses most of the materials discussed, however, in addition to the more unusual 'Cheetah' and 'igus' materials, BEP uses environmentally conscious alternatives to two of the more common filaments.

BEP uses the company 'Filamentive' as its primary supplier of two materials, PLA and PC. The PLA used by BEP is called 'rPLA' (recycled PLA), it is made of up to 90% recycled material and is 100% recyclable (Filamentive, 2019). The use of this PLA would reduce the amount of newly consumed plastic that BEP would otherwise consume. The PC is called

'bioPC' and contains no BPA, this is a significant improvement due to the serious health risks associated with exposure to BPA, as described in the literature review.

These materials allow the ET department in BEP to act more responsibly both environmentally and ethically.

These materials were investigated for their reliability when printing parts in BEP before their implementation, there was found to be no noticeable difference in either performance or visual appeal of the prints, thus due to the relatively positive environmental impact they would have, the materials were adopted as the standard to be used in BEP.

Case studies

Example 1 – Cold test seals

On the Dragon assembly line there was an issue reported with adaptors, which were temporarily attached to an engine while it went through cold test, were leaking causing engines to fail their quality check whilst not being faulty.

To attempt to solve this it was proposed that seals could be added to the adaptors. Four were needed per adaptor (Fig 16).



Figure 16: Cold test seals inserted into an adaptor

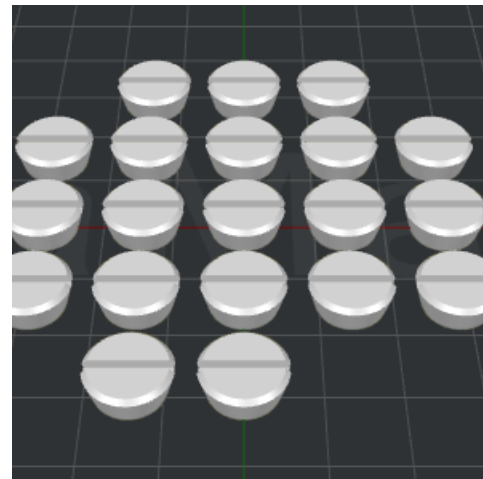


Figure 15: Cold test seals in Slicing software

A test

batch of seals were created and tested, they were found to work to their desired purpose. The same adaptor was tested many times on engines and the seals continued to hold strong. The rest of the required seals (800 in total, fig 17) were

then 3D printed and rolled out to Dragon assembly to be fitted.

After six months have passed no seals have yet had to be replaced. All 800 seals are used to test an engine at least once per day.



Figure 17: Cold test adaptors all with the AM seals fitted

Cost external/1 (£)	Cost 3D printed/1 (£)	Number required	Cost 3D printed total (£)	Cost external total (£)	Total savings to date
46	0.1	800	97.01*	36,800	36,702.99

Figure 18: Table - Savings of cold test adaptors

Costs derived from Appendix 2.1

* A value £18.46 is added here to show the wages for the initial designing of the part in CAD. One hour of work for a skilled employee.

Example 2 – Socket shrouds

On manual stations on the assembly line in BEP there are 'nut-runners' that rotate and tighten bolts to a certain torque when the operator presses a button. These 'nut-runners' are dangerous to operators if they are wearing gloves as the gloves could easily snag and cause serious harm to the operator's hand. Because of this risk shrouds are used to cover the 'nut-runners' (Fig 19), they are free rotating and can be held onto by a gloved hand whilst performing the required task.

These plastic shrouds are multiple times the cost of the metal

socket on the end of the 'nut-runner' that they cover. Thus they are viewed by many as overly expensive (Moreton, 2019).

There are also many different varieties of these shrouds (thirty nine – Appendix 1).



Figure 19: Socket with standard shroud fitted



Figure 20: Socket shrouds, Orange are externally sourced, yellow are AM

Two of the shrouds were designed and 3D printed (Fig 20) by the ET department at BEP. The shrouds were then tested by operators and engineers for satisfaction and then left on to test their longevity compared to the previous shrouds.

Cost external/1 (£)	Cost 3D printed/1 (£)	Min. number required/year	Cost 3D printed total (£)	Cost external total (£)	Total savings/year
~30**	~1***	40	58.46*	1,200	1,141.54

Figure 21: Table - Savings of socket shrouds

Costs derived from (Moreton, 2019)

* A value £18.46 is added here to show the wages for the initial designing of the part in CAD. One hour of work for a skilled employee.

**A conservative external cost estimate of £30 was used due to the vast differences in some socket sleeves. Some cost in the range of £70-80, whilst most were around £30.

***A generous 3D printed cost estimate of £1 was used due to the vast differences in size of some socket sleeves. Most would cost around £0.4.

Socket shrouds were introduced to various assembly lines. After more than six months none of the socket shrouds had failed. Fig 21 shows a 3D printed shroud after being used for more than six months, it shows signs of age, such as: curved edges and smoothed sides, but still fulfils its purpose.



Figure 22: AM socket shroud after six months of use

Since no shrouds had failed at the time of writing it is difficult to assess their lifetime. However, even if they were to fail after average of six months there would still be minimum yearly savings of around: £1,083.08.

Example 3 – Bearing cover

On the Sigma assembly line in BEP there is a separate head assembly line. Here the head for the engine that comes from the machining line is assembled ready to be inserted onto the main assembly line onto the rest of the engine. These heads move around on the head-line on platens. These platens have bearings (fig 24) with covers



Figure 23: Platen bearing with standard cover

(fig 23) that assist in being moved along a track. Over time the covers become

damaged, through general wear from constant minor collisions and abrasions. It is not easy to identify how long the bearing covers last as they are not traced through the line, however, the engineers from the area found that around 480 are required per year (Herbert, 2018).



Figure 24: Bearing for Sigma platens

These covers for the bearings, like many other parts in BEP, have always been considered expensive (Moreton, 2019). So there was an attempt to create them in the tool room (Fig 26). However, the tool makers were unable to fully replicate the small retaining lip to hold the bearing in on the side it is inserted into.

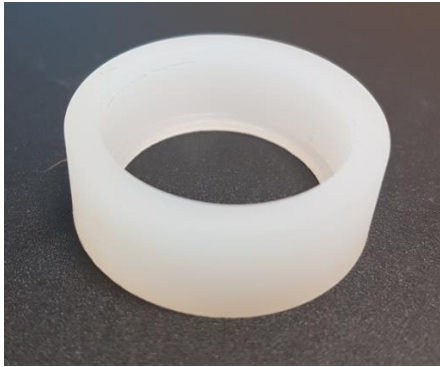


Figure 26: Bearing cover created by BEP tool room



Figure 25: AM bearing cover created out of PLA

The project was then handed over to the ET department. Where a CAD model was created and two bearing covers were printed, one in PLA (Fig 25) and one in PC. These were then tested for size by pressing the bearing into the housing. This was done using a bench vice.

The PLA cover allowed the bearing perfectly (Fig 28), with the bearing having full motion and the housing having no signs of damage.

The PC bearing however, could not take the diameter of the retaining lip and split (Fig 27). There was consideration to attempt to reduce this lip to try and allow the bearing to fit into the housing, it was determined that this could be looked into in the future, and that the PLA covers should be tested in practice first (Herbert, 2018) (Moreton, 2019).



Figure 28: Bearing being fit into PLA AM cover



Figure 27: Split PC cover after bearing fitting

There have been no reports of 3D printed bearing covers having to be replaced after eight months. However, as previously stated, there is minimal traceability of the platens for the Sigma heads, and so it is possible that they have been changed by the maintenance staff who have then not communicated this with the relevant engineers.

Cost external/1 (£)	Cost 3D printed/1 (£)	Number required/year	Cost 3D printed total (£)	Cost external total (£)	Total savings/year
25.49	0.13	480	80.86*	12,235	12,154.34

Figure 29: Table - Savings of AM Bearing covers

Costs derived from Appendix 2.4

* A value £18.46 is added here to show the wages for the initial designing of the part in CAD. One hour of work for a skilled employee.

The saving potential of this item is potentially very impactful and as such consideration will be given to the full implementation of them throughout the Sigma headline as well as other bearing housings that exist throughout BEP.

A wider roll out and then subsequent checks should be carried out next to test how long the housings are holding up so that they are not being changed too often by maintenance staff – this can be done by bearing covers of different batches being printed in different colours. There should also be further attempts to print the housings off in the 'igus' material described in the 'materials' section. This material is ideal for items under abrasive wear such as these bearings.

Example 4 – Tappet grippers

On the Sigma assembly line there is an automatic station in which a robot picks up tappets (Fig 30 – In left tappet gripper) and inserts them into an engine. It does this by placing a specially made 'tappet gripper' (Fig 30 – Right) on the part and initiating air flow to create a vacuum on the top of the tappet, this air



is then switched off when the tappet is in position to be released (Herbert, 2018).

Figure 30: Tappet in 3D printed tappet gripper and non-AM tappet gripper

There are twelve of these tappet grippers on the robot, they occasionally have small collisions due to a misplaced part, and they are changed when they either have damaged prongs or they lose the ability to create a vacuum on the tappets.

A CAD model was created from the original part and the tapped gripper was printed in PC (due to its strength properties) (Fig 30 – Left). However, when this was tested there were issues with creating a vacuum and so the tappets were not able to be picked up. It was also found that the mechanical properties of the item were unable to withstand the small collisions that occur on this station (Fig 31) because of weaknesses in the part caused by layer adhesion not being as strong as continuous material.



Figure 31: Damaged AM tappet gripper

Cost external/1 (£)	Cost 3D printed/1 (£)	Number required/year	Cost 3D printed total (£)	Cost external total (£)	Total savings/year
2,459	0.53	12	43.28*	29,508	29,464.72

Figure 32: Table - Savings of FDM tappet gripper

Costs derived from Appendix 2.4

* A value £18.46 is added here to show the wages for the initial designing of the part in CAD. One hour of work for a skilled employee.

To test whether it was possible to have a tappet gripper created through AM the design to the part was sent to 'Markforged'. Markforged are a company that have industrial 3D printers, one of which prints a continuous layer of carbon into each layer of a plastic printed part to add strength (Moreton, 2019). Enough strength where they claim parts typically created by machining aluminium could be 'replaced' by the carbon laced parts (Markforged, 2018). If this machine was shown to work then consideration would be made to purchase it for the ET department (Moreton, 2019).

The tappet gripper was received in the mail as a free trial and was installed on the tappet robot, while it successfully created a vacuum on the top of the tappet, it quickly broke (Fig 33), in the same way as the PC version, within the first shift it was installed. The carbon printed versions were then not investigated further.



Figure 33: Markforged tappet gripper

Similarly to the Markforged investigation, 'Formlabs' have SLA printers that were shown to the ET department. The tappet gripper design was sent to them where they created the part and sent it to BEP (Fig 35). The part came with the supports that were required to print it still attached (Fig 34).



Figure 35: SLA tappet gripper

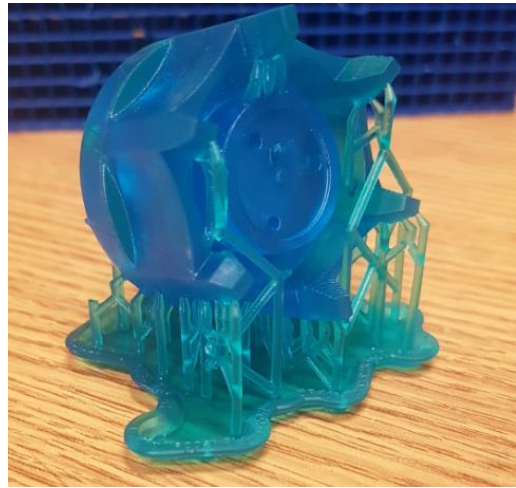


Figure 34: SLA tappet gripper with supports

When these supports were removed it was found that they left a large amount of scarring where they were on the part (Fig 37). While the scarring was clearly avoiding as many of the critical areas as possible, the SLA tappet gripper could not be attached to the robot because of the scarring (Moreton, 2019).



Figure 36: Scars on the SLA tappet gripper

The Technical Centre's RP department have multiple metal AM techniques, they were contacted and it was requested that they create a tappet gripper with one of these machines. They agreed and the aluminium printed part was delivered to BEP (Fig 36).



Figure 37: AM aluminium tappet gripper

The aluminium part was installed onto the tappet robot and was found to fit on the end-effector and create a vacuum to pick up the tappets.

After five months the aluminium AM tappet gripper was still being used, showing a promising potential as a replacement part.

Cost external/1 (£)	Cost DMLS printed/1 (£)	Number required/year	Cost DMLS printed total (£)	Cost external total (£)	Total savings/year
2,459	3.55	12	42.6	29,508	29,465.4

Figure 38: Table - Savings of AM aluminium tappet gripper

Costs derived from appendix 2.4 and (Banks, 2019).

If the aluminium AM tappet gripper, from the Technical Centre, were to be replaced as often as the previous parts then a huge amount of money could be saved year on year. Even if it were to be replaced twice yearly, almost the same amount of money would be directly saved. As long as maintenance replaced the tappet grippers whilst the assembly line was down anyway, on a break time for instance, then no money would be lost for breaking production. To do this efficiently the average life span of a tappet gripper needs to be identified and they must be changed pre-emptively. This could be incorporated to any preventative maintenance schedules that currently exist for this robot.

Challenges

By setting up the AM facilities in BEP there have been some challenges to overcome. These challenges were varied and some had minor ramifications that were solved, others remain unsolved and require additional thinking to overcome.

Learning curve

When first using a 3D printer there are many places to go to for information on how to set up the printer, what materials to use and what settings to use (Moreton, 2019). These mostly take on the form of websites, such as printer and material manufacturers sites (Markforged, 2018) (NinjaTek, 2019) (Raise 3D, 2018) (igus, 2019).



Figure 39: Damaged print bed

Some examples of this learning curve are:

- Fig 39 shows the print bed after a PC part was printed directly onto it. The adhesion between them was such that the only way the component could be removed was by damaging the material of the build platform which would need to be replaced. It was determined that the volume of PC on the bed was too much due to the thickness of

the first layers that remained on the bed, thus the flow-rate at which PC left the print nozzle was reduced.



Figure 41: FDM seal with poor surface finish



Figure 40: FDM seal with good surface finish

- Fig 41 shows the first seal that was attempted to be printed by BEP. The material was stringing and did not fully cover the sealing faces of the seal. In this example, it appeared as though the extruded material was thinner than the 0.4mm nozzle, meaning that it was struggling to come through, thus the flow-rate and extrusion temperature for Cheetah were increased. Fig 40 shows the resulting seal from these changes. It performed successfully, replacing a legacy seal that was no longer available to order from the manufacturer.
- In Fig 42 a bearing cover, as discussed in 'Example 3 – Bearing cover', can be seen. This bearing cover was printed in the 'Igu' material that was previously mentioned that this component should be tested with. There is stringing going on as well as a lot of nodules on the interior of the cover, these nodules would



Figure 42: Igu bearing cover with stringing

cause an issue with fitting the bearing due to the tight fit built into the design of the housing, and adds more post-processing to the process. These nodules are created when the printing nozzle still has material in it when it moves away from where it has just finished printing. To reduce this the speed when no printing is occurring was

increased as well as the retraction setting (which relieves the pressure from the filament that's feeding into the hot-end) (Landry, 2015).

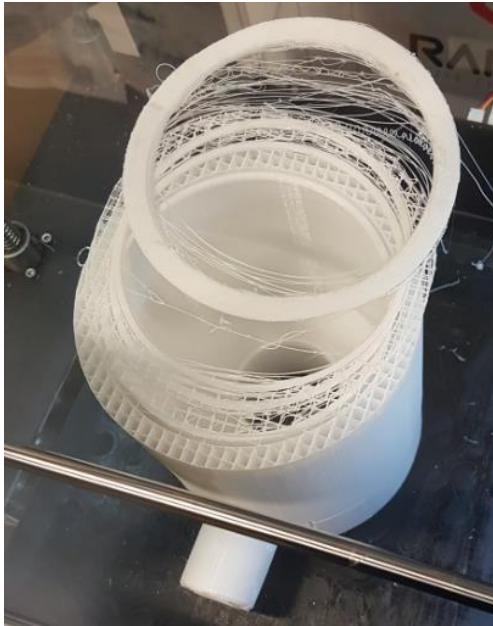


Figure 44: Component suffering from shifting axis

- Figs 43 and 44 both show two repercussions of the same issue in regards to printing with PC. It is commonly cited by many hobbyists (Cahoon, 2017) (Tyson, 2017) that PC can be difficult to print with because it can be difficult to get it to adhere to the print bed where it will curl up on the edges (as can be more clearly seen in (fig 43) When the edges raise in such a way, not only does it mean that the component is no longer conforming to the specification of the design, but it means that when the nozzle is printing over this area a build-up of material can occur. This material will then cool and, because of the build-up, the printing nozzle can catch, causing the motors to shift position, this



Figure 43: Component with poor bed adhesion

caused the issue seen in Fig 44 Where the print continued but not in the correct position. The easiest way to combat this is to increase the printing temperature and ensure that there is no form of cooling whilst printing with PC (Tyson, 2017).

- Finally, in fig 43 can be seen two prints of the same component, they were printed with the same settings but the orientation of the parts were 180° different. Because of this difference the supports that were required were either internal (Fig 43 - left) or external (Fig 43 – right). The supports are necessary to ensure that any parts of a component's design that overhang the previous layer too much or droop and lose their structural integrity. Some types of support leave less scarring than seen in fig 43 – Right, however, for this part it was determined that the component with more external scarring was more suitable than the one with internal scarring. This was because the internal diameters and measurements were critical to the components function, while the external ones were not.



Figure 45: Left - component with good surface finish. Right - same component with surface scarring

These challenges, whilst creating waste in the process, allowed for the ET department to learn from its mistakes and be able to better assess how new components should be handled in the future. This makes it clear that any future members of the team need to be trained on the different material behaviours, as well as 'best practices' whilst using the 3D printers.

Culture

BEP has been in operation for forty years, and as such the practices that have been accepted for this time are now in-grained into many among the work-force (Moreton, 2019). As such, there has been some resistance to the introduction of AM into BEP.

Since the ET department is relatively new and still 'finding its feet' there is currently no official strategy in place to help make this change in the BEP culture. There are educational moments when people visit the department to complain about the presumed goal of the department as job elimination. But these fears are quelled after it is explained that the purpose of the department is, primarily, to reduce costs paid to external suppliers and to streamline internal processes.

Once the department wishes to expand its reach further it would be worthwhile to attempt to manage this change via an established method, such as Kurt Lewin's three step model change theory. In this way outdated behaviours are 'unfrozen' then 'changed' and then 'frozen' in the new desired state (Lewin, 1947).

Wastes of AM

As previously discussed, all manufacturing processes are likely to have one or more of the eight wastes described by Ōno, (1988). The AM process run by the ET department attempts to reduce the wastes created by the other processes involved in the spare parts supply chain. Despite this, there are still wastes that must be understood if this department is to succeed.

Delay/waiting – The ET department seeks to reduce this waste in comparison to the current processes, by emailing the customer that their component(s) is ready. However, there is still delay waste of waiting for a part to be printed, this may be exacerbated by other prints using the machines making them temporality unavailable for new prints.

Over production – Currently, parts made in the ET department are made to order, meaning that items are not over-produced. This should be the case even if the stores begin to be partially replaced with AM parts as only the required number of parts would be ordered.

Over Processing – Due to the nature of AM the final processing of the printed parts is built into the design of the component, therefore over-processing shouldn't be an issue.

Transportation – The only transportation of any products created by the ET department is when the product is moved from the printing facility to the area of the customer, this could be reduced if the facilities were closer, but because the areas of BEP are so spread out there will always be an area that is far away (Moreton, 2019).

Unnecessary movement – The physical interaction by an operator when creating a 3D printed part is minimal: They create a CAD model on a PC and walk to the 3D printer, set off the printer and then return once complete. This could be improved in the future by moving the design PC and the 3D printers closer together, this would only be a negligible saving.

Inventory – The only inventory kept by the ET department is the material (filament) that is used to create parts on the 3D printers. This filament is currently over-subscribed for the needs of the ET department – this should become more efficient as the department discovers how much filament it truly uses over a set period such as a year. Items created by the ET department are removed from the department by the next working day, so there is minimal inventory in terms of created parts.

Defects – This is likely to be the biggest waste created by AM in BEP especially due to the 'learning curve' and the associated defects previously discussed. Defects can also occur due to poor design of components, such as: inaccurate measurements or poor understanding of the application. Any defects that occur waste time in printing and material.

Underutilising staff skills – Staff that run the ET department's 3D printing suite will be skilled, either ECSs or MMCs, meaning that their practical skills may not be fully utilised due to the nature of the department having little to do with control systems etc. However, their knowledge of manufacturing processes and design will be fully engaged.

Costs and savings

Time - Value Stream Mapping

As discussed in the literature review of this paper, VSM can be used to visually represent a supply chain process. To achieve this the supply chain must be followed for the map and the process must be timed to get an accurate picture of product flow. Data must be gathered for this.

Data

First, the tool room was given three parts, at different times, to create. These parts were designed and created by the tool makers. The author then went to collect these (sometimes multiple trips to check on progress were required). The finding of this investigation are found in fig 46.

<u>Tool room</u>	Time from order to receiving part (working hours)	Estimated design time (hours)	Estimated machine time (including set-up) (hours)	Estimated no-work time (hours)	Person hours
Part 1	22	1	6	15	7
Part 2	6	0.5	2	3.5	2.5
Part 3	15	0.5	3	11.5	3.5
Average	14.33	0.67	3.67	10	4.33

Figure 46: Table - Time taken for delivery from tool room

Next, three parts that were already on BEP's stores system were ordered from external suppliers. The design of these parts had already been agreed and implemented previously, this was purely a measurement of the external supplier's reaction to deliver the parts to BEP (fig 47).

<u>External supplier</u>	Time from order to receiving part (working hours)
Part 4	80
Part 5	64
Part 6	88
Average	77.33

Figure 47: Table - Time taken for delivery from external suppliers

Finally, the same six parts (named in the figs 46 and 47) were sent to the ET department, one at a time, and the results received were recorded in fig 48.

<u>3D Printed</u>	Time from order to receiving part (working hours)	Estimated design time (hours)	Estimated machine time (including set- up) (hours)	Estimated no-work time (hours)	Person hours
Part 1	5	0.66	3	1.09	0.91
Part 2	3	0.33	1.5	0.92	0.58
Part 3	10	1.5	6	2.25	1.75
Part 4	6	0.66	2	3.09	0.91
Part 5	8	0.66	5	2.09	0.91
Part 6	5	0.5	2.5	1.75	0.75
Average	6.17	0.72	3.33	1.87	0.97

Figure 48: Table - Time taken for delivery from ET department

Method

The method of data collection involved the author timing the journey of each component from being requested to possessing the completed component. In the tool room examples, this timing was started after the final conversation with the tool maker agreeing to make it and the relevant MRF being sent. The external supplier examples were all sent at 9:00 AM on weekdays to maximise the likelihood that their processing department received the order as they began work. The 3D printed parts were timed from when an email was sent to the ET department with all the details they required to create the part.

These results are all based on 'working hours' i.e. day shift for employees in BEP. The hours worked per day for this shift are: Monday – Thursday, 7AM – 3:30PM and Friday, 7AM – 12:30PM. This was done to replicate the hours that a machine might be down for on this shift pattern. This pattern is the lowest impact in these terms, meaning that if the hypothetical machine in question was broken down and the line was on two-shifts, then even more time would be lost (almost double).

All of the parts that were made via AM have a design time value added to them, this is always relevant for bespoke one-off parts. But for the comparative stores items this time would only be included once, as the designs are now on BEP's internal systems and can be produced without redesign at any point in the future. All estimates of design time were self-reported by those who designed the parts.

To receive the tool room components, it was necessary to physically check whether they were complete due to the system in place currently. This resulted in multiple wasted trips for

collection – it should be noted that none of this wasted time has been included in these results.

When the externally supplied components were delivered, there were no enquiries as to whether they were made after or before the time of the order, therefore these timing results could differ.

Analysis

It is clear from Fig 49 that in all cases 3D printing was quicker in overall lead time than the alternative methods. The closest component 'part 2' with a difference of three hours, and the largest difference was fifty-six hours.

There is no correlation between the amount of time it takes for a part to be 3D printed and the amount of time it takes to carry out one of the other two methods.

Comparing tables 46, 47 and 48 it is clear that sourcing spare parts through AM techniques rather than the tool room reduces the waste of non-working hours in the process to less than 20%.

The savings in overall lead time and wasted time are large and if scaled up would likely have a huge positive impact on the supply chains within BEP.

This process was purely an investigation of lead time of components, and does not take into account the usability and longevity of the items in question. It also only consisted of a small sample size, for meaningful results and conclusions to be drawn, a much larger sample size of a range of components would be required.

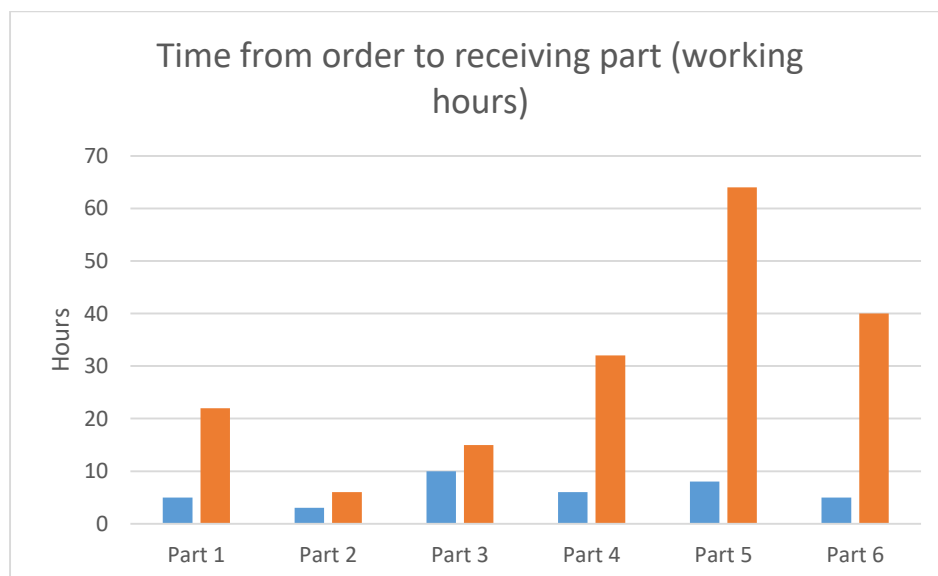


Figure 49: Graph - Delivery time for parts from three sources

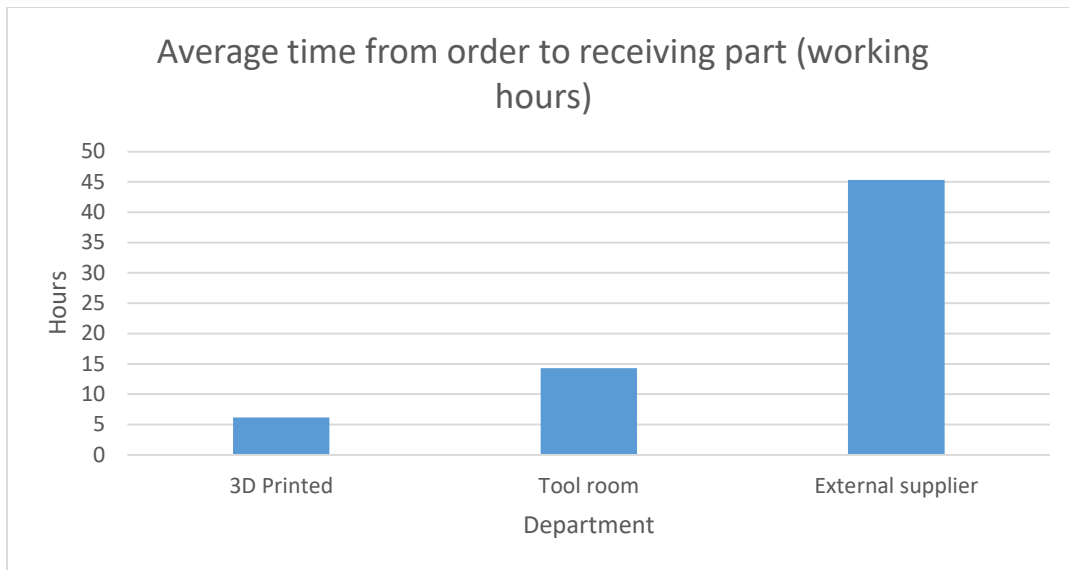
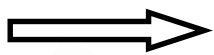


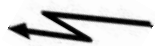
Figure 50: Graph - Average time for delivery from three sources

Symbols for VSM

In the following VSMs the below symbols will be used:



Movement of physical product



Electronic information flow



Manual information flow



Final customer/Supplier



Timeline



Shipping

Current supply chains

As discussed, BEP's requirement for spare parts is satisfied from one of two sources, the external suppliers, through the stores, and the internal tool room. Basic value stream maps have been created to visually demonstrate the current systems in place, as well as the proposed systems that could run concurrently.

External suppliers

The VSM for suppliers (seen in Fig 51) shows the basic process as seen from the perspective of BEP. This representation uses the assumption that the components in question have already been provided previously by the supplier and thus no design action is taken. There are no timings for the individual processes undertaken by the external manufacturer as these are not available to BEP. The overall lead time is used, which was found earlier in this section.

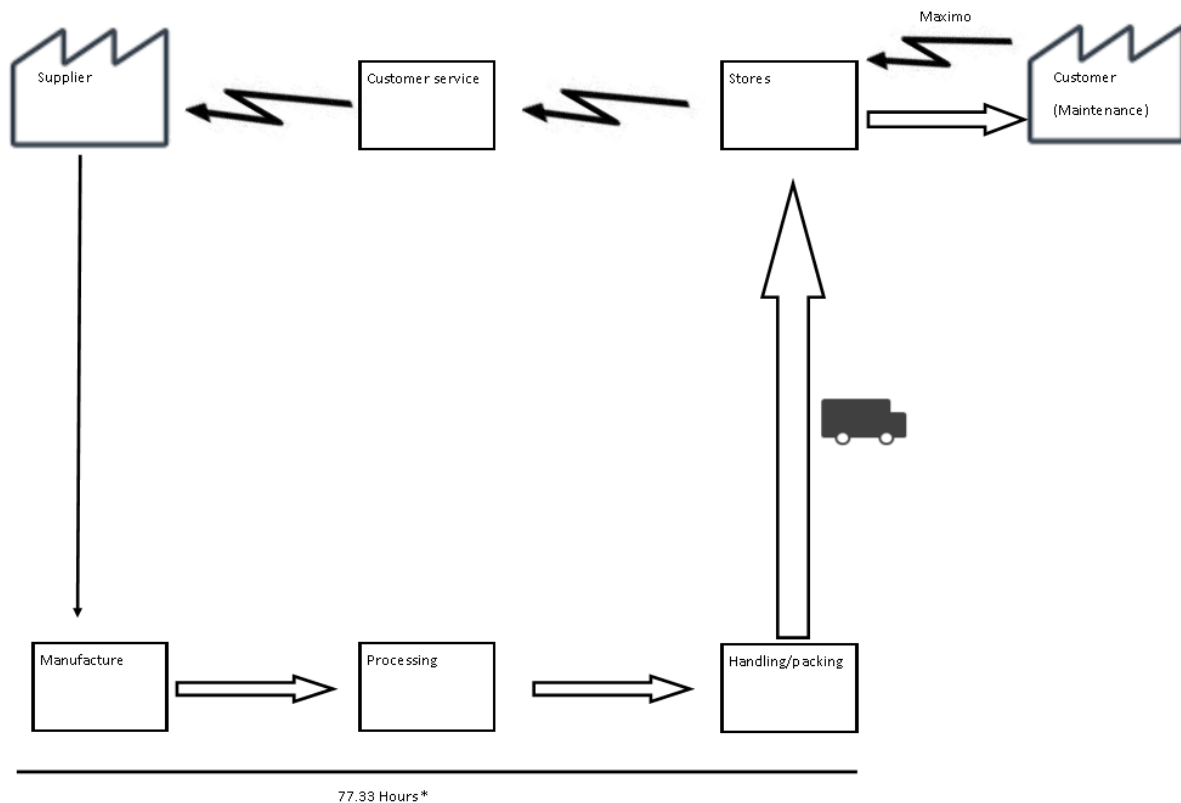


Figure 51: VSM for BEP's external suppliers

* Times taken from table

Tool room

The VSM for the tool room (seen in Fig 52) shows the overall process as seen from the perspective of a skilled maintenance employee. This representation the assumption that the components in question have already been designed by said skilled employee and thus no further design work is required. There are no timings for the individual processes undertaken by the tool room. The overall lead time is used, which was found earlier in this section.

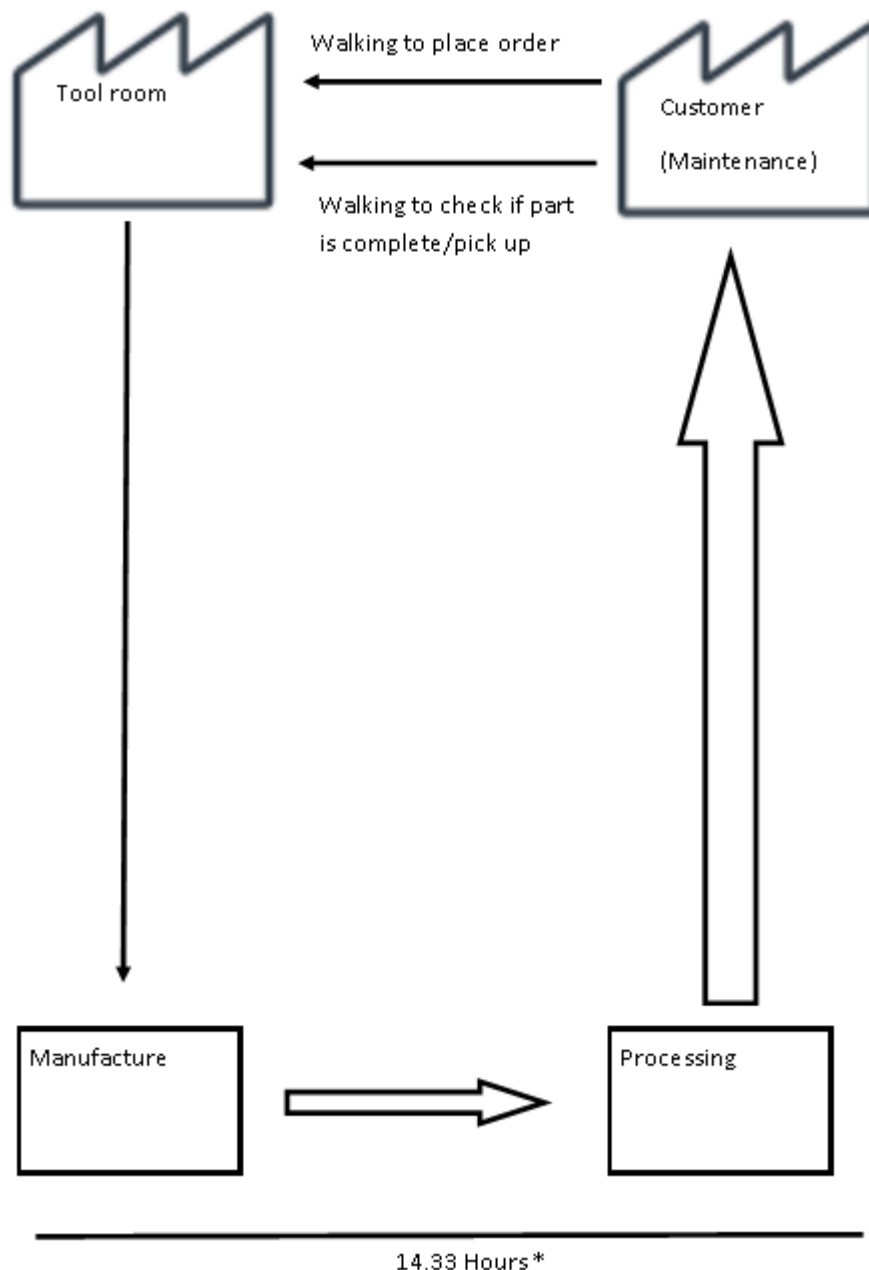


Figure 52: VSM for BEP's tool room

* Times taken from table

Proposed supply chain

Through the use of AM previously discussed, these following value maps show how the processes could potentially work along-side the processes that are currently occurring.

AM – Stores items

The VSM for the ET department creating stores items (Fig 53) shows how many stages are skipped out, including delivery from a different external location. The time in map assumes that design has occurred, however this will only be true the first time a part is ordered, after this first order the part will be stored on FMC's intranet and will be reused for future orders. The overall lead time is used, which was found earlier in this section.

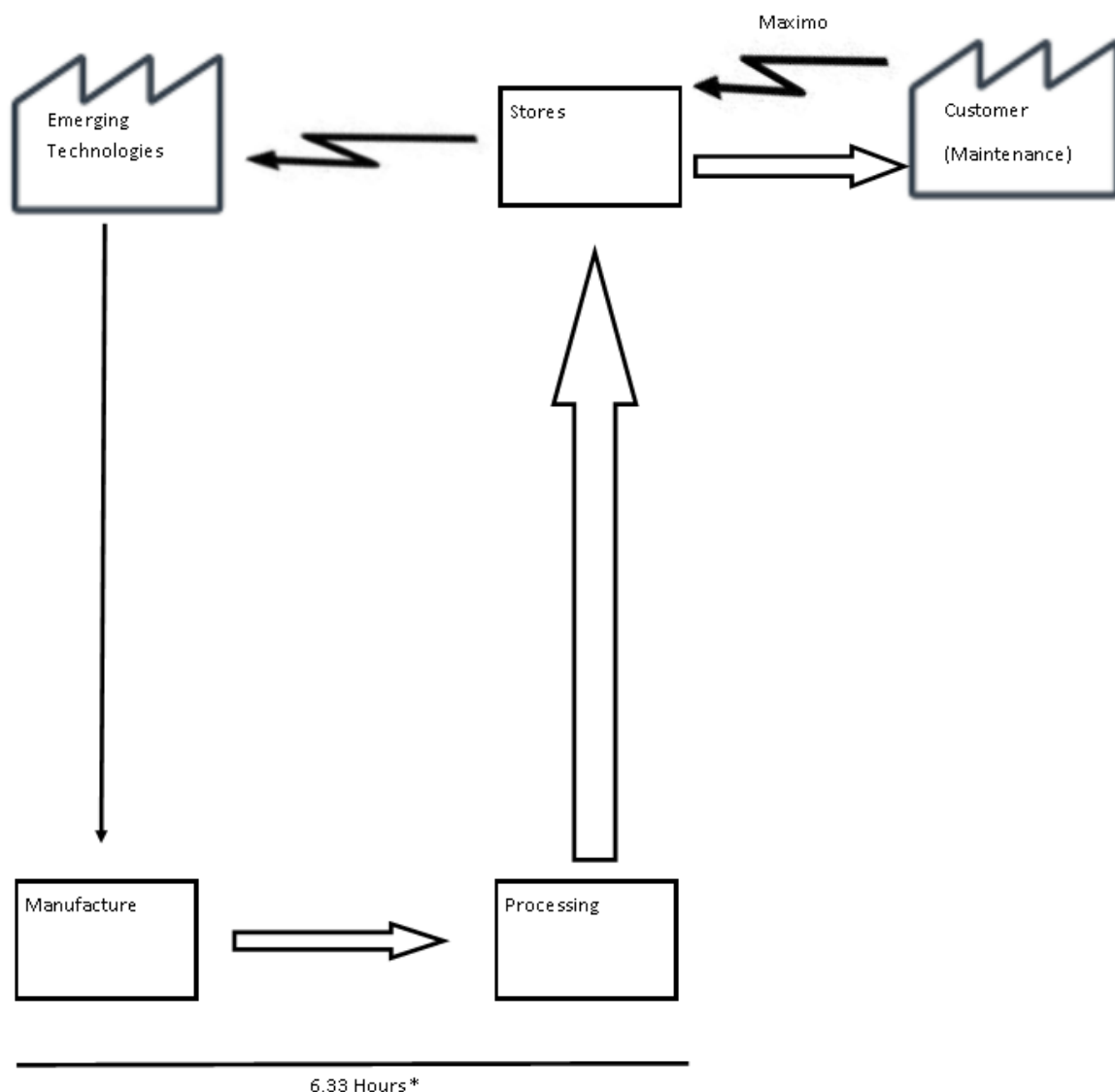


Figure 53: VSM for ET department creating stores items

* Times taken from table, items 4-6

AM – Bespoke parts

The VSM for the ET department creating bespoke components (Fig 54), shows how much simpler it would be for skilled employees to receive their items with no need to waste time walking down to check whether their order has been fulfilled. This process includes the design process that is required of the ET department. The overall lead time is used, which was found earlier in this section.

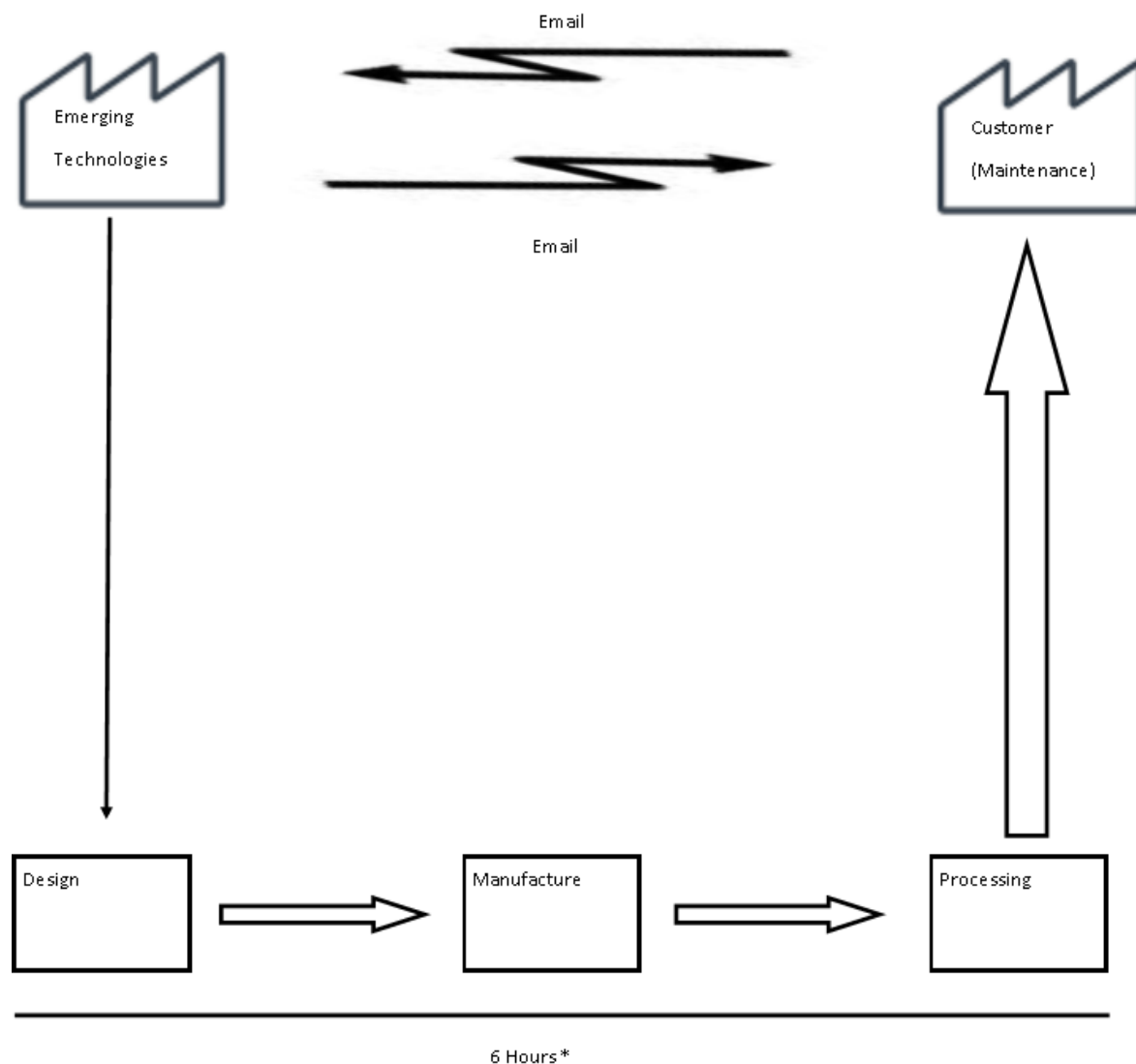


Figure 54: VSM for ET department creating bespoke items

* Times taken from table, items 1-3

Costs and cost savings

The main reason that BEP began developing the AM technology that it held was to reduce costs of components and save money when manufacturing the engines made, this remains the main goal (Moreton, 2019).

Moreton, (2018), predicted that the savings incurred by 3D printing would be returned within the first three months of the ET department being set up, because of significant savings on certain individual parts.

Set-up costs

The set-up costs of the ET department's integration of AM are currently:

<u>Start-up costs</u>	
Item	Cost (£)
3 x 3D printers	12,000
Filament	150
Training (CAD)*	N/A
PCs**	N/A
Software***	N/A
Total	<u>12,150</u>

Figure 55: Table - Start-up costs of AM in BEP

* Provided by BEP's training department, figures are confidential.

** Leased by BEP, costs not associated with ET department directly.

*** Software is accessible by any FMC department with no direct cost to the department.

Running costs going forward

The estimated running costs at the current demand are:

<u>Running costs/Year</u>	
Item	Cost (£)
PLA Filament	1,300
PC Filament	433.33
Cheetah Filament	1,040
Igus Filament	433.33
Electricity*	N/A
1 x skilled staff	34,000
Total	<u>37,207</u>

Figure 56: Table - Running costs of AM in BEP

*Unmeasured, permission not granted to use power meter onsite.

The breakdown of the materials are as follows:

- PLA 1Kg per week
- PC 1Kg Per 3 weeks
- Cheetah 1Kg Per 2 weeks
- Igus 1Kg per 6 weeks

Savings – Presently

Appendices 2.0 – 2.4 show the tables that are generated when a part is printed in the ET department. The estimated costs of an external supplier are quotes given to the engineers who request the component to be made.

The total savings from the parts created by the ET department between 01/08/2018 – 01/04/2019 are as follows:

<u>Current savings</u>	
Area	Savings (£)
AJ Assembly	3,973.70
Dragon Assembly	52,717.66
Plant Engineering	6,195.44
Sigma Block Machining	942.00
Sigma Assembly	63,566.12
Total	<u>127,394.92</u>

Figure 57: Table - Current savings of AM in BEP

When taking into account the start-up costs and the running costs thus far:

<u>To-date savings (01/04/2019)</u>	
Calculation	Savings (£)
Total savings	127,394.92
Start-up costs	12,150.00
Running costs (8 months)	24,804.67
Total	<u>90,440.25</u>

Figure 58: Table - To-date savings of AM in BEP

As previously mentioned, there are some costs that cannot be accounted for currently that would slightly lower the savings derived here. These costs however, such as electricity costs, are likely to be negligible in comparison to the overall saving. King (2014) explained that there is a lot of mystery regarding the true cost of 3D printing. King (2014) goes on to explain that when looking at the overall cost of 3D printing, the electricity used is negligible in comparison, they discovered that a five-hour print costs around £0.04 in electricity.

Savings – Potential

In a previous section ('Spare parts'), the stores in BEP were described. It was also noted that Phil Moreton, (2019) believed that many of these items could be replaced by AM parts. To assess this, the author began a walk of the stores, going through each 'bin' on each shelf. Each of these bin contain multiple items, these were assessed as to whether the author believed they could create the item on CAD and print it, using their experience with the technology and knowledge of CAD design.

The resulting table can be found in Appendix 3.0. This list of 175 items creates estimated total savings of £20,775.44. These items represent what has been identified as possible to print from just 25% of the total stock in the BEP stores, time constraints meant that the rest of the stores walk must be done at a point in the future. If the stores walk were to continue at the same rate then the overall potential savings could be £83,101.76.

To arrive at this amount, each component that was inspected and assessed to be printable was measured and its value found on FMC's parts ordering system. These measurements were then applied to either a cube or cylinder, whichever was a closer approximation, where they were sliced in the slicing software, which then gave out an estimate of the weight of material that would be used. This was then used to calculate the cost of printing and compared to the cost of ordering the same component from an external supplier. These shapes were used as they would overestimate the volume of the part, due to the nature of 3D printing any extra complexity will reduce print time and material used, thus reducing the cost. By overestimating the potential costs it means that the savings incurred should not be less than expected, and should be more, if anything.

These calculations also don't take into account the cost of designing the components on an individual basis, however, since the cost of a skilled staff member is taken into account when calculating the running costs, this is not an issue. They also do not take into account how many of each component are used in a given year, the figures given are the value derived from replacing the stock currently held in the BEP stores. It's likely that the amount of components used in a given year, is at minimum the amount held in stores, although many components may be ordered and replaced weekly (Duckett, 2019). Finally, the calculations do not account for the costs saved by reducing the need to store the parts on hand, when at least some can be printed when one is removed from stores, meaning that more than one won't be required in the stores. This reduces the waste of 'inventory' previously described.

Money savings are also made through time savings, however the amount of savings made because of time can vary wildly. It is possible, on the AJ133 line for example, that savings

could be anywhere up to £10,000 per 96 seconds due to the value of the engines made in this area.

Product creation process

In the initial stages of implementing AM into BEP it was found that there were various routes to creating a component depending on what is started with. These stages include:

1. Current part – These are parts that are currently stored on BEP's internal servers. These parts simply need to be sliced using the slicing software (it is even possible to store a sliced file and skip this step) and printed on the printer. Any post-processing, such as removing supports, can now be done and the component is ready to give to the customer.
2. Current part (not yet made additively in BEP) – This part must be designed via a CAD package and optimised for printing, first though the specification of the part should be reviewed to ensure that the created product will be fit for purpose. Then the process for 1. should be followed.
3. Discontinued/legacy part – It must be decided how the part is to be created – if one is available it can be reverse engineered either via hand measuring or 3D scanning, or a new design can be undertaken. If there is a previous specification this should be located and the part should be assessed as to whether the designer believes that it is suitable to be printed. Then the process for 2. and then 1. should be followed.
4. New part – New parts follow the same process as a discontinued/legacy part, except there won't be any previous drawings or specifications or left-over parts to reverse engineer from.

Fig 59 shows a flowchart for creating a part via the ET department's AM facilities (a larger version of this can be found in Appendix 4.0). This flowchart can be given to a less experienced, skilled employee tasked with creating a 3D printed component to assist them in the stages that they must ensure they go through.

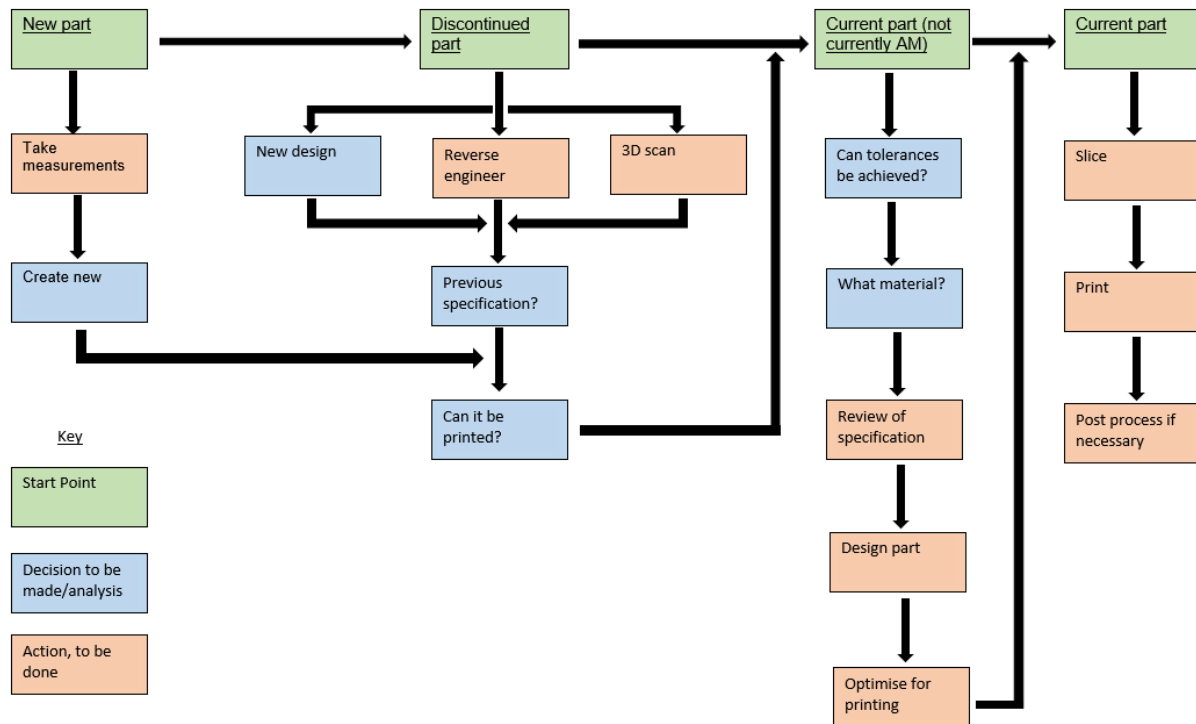


Figure 59: Flowchart for the creation of AM components

Issues with FDM implementation

A concern with the use of FDM printing in the current BEP engineering environment is the strength of the finished part. The main concern is that the method in which these components are created involve building up the shape by layering material upon the previous layer. These layers mean that the part is not isotropic (and is therefore anisotropic) and so loadings from different angles will have different affects, building weaknesses into the structure (Ngo, et al., 2018). This is the reason that optimisation for 3D printing through FDM is critical, the orientation of the part whilst being printed can have a large effect on where the main strength of the component will lie. Ideally, layers should be at 90° to the direction of the force (Sood, et al., 2012).

The design of the component itself is also important due to the method of manufacture. As such, designers who are used to designing parts for traditional subtractive systems must alter their methods as the components that would be designed this way are not always suitable for FDM printing (Kritzinger, et al., 2018). This is a culture change that will need to be managed and re-enforced to ensure minimal resistance and a smoother transition.

Due to the emerging nature of AM technologies a large amount of trial and error can occur (Wu & Chen, 2018) as seen in the 'Challenges' section. These challenges can include the required settings for print speeds, bed and nozzle temperatures, retraction rates etc. for all

used materials. Once these have been overcome, these settings should remain relevant for as long as the printer remains un-modified and the materials remain the same.

The future of AM in BEP

As this paper has established, there is a strong call for additive manufacturing systems in BEP. This is the case even without a managed change in culture or plant-wide knowledge of the availability of systems. As it stands, three FDM printers are currently supporting the production of spare parts in BEP. These printers are running almost constantly during the day and are left to run overnight until the prints set on them are complete.

SLA printers have been found to not be suitable for all spare parts that would be required of the machine so no investment would be recommended into this avenue. However, SLS and SLM prints have been shown to be of competent standard so it's likely that the ET department would consider investment into these areas.

Perhaps if an SLS machine is identified as the best solution in supporting the spare parts supply chain, FMC's The Technical Centre facility can be worked with based on their experience to find the most suitable machine for BEP.

If evidence can be provided to management teams then further investment is likely to be driven into the ET department allowing the purchase or lease of further equipment (Moreton, 2019).

Conclusion

The objective of this paper was to investigate how the implementation of FDM techniques could impact the supply chain of spare parts in FMC's BEP through practical implementation. Initially a literature review was done on the subject, but academic sources were found lacking in volume and scope. That is until recently, where journals have begun publishing papers on AM in the supply chain in a response to this gap. These papers were found to be interesting but ultimately not exactly what was required. Due to the external manufacture of these parts, the supply chains do not match the culture within BEP. The discussion found in the literature review in regards to AM's role to play in the implementation of industry 4.0 was of particular interest. The potential AM has as a disruptive technology should not be underestimated, especially for companies that may be starting to be left behind in terms of adoption. FDM printing is relatively low cost and offers a path to levelling the playing field.

The paper used case studies of multiple components and concluded that all of them were suitable to be manufactured via FDM techniques with a substantial monetary saving. There was also an investigation into the value stream of the techniques that were exclusively used previously and the value streams of the proposed additional techniques. This is where it was found that significant time savings could also be made in the delivery of many spare parts, this in itself would have a knock-on effect of saving even more money if it allows a production line to start back up sooner.

It was found that a large portion of the existing non-product stores components that BEP consistently stocks can be replaced by FDM components created in-house by the ET department. This investigation requires further work and more detailed estimates to be made, specifically in regards to the number of times a component is predicted to be required in a certain timeframe.

FDM techniques have long been assessed as the domain of hobbyists, however, it has been found in this paper that these machines when utilised correctly have the potential for practical implementation and usage and therefore huge savings in money and time.

Recommended further work

Although this paper has discussed many benefits of implementing FDM techniques into BEP there is a large amount of potential investigation work that should be carried out before further integration of AM systems in the spare parts supply chain.

Dimensional accuracy is crucial to engineering design and as such it must always be ensured that critical dimensions are always within tolerance. An investigation into the dimensional accuracy of components was beyond the scope of this paper, however initial findings (using digital calipers on FDM printed parts) demonstrates that the item's external circumferences were 0.3mm larger than in CAD models and internal diameters were 0.3mm smaller. This is an essential component to investigate and should be given priority.

The cost of SLS systems are substantial in comparison to that of the current FDM printers (£300,000 compared to £4,000 (Moreton, 2019)). Therefore, to justify this cost the stores walk should be completed and the frequency that each part is used must be catalogued. An estimate can then be gathered as to the yearly cost savings of replacing these stores components with AM parts. This in combination with the tracked non-stores work that the ET department currently handles would indicate the true potential savings of these techniques in BEP.

To truly allow staff to understand and correctly implement the discussed techniques formal training courses could be undertaken by anyone who is to use the facilities so that the knowledge of design for AM and settings is universal amongst the team. Managing the change of these methods to ensure that they are truly absorbed is key.

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Appendix

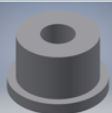
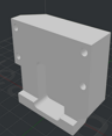
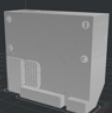
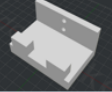
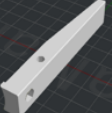
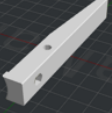
Appendix 1.0 – List of socket covers

MCC Description
SOCKET & SLEEVE UG-18MM 15
EXTENSION & SLEEVE UG-EX-250-8
SOCKET & SLEEVE UG-SF-13MM 13
EXTENSION & SLEEVE UG-EX-370-2
EXTENSION & SLEEVE UG-EX-376-5
SOCKET & SLEEVE UG-EX-370-4
SOCKET & SLEEVE UG-10MM 23
SOCKET & SLEEVE UG-10MM 13
SOCKET & SLEEVE UG-M-838
SOCKET & SLEEVE UG-8MM 13
EXTENSION & SLEEVE UG-EX-376-6
SOCKET & SLEEVE UG-MB-10MM 23
SOCKET & SLEEVE UG-SF-10MM 23
EXTENSION & SLEEVE UG-EX-376-10
SOCKET & SLEEVE UG-SF-15MM 15
EXTENSION & SLEEVE UG-EX-250-2
SOCKET & SLEEVE UG-MB-8MM 23
SOCKET & SLEEVE UG-17MM 13 SALTUS
SOCKET & SLEEVE UG-13MM 23
SOCKET & SLEEVE UG-M-10MM 11
EXTENSION & SLEEVE UG-EX-376-3
EXTENSION UG-EX-320-6 QUOTE REF: ID129-021014
SOCKET & SLEEVE UG-8MM 23
SOCKET & SLEEVE UG-SF-21MM 25
EXTENSION & SLEEVE 3/8"SQ.DRIVE,4"LONG UG-EX-376-4 QUOTE REF: FOR011221113CD
SOCKET & SLEEVE UG-M-8MM 21
EXTENSION & SLEEVE UG-EX-370-3
SOCKET E10 TORX DRIVE 3/8"SQ DRIVE U-GUARD UG-TX-3110 QUOTE REF: FBR4185DM/05/KAL
EXTENSION & SLEEVE UG-EX-503
SOCKET & SLEEVE UG-M-8MM 23
EXTENSION & SLEEVE UG-376-4
SOCKET & SLEEVE UG-13MM 13
SOCKET & SLEEVE UG-8MM 21
EXTENSION C/W SLEEVE 3/8"SQ DRIVE MALE, 1/4" HEX MALE, 8" LONG UG-EX-370-8
SOCKET & SLEEVE UG-SF-8MM 13
SOCKET (MAGNETIC) UG-MB-13MM 23
SOCKET & SLEEVE UG-SF-8MM 23
SOCKET & SLEEVE UG-SF-15MM 23
SOCKET & SLEEVE UG-838

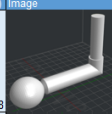
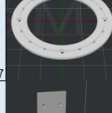
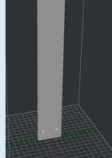
Appendix 2.0 – AJ Assembly

Item	Time (DD:HH:MM)	Main Material	Support/Raft Material	Material Weight (g)	Cost/1 (€)	External Cost/1 (€)	Saving/1 (€)	# Units	Total Cost (€)	Total Cost External (€)	Total Savings (€)	Image
Check Valve Expander	0:04	PLA	N/A	0.3	0.01	5	4.99	1	0.01254	5.00	4.99	
Check Valve Nut	0:06	PLA	N/A	0.7	0.03	5	4.97	1	0.02926	5.00	4.97	
Dowel Pusher Center	1:44	PLA	N/A	20.6	0.86	150	143.14	1	0.86108	150.00	143.14	
Dowel Pusher Sleeve	1:35	PLA	N/A	20.2	0.84	100	99.16	1	0.84436	100.00	99.16	

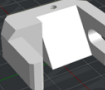
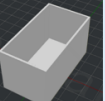
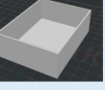
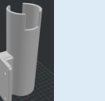
Mounting Bracket Sleeve	7:18	PLA	N/A	70.4	2.94	350	347.06	2	5.86544	700.00	694.11	
Strike Collar	6:25	NinjaFlex	N/A	67.2	5.13	85	79.87	2	10.262784	170.00	159.74	
Unlock collar clip	0:32	PLA	PLA	6.3	0.26	50	49.74	2	0.52668	100.00	99.47	
.005ze001h10245 Sleeve	2:25	PLA	N/A	23.3	0.97	50	49.03	5	4.8697	250.00	245.13	

Oil Gallery Leak Test Seal	1368.00	Cheetah	N/A	4.1	0.30	3.98	20	6	193.60	193.60		
A Bank Lift Locator	4.24	PC-Max	N/A	64.5	4.90	€631.65	1	4.9	631.65	626.75		
B Bank Lift Locator	5.02	PC-Max	N/A	83.5	3.95	367.51	1	3.95	367.51	363.56		
CTDA Holder	5.22	PLA		105.9	2.45	450	2	4.9	900.00	895.10		
Plastic Latch 005	2.13	PLA		21.2	0.49	110	2	0.98	220.00	219.02		
Plastic Latch 007	2.20	PLA		22.3	0.52	110	2	1.04	220.00	218.96		
	1407.32			510.50	23.67	695.00	685.18	43.00	17.90	4018.76	3973.70	

Appendix 2.1 – Dragon assembly

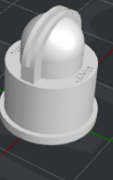
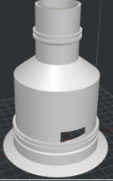
Item	Dept.	Time (DD:HH:MM)	Main Material	Support/Raft Material	Material Weight (g)	Cost/1 (£)	External Cost/1 (£)	Saving (£)	# Units	Total Cost	Total Cost External (£)	Total Savings (£)	Image
Assembly Handle Mk1	Dragon	4:43	PLA	N/A	59.9	2.50	350	347.50	4	10.02	1,400.00	1,389.98	
Assembly Handle Mk2	Dragon	2:42	PLA	N/A	40.1	1.68	200	198.32	2	3.35	400.00	396.65	
Oil Filter Seal	Dragon	0:33	PLA	N/A	6.6	0.28	200	199.72	3	0.83	600.00	599.17	
Rest Pad	Dragon	10:42	PLA	N/A	143.7	6.01	200	193.99	2	12.01	400.00	387.99	

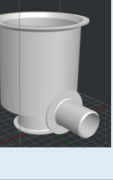
Shroud Extension	Dragon	0.49	PLA	N/A	7.9	0.33	150	149.67	4	1.32	600.00	598.68	
RTV Wiper	Dragon	1.00	PLA	N/A	13.1	0.55	45	44.45	8	4.38	360.00	355.62	
CTDA Seal	Dragon	0.21	Cheetah	N/A	1.2	0.10	46	45.90	800	78.55	36,800.00	36,721.45	
Phasor Lock	Dragon	1.30	Cheetah		11.3	0.37	786	785.63	4	1.48	3,144.00	3,142.52	
HDR Wheel Tool	Dragon	8.15	PLA		45.7	1.40	1643	1641.60	1	1.40	1,643.00	1,641.60	
Turbo Cap	Dragon	0.25	PLA		10.2	0.16	1	0.84	40	6.40	40.00	33.60	

Fuel Pipe Clamp Tool	Dragon	2.04	PC-Max		34.6	2.03	1464	1461.97	2	4.06	2,928.00	2,923.94	
20mm Spacer	Dragon	0.35	PLA		24	0.68	50	49.32	6	4.08	300.00	295.92	
Parts Box (Small)	Dragon	2.25	PLA		44.1	1.02	350	348.98	2	2.04	700.00	697.96	
Parts Box (Large)	Dragon	3.44	PLA		67	1.55	450	448.45	2	3.10	900.00	896.90	
Socket Shroud	Dragon	4.57	Cheetah		23.4	1.46	110	108.54	1	1.46	110.00	108.54	
RTV Holster	Dragon	36.25	PLA		483.3	12.41	575	562.59	2	24.82	1,150.00	1,125.18	

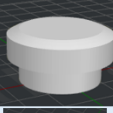
Bearing Liner	Dragon	7.25	PLA		81.6	2.04	1242	1239.96	1	2.04	1,242.00	1,239.96	
		88.35			1097.70	34.56	7862.00	7827.44	884.00	161.34	52717.00	52555.66	

Appendix 2.2 – Plant engineering

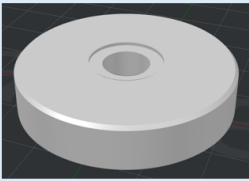
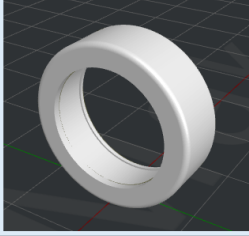
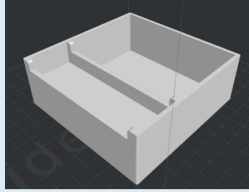
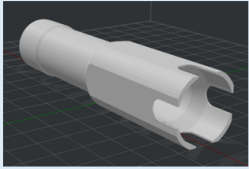
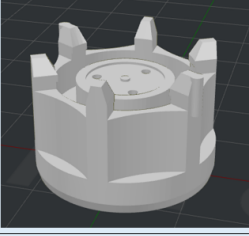
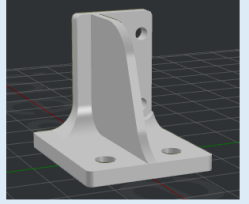
Item	Time (DD:HH:MM)	Main Material	Support/Raft Material	Material Weight (g)	Cost/1 (£)	External Cost/1 (£)	Saving/1 (£)	# Units	Total Cost (£)	Total Cost External (£)	Total Savings (£)	Image
Leak Funnel	62:26	PLA	N/A	798.8	33.39	150	116.61	1	33.38984	150.00	116.61	
Water Blade with Insert	1:18	PLA	N/A	3.9	0.16	5.7	5.54	200	32.604	1,140.00	1,107.40	
Urinal Trap (part 1)	32:09	PC-Max	PLA	465.8	22.02	400	377.98	6	132.110196	2,400.00	2,267.89	

Urinal Trap (part 2)	51:47	PC-Max	N/A	507	23.97	450	426.03	6	143.79534	2,700.00	2,556.20	
Step Sign	7:00	PLA		114.9	2.66	150	147.34	1	2.66	150.00	147.34	
	154:40			1890.40	55.57	1155.70	500.13	214.00	198.10	3690.00	6195.44	

Appendix 2.3 – Sigma block machining

Item	Time (DD:HH:MM)	Main Material	Support/Raft Material	Material Weight (g)	Cost/1 (£)	External Cost/1 (£)	Saving (£)	# Units	Total Cost (£)	Total Cost External (£)	Total Savings (£)	Image
Op 150 Leak Machine Seal	1:37	NinjaFlex	PLA	21.6	1.65	157	155.35	6		942.00	942.00	
Trolley Handles	2:29	PLA		35.7	1.54	75	73.46	2		150.00	150.00	
	1:37			21.60	1.65	157.00	155.35	6.00	0.00	1092.00	942.00	

Appendix 2.4 – Sigma assembly

Item	Time (DD:HH:MM)	Main Material	Support/Raft Material	Material Weight (g)	Cost/1 (£)	External Cost/1 (£)	Saving/1 (£)	# Units	Total Cost (£)	Total Cost External (£)	Total Savings (£)	Image
Roller	1:14	PLA	N/A	21.40	0.89	38.16	37.27	240	214.68	9,158.40	8,943.72	
Guide Roller	0:17	PLA	N/A	3.10	0.13	25.49	25.36	480	62.20	12,235.20	12,173.00	
Oil Sensor Tray	10:16	PLA	N/A	141.80	5.93	350.00	344.07	1	5.93	350.00	344.07	
Oil Pump Tool	3:20	PLA	N/A	34.10	1.43	158.05	156.62	2	2.86	316.10	313.25	
Tappet Picker	1:04	PC-Max	N/A	11.30	0.53	2459.00	2458.47	12	6.41	29,508.00	29,501.59	
Op155 Bracket	1:36 18:03	PLA	N/A	19.30 234.00	0.81 9.21	100.00 3156.19	99.19 3046.98	2 1215.00	1.61 435.16	200.00 63,802.90	198.39 63,566.12	

Appendix 3.0 – Stores components

DESCRIPTION	QUANTITY IN BIN	STORES COST PER PART (£)	ORIGINAL MATERIAL	APPROX DIMENSIONS	3D MATERIAL	3D PRINT COST ESTIMATE (£)	Saving/1 (£)	Saving (£)
Ex Socket shroud	1	42.66	Plastic	L 90mm x Ø25mm	PLA	0.41	42.25	42.25
Bit holder shroud	1	48.08	Plastic	L 85mm x Ø 25mm	PLA	0.39	47.69	47.69
Gentle Jaws, Vice	6	7.89	Plastic	L 150mm x 35mm	PLA/CHEETAH	N/A		
Socket shroud	2	45.5	Plastic	L 60mm x Ø 40mm	PLA	0.39	45.11	90.22
Socket shroud	2	36.35	Plastic	L 40mm x Ø 35mm	PLA	0.24	36.11	72.22
Socket shroud	1	9.41	Plastic	L 25mm x Ø 18mm	PLA	0.1	9.31	9.31
Socket shroud	1	26.03	Plastic	L 25mm x Ø 25mm	PLA	0.12	25.91	25.91
Ex Socket shroud	4	28.71	Plastic	L 40mm x Ø 15mm	PLA	0.13	28.58	114.32
Socket shroud	1	27.19	Plastic	L 50mm x Ø 25mm	PLA	0.23	26.96	26.96
Socket shroud	2	34.04	Plastic	L 50mm x Ø 25mm	PLA	0.23	33.81	67.62
Socket shroud	3	31.79	Plastic	L 50mm x Ø 25mm	PLA	0.23	31.56	94.68
Socket shroud	5	32.85	Plastic	L 50mm x Ø 25mm	PLA	0.23	32.62	163.1
Socket shroud	2		Plastic	L 35mm x Ø 25mm	PLA	0.17	-0.17	-0.34
Socket shroud	1	37	Plastic	L 53mm x Ø 25mm	PLA	0.25	36.75	36.75
Socket shroud	1		Plastic	L 50mm x Ø 25mm	PLA	0.23	-0.23	-0.23
Ex Socket shroud	2	42.11	Plastic	L 90mm x Ø 25mm	PLA	0.41	41.7	83.4
Socket shroud	3	38	Plastic	L 50mm x Ø 25mm	PLA	0.23	37.77	113.31
Ex Socket shroud	1	50.26	Plastic	L 165mm x Ø 20mm	PLA	0.63	49.63	49.63
Nylon hammer inserts	70	0.37	Plastic	L 25mm x Ø 25mm	PLA	N/A		
Nylon hammer inserts	10	0.7	Plastic	L 25mm x Ø 25mm	PLA	N/A		
Ex Socket shroud	2	36.74	Plastic	L 15mm x Ø 15mm	PLA	0.05	36.69	73.38
Socket shroud	1	33.58	Plastic	L35mm x Ø25mm	PLA	0.17	33.41	33.41
Ex Socket shroud	1	52.93	Plastic	L235mm x Ø33mm	PLA	1.21	51.72	51.72
Socket shroud	1		Plastic	L50mm x Ø25mm	PLA	0.23	-0.23	-0.23
Ex Socket shroud	2	36.4	Plastic	L15mm x Ø20mm	PLA	0.07	36.33	72.66
Socket shroud	1	39.37	Plastic	L45mm x Ø15mm	PLA	0.15	39.22	39.22
Ex Socket shroud	2	37.16	Plastic	L38mm x Ø20mm	PLA	0.15	37.01	74.02
Socket shroud	1	30.9	Plastic	L35mm x Ø25mm	PLA	0.17	30.73	30.73
Socket shroud	1	35.66	Plastic	L40mm x Ø25mm	PLA	0.19	35.47	35.47
Socket shroud	2	32.49	Plastic	L40mm x Ø25mm	PLA	0.19	32.3	64.6
Socket shroud	1	39.01	Plastic	L50mm x Ø25mm	PLA	0.23	38.78	38.78
Socket shroud	2	33.35	Plastic	L33mm x Ø25mm	PLA	0.16	33.19	66.38
Socket shroud	2	42.67	Plastic	L80mm x Ø20mm	PLA	0.31	42.36	84.72
Ex Socket shroud	2	43.65	Plastic	L115mm x Ø25mm	PLA	0.53	43.12	86.24
Ex Socket shroud	5	41.03	Plastic	L65mm x Ø25mm	PLA	0.3	40.73	203.65
Socket shroud	1	34.13	Plastic	L40mm x Ø25mm	PLA	0.19	33.94	33.94
Socket shroud	2	41.19	Plastic	L40mm x Ø30mm	PLA	0.22	40.97	81.94
Socket shroud	1	32.36	Plastic	L25mm x Ø20mm	PLA	0.1	32.26	32.26
Ex Socket shroud	3	35.14	Plastic	L20mm x Ø25mm	PLA	0.1	35.04	105.12
Ex Socket shroud	1	51.37	Plastic	L240mm x Ø25mm	PLA	1.04	50.33	50.33
Block (Jig)	2	262.28	Nylon	50mm x 50mm x 100mm	PLA	2.54	259.74	519.48
Block (Jig)	1	53.79	Nylon	50mm x 50mm x 100mm	PLA	2.54	51.25	51.25
Support pad	1	53.02	Nylon	55mm x 15mm x 25mm	PLA	0.31	52.71	52.71
Roller	100	3.34	Nylon	17mm x Ø15mm	Igus	0.15	3.19	319
Seal	1	390	Rubber	13mm x Ø25mm	Cheetah/Ninjaflex	0.4	389.6	389.6
Bearing collar	2	23.59	Igus	30mm x Ø35mm	Igus	1.02	22.57	45.14
Seal	1	148.9	Rubber	15mm x Ø30mm	Cheetah/Ninjaflex	0.6	148.3	148.3
Cradle	1	275	Plastic	170mm x 70mm x 7mm	PLA	1.3	273.7	273.7
Proxy holder	11	21.83	Acetyl	25mm x 20mm x 20mm	?? (Acetyl)	0.6	21.23	233.53
Handle	1	6.36	Plastic	140mm x 45mm x 25mm	PLA	1.74	4.62	4.62
Roller	1	35.95	Plastic	L20mm x Ø25mm	PLA	0.12	35.83	35.83
Barcode scanner holder	6	70.11	Plastic	140mm x 45mm x 95mm	PLA	5.76	64.35	386.1
Chain guide plate	1	318.33	Nylon	340mm x 15mm x 150mm	Igus	18	300.33	300.33
Spacer plate	5	3.82	Plastic	30mm x 15mm x 30mm	PLA	0.2	3.62	18.1
Seals	1	149.35	Rubber	L10mm x Ø40mm	Cheetah/Ninjaflex	0.4	148.95	148.95
Pallet guide	4	4.39	Plastic	300mm x 25mm x 10mm	PLA	1.09	3.3	13.2
Support roller	4	1.5	Plastic	L35mm x Ø18mm	PLA	0.11	1.39	5.56
Distance plate	1	163.78	Plastic	85mm x 60mm x 50mm	PLA	2.59	161.19	161.19
Seal	2	22.22	Rubber	L10mm x Ø18mm	Cheetah/Ninjaflex	0.09	22.13	44.26
Cap	1	29.56	Nylon	20mm x Ø25mm	Igus	0.37	29.19	29.19
Cap	1	38.47	Nylon	15mm x Ø20mm	Igus	0.19	38.28	38.28
Seal	1	14.58	Rubber	8mm x Ø25mm	Cheetah/Ninjaflex	0.14	14.44	14.44
Clamp	2	34.07	Plastic	50mm x 20mm x 30mm	PLA	0.39	33.68	67.36
Helix	1	628.65	Nylon	100mm x Ø80mm	Igus	56.31	572.34	572.34
End stops	108	7.65	Rubber	25mm x Ø25mm	Cheetah/Ninjaflex	0.41	7.24	781.92
Buffer	1	67.39	Plastic	15mm x Ø45mm	PLA	0.48	66.91	66.91
Sleeve	1	106.82	Plastic	60mm x Ø65mm	PLA	2.1	104.72	104.72
Bracket	1	230.05	Plastic	200mm x 50mm x 6mm	PLA	4.13	225.92	225.92
Seal	1	41.64	Rubber	3mm x Ø20mm	Cheetah/Ninjaflex	0.04	41.6	41.6
Plate	1	262.28	Rubber	175mm x 35mm x 20mm	Cheetah/Ninjaflex	5.08	257.2	257.2
Plate	1	49.68	Nylon	160mm x 50mm x 15mm	Igus	4.99	44.69	44.69
Plate	1	81.22	Plastic	225mm x 120mm x 50mm	PLA	17.33	63.89	63.89
Knob	1	98.97	Nylon	65mm x 45mm x 45mm	Igus	4.39	94.58	94.58
Bracket	1	177.42	Plastic	200mm x 50mm x 6mm	PLA	1.77	175.65	175.65
Plate	2	157.47	Nylon	480mm x 185mm x 5mm	Igus	25.07	132.4	264.8
Seal	1	148.9	Rubber	15mm x Ø50mm	Cheetah/Ninjaflex	0.8	148.1	148.1
Seal	1	214.5	Rubber	8mm x Ø65mm	Cheetah/Ninjaflex	0.53	213.97	213.97
Sprocket	1	70.51	Nylon	25mm x Ø85mm	Igus	12.92	57.59	57.59
Roller	1	43.22	Nylon	8mm x Ø45mm	Igus	1.44	41.78	41.78
Roller	6	9.56	Nylon	20mm x Ø35mm	Igus	2.18	7.38	44.28
Block (Jig)	2	159.87	Nylon	50mm x 50mm x 50mm	PLA	10	149.87	299.74
Dampener	1	52.14	Plastic	50mm x Ø65mm	PLA	2.43	49.71	49.71
Support	17	19.84	Plastic	15mm x Ø10mm	PLA	0.03	19.81	336.77
Seal	4	21.9	Rubber	8mm x Ø40mm	Cheetah/Ninjaflex	0.3	21.6	86.4
Collar	4	6.14	Plastic	20mm x Ø25mm	PLA	0.21	5.93	23.72
Seal	24	8.02	Rubber	15mm x Ø30mm	Cheetah/Ninjaflex	0.46	7.56	181.44
Seal	4	11.39	Rubber	55mm x 50mm x 15mm	Cheetah/Ninjaflex	1.77	9.62	38.48
Clamp	2	7.89	Plastic	100mm x 40mm x 50mm	PLA	3.9	3.99	7.98
Disc	1	7.79	Plastic	10mm x Ø55mm	PLA	0.81	6.98	6.98
Roller	3	38.16	Plastic	15mm x Ø65mm	PLA	1.35	36.81	110.43
Seal	15	14.61	Rubber	10mm x Ø30mm	Cheetah/Ninjaflex	0.32	14.29	214.35
Seal	4	39.54	Rubber	8mm x Ø12mm	Cheetah/Ninjaflex	0.06	39.48	157.92
Spacer	5	1.62	Plastic	30mm x 30mm x 5mm	PLA	0.26	1.36	6.8
Seal	5	21.9	Rubber	8mm x Ø40mm	Cheetah/Ninjaflex	0.3	21.6	108
Bumper	1	36.96	Rubber	175mm x 35mm x 20mm	Cheetah/Ninjaflex	6.98	29.98	29.98
Caps	35	8.92	Plastic	15mm x Ø30mm	PLA	0.18	8.74	305.9
Block (Spring)	1	79.8	Nylon	100mm x 40mm x 5mm	Igus	1.45	78.35	78.35
Seal	2	3.25	Rubber	3mm x Ø30mm	Cheetah/Ninjaflex	0.08	3.17	6.34
Block (Spring)	1	79.8	Nylon	100mm x 40mm x 5mm	Igus	1.45	78.35	78.35

Stop	1	100.63	Rubber	15mm x Ø40mm	Cheetah/Ninjaflex	0.54	100.09	100.09
Seal	2	9.8	Rubber	15mm x Ø10mm	Cheetah/Ninjaflex	0.04	9.76	19.52
Cylinder (Spring)	1	116.55	Plastic	100mm x Ø65mm	PLA	4.13	112.42	112.42
Coupling	49	0.81	Plastic	10mm x Ø35mm	PLA	0.16	0.65	31.85
Roller	1	50.92	Rubber	60mm x Ø15mm	Cheetah/Ninjaflex	13.52	37.4	37.4
Guide	1	346.35	Plastic	350mm x 150mm x 20mm	PLA	15.4	330.95	330.95
Seal	12	30	Rubber	30mm x Ø15mm	Cheetah/Ninjaflex	0.21	29.79	357.48
Guide	1	19.12	Plastic	420mm x 23mm x 18mm	PLA	3.01	16.11	16.11
Washer	2	145.52	Rubber	10mm x Ø20mm	Cheetah/Ninjaflex	0.12	145.4	290.8
Block (Stop)	1	63.16	Plastic	100mm x 50mm x 15mm	PLA	1.29	61.87	61.87
Buffer	3	11.36	Rubber	10mm x Ø160mm	Cheetah/Ninjaflex	4.63	6.73	20.19
Block	2	326.69	Plastic	190mm x 90mm x 30mm	PLA	7.19	319.5	639
Seal	10	4.5	Rubber	15mm x Ø20mm	Cheetah/Ninjaflex	0.18	4.32	43.2
Fitting	1	189.2	Plastic	65mm x Ø35mm	PLA	0.7	188.5	188.5
Seal	1	9.95	Rubber	8mm x Ø40mm	Cheetah/Ninjaflex	0.3	9.65	9.65
Spout	1	329.93	Plastic	27mm x Ø130mm	PLA	2.47	327.46	327.46
Seal	6	18.04	Rubber	6mm x Ø22mm	Cheetah/Ninjaflex	0.09	17.95	107.7
Seal	7	20.65	Rubber	10mm x Ø37mm	Cheetah/Ninjaflex	0.33	20.32	142.24
Seal	10	3.43	Rubber	10mm x Ø60mm	Cheetah/Ninjaflex	0.76	2.67	26.7
Adaptor	2	130	Plastic	55mm x Ø30mm	PLA	0.49	129.51	259.02
Clip	1	9.05	Plastic	20mm x Ø68mm	PLA	0.51	8.54	8.54
Seal	25	1.56	Plastic	4mm x Ø25mm	PLA	0.04	1.52	38
Seal	39	37.79	Rubber	6mm x Ø108mm	Cheetah/Ninjaflex	1.4	36.39	1419.21
Seal	30	6.95	Rubber	12mm x Ø78mm	Cheetah/Ninjaflex	1.43	5.52	165.6
Spacer	2	38.04	Plastic	10mm x Ø80mm	PLA	0.5	37.54	75.08
Seal	4	1.75	Rubber	10mm x Ø50mm	Cheetah/Ninjaflex	0.94	0.81	3.24
Seal	7	2.25	Rubber	6mm x Ø85mm	Cheetah/Ninjaflex	1.72	0.53	3.71
Seal	1	0.82	Rubber	8mm x Ø27mm	Cheetah/Ninjaflex	0.19	0.63	0.63
Seal	1	19.62	Rubber	10mm x Ø125mm	Cheetah/Ninjaflex	5.62	14	14
Seal	6	0.94	Rubber	10mm x Ø46mm	Cheetah/Ninjaflex	0.81	0.13	0.78
Seal	1	3.32	Rubber	5mm x Ø33mm	Cheetah/Ninjaflex	0.24	3.08	3.08
Seal	1	3.32	Rubber	10mm x Ø115mm	Cheetah/Ninjaflex	4.62	-1.3	-1.3
Seal	6	2.22	Rubber	6mm x Ø50mm	Cheetah/Ninjaflex	0.61	1.61	9.66
Seal	1	12.75	Rubber	20mm x Ø85mm	Cheetah/Ninjaflex	4.86	7.89	7.89
Seal	9	1.35	Rubber	4mm x Ø30mm	Cheetah/Ninjaflex	0.17	1.18	10.62
Seal	2	3.08	Rubber	8mm x Ø50mm	Cheetah/Ninjaflex	0.7	2.38	4.76
Seal	50	2.32	Rubber	10mm x Ø100mm	Cheetah/Ninjaflex	2.19	0.13	6.5
Strip	1	32.7	Rubber	5mm x 8mm x 290mm	Cheetah/Ninjaflex	0.82	31.88	31.88
Clip	6	9.35	Plastic	15mm x Ø80mm	PLA	0.93	8.42	50.52
Seal	25	1.56	Plastic	5mm x Ø25mm	PLA	0.06	1.5	37.5
Seal	30	6.95	Rubber	20mm x Ø75mm	Cheetah/Ninjaflex	2.42	4.53	135.9
Disc	9	8.62	Rubber	4mm x Ø43mm	Cheetah/Ninjaflex	0.21	8.41	75.69
Seal	2	0.68	Rubber	15mm x Ø60mm	Cheetah/Ninjaflex	1.23	-0.55	-1.1
Seal	2	0.45	Rubber	8mm x Ø28mm	Cheetah/Ninjaflex	0.18	0.27	0.54
Seal	9	2.27	Rubber	5mm x Ø30mm	Cheetah/Ninjaflex	0.14	2.13	19.17
Seal	2	9.87	Rubber	10mm x Ø55mm	Cheetah/Ninjaflex	0.73	9.14	18.28
Seal	2	1	Rubber	8mm x Ø80mm	Cheetah/Ninjaflex	1.19	-0.19	-0.38
Seal	5	4.57	Rubber	5mm x Ø22mm	Cheetah/Ninjaflex	0.08	4.49	22.45
Seal	1	9.31	Rubber	8mm x Ø32mm	Cheetah/Ninjaflex	0.23	9.08	9.08
Seal	1	1.07	Rubber	13mm x Ø68mm	Cheetah/Ninjaflex	1.36	-0.29	-0.29
Seal	4	1.76	Rubber	5mm x Ø28mm	Cheetah/Ninjaflex	0.12	1.64	6.56
Seal	23	7.22	Rubber	10mm x Ø15mm	Cheetah/Ninjaflex	0.08	7.14	164.22
Seal	43	0.68	Rubber	4mm x Ø13mm	Cheetah/Ninjaflex	0.03	0.65	27.95
Seal	4	5.33	Rubber	6mm x Ø125mm	Cheetah/Ninjaflex	2.17	3.16	12.64
Seal Plug	20	54.17	Rubber	20mm x Ø31mm	Cheetah/Ninjaflex	0.51	53.66	1073.2
Elbow Piece	10	7.82	Plastic	40mm x 40mm x 70mm	PLA	1.23	6.59	65.9
Plug	1	3.01	Plastic	20mm x Ø25mm	PLA	0.19	2.82	2.82
Pilot Demag	1	1.93	Plastic	155mm x 15mm x 5mm	PLA	0.29	1.64	1.64
Seal	1	21.05	Rubber	2mm x Ø285mm	Cheetah/Ninjaflex	5.02	16.03	16.03
Gaiter	2	5.36	Rubber	50mm x 50mm x 80mm	Cheetah/Ninjaflex	8.97	-3.61	-7.22
Gaiter	1	27.85	Rubber	50mm x 50mm x 220mm	Cheetah/Ninjaflex	24.39	3.46	3.46
Handle	1	11.3	Rubber	40mm x 15mm x 265mm	Cheetah/Ninjaflex	7.91	3.39	3.39
A Bank Locator	2	631.65	Nylon	81mm x 70mm x 33mm	Igus	2.58	629.07	1258.14
B Bank Locator	2	367.51	Nylon	81mm x 70mm x 33mm	Igus	4.75	362.76	725.52
Spacer	1	54.75	Rubber	25mm x Ø285mm	Cheetah/Ninjaflex	37.8	16.95	16.95
Wiper	1	62.78	Rubber	50mm x Ø290mm	Cheetah/Ninjaflex	42.77	20.01	20.01
Housing	1	41	Plastic	50mm x 40mm x 45mm	PLA	1.02	39.98	39.98
							TOTAL SAVINGS	20775.44

Appendix 4.0 – AM design flowchart

