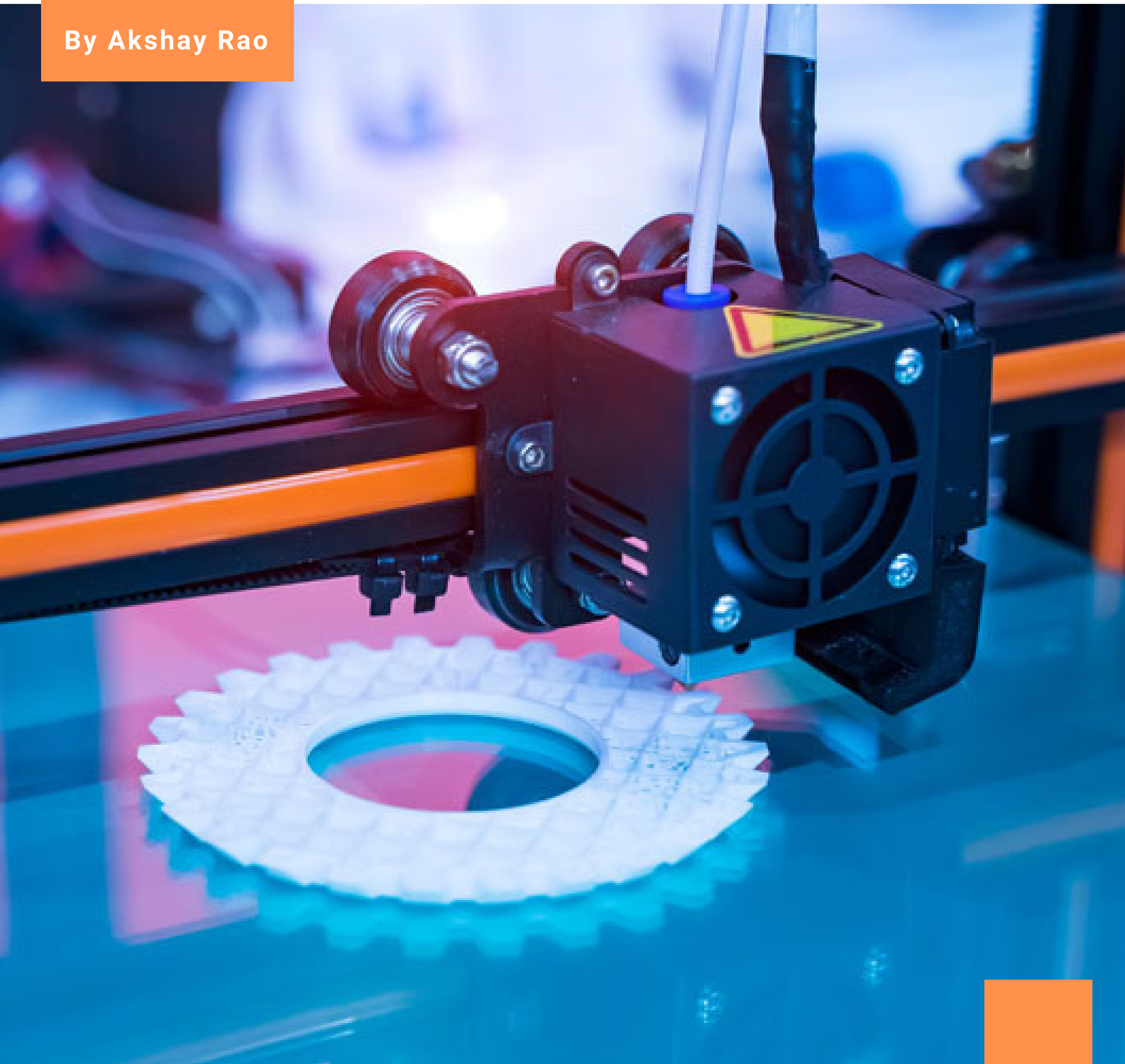
THE FUTURE OF ADDITIVE MANUFACTURING OF SPARE PARTS

By Akshay Rao



Cover photo source: ledgerinsights.com
https://www.ledgerinsights.com/ge-research-blockchain-3d-printing-additive-manufacturing/

The Future of Additive Manufacturing of Spare Parts

Master thesis submitted to Delft University of Technology

in partial fulfilment of the requirements for the degree of

MASTER OF SCIENCE

in **MANAGEMENT OF TECHNOLOGY**

Faculty of Technology, Policy and Management

by

Akshay Rao

Student number: 5058805

To be defended in public on August 26th, 2021

Graduation committee

Chairperson : Dr. G. Van de Kaa, Economics of Technology and Innovation
First Supervisor : Ir. M.W. Ludema, Transport and Logistics
Second Supervisor: Dr. G. Van de Kaa, Economics of Technology and Innovation
External Supervisors: Stefan Zimmermann, Hans Kwaspen, Raul Cuadrado

[This page left blank intentionally]

Preface

Firstly, I would like to thank my parents who believed in me, gave me the courage to achieve my dreams and supported me at every stage during the process. Their unconditional love and support meant a lot to me during the entire course of my student life. I am extremely grateful to them for instilling the confidence in my capabilities and always motivating me to go the extra mile to achieve more without giving up. I strongly feel my indebtedness to them is way beyond what can be described here, something that cannot be expressed only in words.

Secondly, I would like to express my sincere gratitude to the supervising committee for guiding me at every stage of the master thesis. Firstly, I would like to thank Menno Blanken and Hans Kwaspen for providing me the opportunity to work at Atos and ensuring a smooth onboarding process. I thank my Atos project supervisors Stefan Zimmermann, Hans Kwaspen and Raul Cuadrado who were always very kind and supportive. Be it with collecting data, contacting experts or modifying the report, they motivated me with constant help, advice and feedback which I value to a great extent. Further, I would like to thank my TU Delft supervisor Ir. Marcel Ludema (1st supervisor) who always provided me constructive feedback during the research process. His feedback, comments and questions helped me improve the quality of my research. His approachable nature proved to be very crucial in the completion of my master thesis. Furthermore, I would like to thank Dr. Geerten Van de Kaa (Chairperson and 2nd supervisor) for his advice and suggestions to improve my thesis work and his questions which made me think beyond my capabilities. Overall, it was a pleasure working with all the project supervisors and this was indeed an enriching experience.

Lastly, I would like to thank my cousins and friends back home who were always by my side through the ups and downs. Those amazing conversations we had, the movies we watched and the delicious food we ate always lingers in my memory. My cousins and friends literally mean the world to me. Especially during the pandemic, I realised what it means to have a great circle of friends and cousins. I would also like to thank my roommates and friends at Delft who made my masters journey memorable. I will always cherish those weekend parties, spontaneous meetups and movie nights I had along with my group of friends at Delft.

Akshay Rao

Delft, 2021

[This page left blank intentionally]

Summary

The thesis project explores the spare parts business based on the evidence available on how well it contributes to the revenues and profits of firms. With increasing product variety, shorter product lifecycles and market competition, it is necessary for firms to supply spare parts to customers for keeping the products functional. Forecasting for the spare parts business is difficult due to fluctuating demand rates. These issues make spare parts management challenging. Moreover, the covid-19 pandemic has complicated spare parts management and increased its importance. Therefore, the spare parts business presents opportunities to utilize technology, particularly Additive Manufacturing (AM) for solving these issues, which is the focus of this master thesis project.

The thesis project has been carried out at Atos SE in the manufacturing consulting domain. Atos aims to identify the technical and economic criteria for selecting spare parts to be produced by AM technology and explore various business models to print and deliver spare parts to customers. This calls for a study of AM technologies and spare parts, research on technical & economic criteria and business models to enable AM production of spare parts. Therefore, the overall thesis objective (deliverable) is an approach to facilitate companies in their awareness and discussion of application possibilities for AM in spare part production. This could be achieved by conducting a market study, answering the research questions and developing a support process (design objective). The design objective is - ***"To develop a support process for machine users and machine producers (OEMs and their suppliers) to make the right selection of spare parts for AM and decide on the appropriate business models to produce the spare parts by AM."***

To develop the support process, the following research questions need to be answered:

1) What could be the criteria to describe the perceived usefulness of AM for those producing spare parts?
2) Based on the criteria, how could spare parts be selected to be produced by AM?
3) What could be the possible business models to produce the spare parts with AM, given the spare part criteria?

The support process is shown in the figure below:

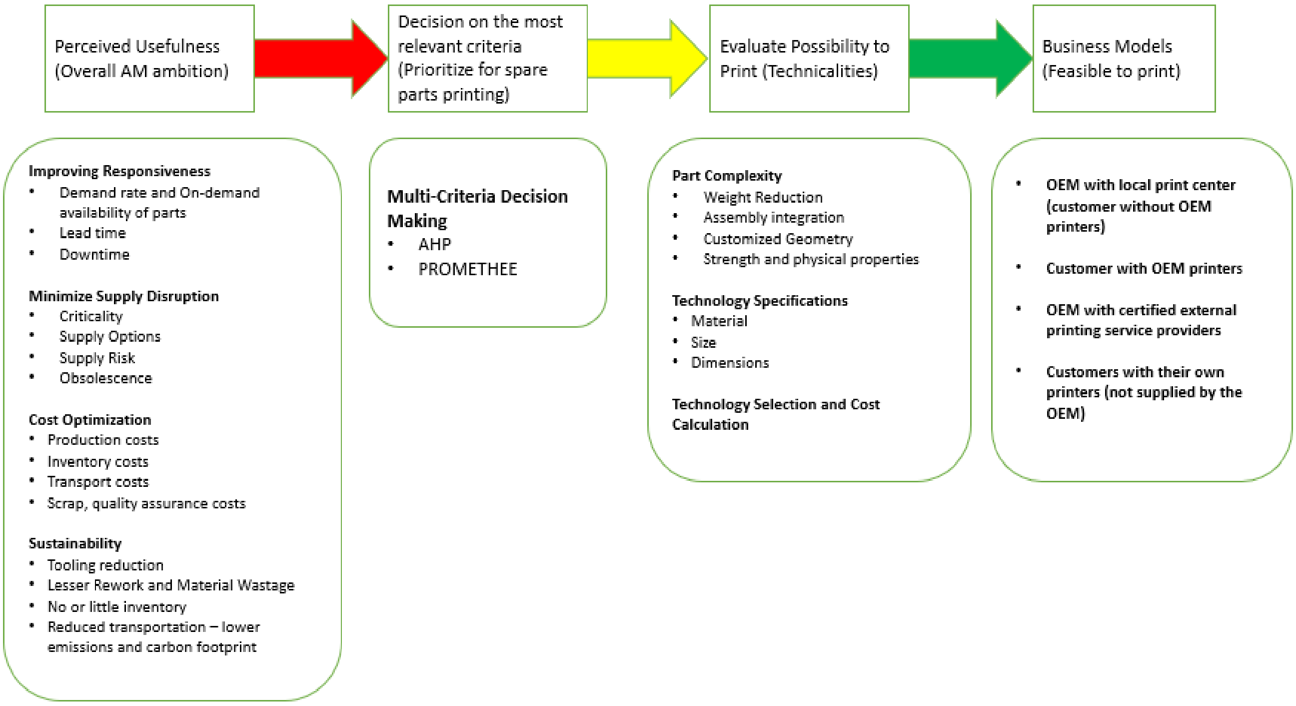


Figure: Support Process

Previously, research conducted on the perceived usefulness of AM was done from a technology perspective without considering the characteristics of spare parts and the nature of the spare parts business. This study brings into focus the technical and economic criteria to describe the perceived usefulness of AM for spare part production. Furthermore, to select spare parts for AM, previously multi-criteria decision-making Tools (MCDM) such as AHP have been used. This study uses the AHP (Analytical Hierarchy Process) and supports it with another tool called PROMETHEE (Preference Ranking Organisation Method for Enrichment Evaluation) to prioritize spare parts ranking wise for AM production. Moreover, as per the researcher's knowledge, the topic of AM enabled business models for spare part production is new and no research has been carried out previously on this. AM - based business models have been compared with the traditional business models in earlier research based on the advantages and disadvantages of each technology. The societal, economic and environmental impact of AM - based business models have been explored. In this study, four AM business models for producing spare parts have been described.

As the project is explorative in nature, qualitative approaches have been used. The data for this project has been collected through two approaches namely literature review and interviews. The literature review includes scientific papers, consulting reports, industry use cases, news databases and company documents. As the project requires in - depth information for research, semi – structured interviews have been conducted. The interview sample consists of an OEM, a printer producer, AM materials producer and two AM solutions providers. The data analysis has been done by preparation of interview notes, translation of interview notes into digital text and verification with respondents.

A market study has been conducted on AM technologies, AM materials, cost drivers for AM adoption and the challenges to AM adoption in spare parts. It was found that Powder Bed Fusion (PBF) is the most industry ready AM technology due to its high processing speed, material compatibility, high strength & mechanical properties and the non - requirement of support structures. Other AM technologies like Stereolithography (SLA), Fused deposition modelling (FDM) and HP Multi jet fusion do see increasing adoption, but not to the extent of PBF technologies like selective laser sintering (SLS), direct metal laser sintering (DMLS) and selective laser melting (SLM). The materials commonly used in AM processes are Nylon PA 11 and PA 12, ABS, PLA, Aluminium, Titanium and Stainless Steel. The cost factors were found to be machine, materials, post – processing, labour and energy. The challenges to AM adoption were found to be technology awareness, intellectual property (IP) issues, costs and return on investment (ROI), strength and physical properties of AM produced parts.

The first research question has been answered by describing the perceived usefulness of AM for spare parts in terms of parameters such as increased responsiveness, minimized supply disruption, cost optimization, part complexity and sustainability. The increased responsiveness concept has been explained using the criteria of demand rate, on -demand availability of parts, lead times and downtime. Following this, the concept of minimized supply disruption has been described by criticality, supply options, supply risk and obsolescence. Next, cost optimization has been described by the costs associated with production, quality assurance & scrap, inventory and transportation. Part complexity has been explained by the ability of AM to produce difficult to create parts, provide customized geometry, minimize weight, integrate assemblies and use different materials to obtain the desired physical properties. Technology characteristics such as costs, material supportability, build sizes and dimensional accuracy have been considered. Lastly, the sustainability of AM processes has been explained with the criteria of tooling reduction, reduced material wastage & rework, minimized transportation and inventory.

To answer the second research question, MCDM tools such as AHP and PROMETHEE have been used. These tools have been used due to their ability to handle as many objectives and alternatives as possible and their success in decision making problems. The usage of both the MCDM tools has been demonstrated in two use cases. In one use case, it was possible to apply both the AHP and PROMETHEE tools. However due to constraints, in the other use case it was possible to only apply the AHP tool, but not the PROMETHEE tool.

To answer the third research question, four business models were studied. The business models are shown diagrammatically below along with the activities (shown in tables) that are performed by each of the stakeholders.

1a) OEM with local print center (customer without OEM printers)

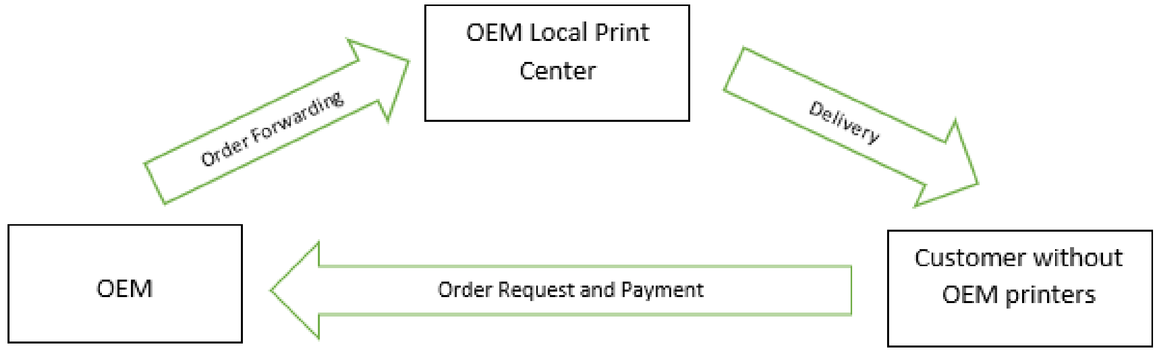


Figure: Business model 1a - OEM with local print center (own illustration)

Table: Activities performed by stakeholders in business model 1a

OEM	OEM Local Print Center	Customer without OEM printers
Checking the spare parts catalogue for the design	Process the order from the OEM	Places request order to the OEM
Approving customer orders	Printing setup activities and printing of spare parts	Makes payment to the OEM for the physical part
Forward the customer order to its own local print center	Delivery to customer	
IP Protection	Ensure quality and compliance of printed parts during printing process	
Invoice processing and order monitoring		
Establish quality and compliance of printed parts during printing process		

1b) Customer with OEM printers

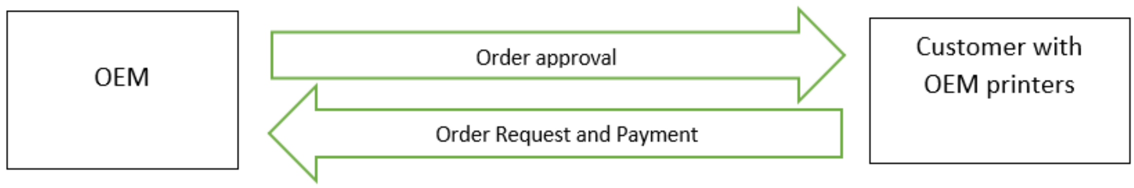


Figure: Business model 1b - Customer with OEM printers (own illustration)

Table: Activities performed by stakeholders in business model 1b

OEM	Customer with OEM printers
Checking the spare parts catalogue for the design	Places request order to the OEM
Approving the customer orders and sending the digital design file to the customer	Makes payment to the OEM for the digital design file and receives it
Invoice processing, order monitoring	Printing setup activities and printing of spare parts
IP protection	Ensuring quality and compliance of printed parts during printing process
Establish quality and compliance requirements of printed parts	

2) OEM with certified external printing service providers

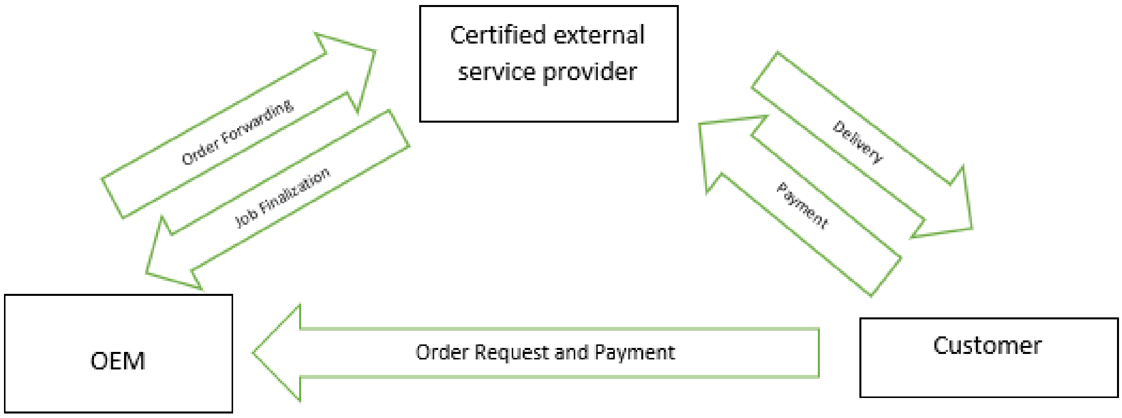


Figure: Business model 2 - OEM with certified external printing service providers (own illustration)

Table: Activities performed by stakeholders in business model 2

OEM	Certified External Service Provider	Customer
Checking the spare parts catalogue for the design and approves customer orders	Order processing from OEM	Places request order to the OEM
Sends the digital design file to the external service provider and monitors the order	Printing setup activities and printing of spare parts	Makes payment to the OEM for the design file and pays the service provider for the physical part
Certifying the service provider and assigning a service provider based on customer request	Delivery of parts to customer	
Invoice processing for design file	Invoice processing for part printing and delivery	
IP protection	Ensuring quality and compliance of printed parts during printing process	
Establish quality and compliance requirements of printed parts		

3) Customers with their own printers (not supplied by the OEM)

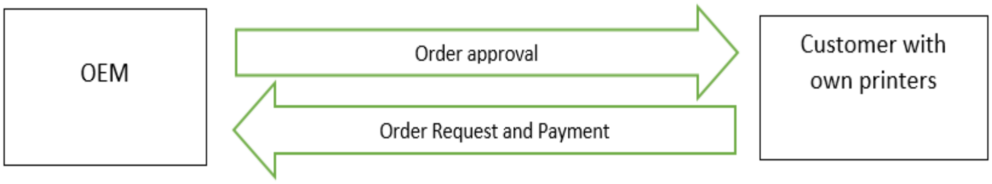


Figure: Business model 3 - Customers with their own printers (own illustration)

Table: Activities performed by stakeholders in business model 3

OEM	Customer with own printers
Checking the spare parts catalogue for the design	Places request order to the OEM
Approving customer orders	Makes payment to the OEM for the design file and receives the file.
Sends the digital design file to the customer. Monitoring of the order process	Certifies the material, machine.
Invoice processing	Printing setup activities and printing of spare parts
IP protection	
Establish quality and compliance requirements of printed parts	Ensuring quality and compliance of printed parts during printing process

From the study, it was found that models 1a and 1b would be capital intensive for the OEMs, whereas models 2 and 3 would be cost effective for the OEMs. Models 1b and 3 would be better suited to address lead time, criticality and downtime as the printer is at the customer location, minimizing logistics risks. Models 2 and 3 are more technologically flexible than models 1a and 1b. Furthermore, it was found that models 1a and 1b would be helpful in quickly reacting to demand and is economically useful when used frequently. From the interviews, it has been found that the business models that could see increasing adoption in future are the first three as described above. The respondents expressed it would be difficult to implement Model 3 because at the moment, it is not easy to convince customers to invest in 3D printing. Adding on, the MTO, MTS and ETO approaches have been studied in relation to each of the business models. For model 1a, it was found that the combination of the MTS and MTO approaches would be ideal, considering the spare parts demand and the high capital investment costs for AM technology. For model 1b, the MTO approach would be ideal as the customer is printing for themselves. For models 2 and 3, a combination of MTO and ETO approaches could be used.

From the entire study, it can be concluded that currently 3D printing the entire quantity of spare parts of different varieties across firms will not be possible. The parts which are generally difficult to design, produce and manage in the conventional scenario should be preferred for AM production. It is shown previously in research and the interviews conducted that the slow - moving spare parts for phased - out products are difficult to manage, whereas the high - demand spare parts for latest products with a high installed base is easy to manage. Firms utilize a combination of make-to-stock (MTS) and make-to-order (MTO) approaches as discussed previously. Therefore, AM would be ideally suited to complement the ongoing MTS approach with MTO and ETO approaches for producing the slow - moving spare parts. Moreover, the study shows that criteria desired for parts to be AM produced are commonly small lot sizes, fluctuating demand rates, long lead times and downtime, high inventory costs, high supply risks and obsolescence. Overall, AM technology does provide many opportunities in the spare parts business.

The thesis project contributes to academic research on additive manufacturing in spare parts by developing a theory of perceived usefulness. This together with the MCDM tools could be helpful for technology managers and aftermarket business experts to describe their objectives for spare parts management, decide on the relevant criteria and prioritize spare parts for AM. The market study could be useful for industry practitioners to know the current AM market trends with respect to technology, materials, factors driving AM adoption, benefits and challenges of AM in spare parts. With the market study, the appropriate technology can be chosen to print spare parts on demand. For established firms who have adopted AM on a small scale, plan to adopt AM in future, or for start - ups, the business models presented could help them decide whether to perform the AM activities in-house or outsource to external providers. The study moreover contributes to research by incorporating a business perspective which is needed to increase the adoption of AM.

The main limitation of this study was that only one OEM was available for participation. For further research, there are few recommendations which could be helpful. Firstly, it would be advisable to involve more OEMs when studying AM for spare parts as they would be managing spare parts directly. Moreover, the information obtained in this study is qualitative. Quantitative studies featuring numbers and other statistics would definitely be extra helpful in strategizing for AM adoption. Secondly, there is provision to conduct field studies for the utilization of the MCDM tools to help select spare parts for AM. Field studies need to be carried out company wise to apply the MCDM tools in a better way, so that the specific objectives of the company could be addressed. Furthermore, it is recommended to test and validate the business models in the industry to obtain specific quantitative information on costs, downtime, lead times, technology flexibility and other criteria. Issues such as intellectual property (IP) and quality with AM technologies need to be dealt with in greater detail in future studies.

Table of Contents

1. Introduction **1**
1.1. Company Description 3
1.2. Problem Statement 5
1.3. Thesis Objective 7
1.4. Structure of the thesis 7

2. Thesis Project Methodology **9**
2.1. Design Objective and Research Questions 9
2.2. Flow of Activity 11
2.3. Research Process 12
2.4. Research Method 12
2.5. Data Collection 12
2.6. Sampling 15
2.7. Data analysis 15

3. Background – Spare Parts and Additive Manufacturing **17**
3.1. Supply chain management 17
3.2. Spare Parts 18
3.3. Potential for AM in Spare Parts 28
3.4. Additive Manufacturing 31
3.5. Sub – Conclusion for Chapter 3 37

4. Empirical Findings (Interview Observations) **39**
4.1. OEM 39
4.2. Printer producer 40
4.3. Materials producer 41
4.4. Solutions providers 43
4.5. Sub – Conclusion for Chapter 4 44

5. Analysis of Interviews and Literature Study 45
5.1. AM Technology 46
5.2. AM Materials 50
5.3. Factors affecting AM Product Quality and cost drivers for AM adoption 51
5.4. Spare Parts AM 52
5.5. Perceived Usefulness of AM 53
5.6. AM Technology specifications 63
5.7. Sub – Conclusion for Chapter 5 64

6. Selecting spare parts for AM **65**
6.1. Explanation of steps in the MCDM Tools for selecting spare parts for AM 65
6.2. Sub – conclusion for Chapter 6 70

7. AM Business Models for Spare Part Production..71

7.1.Make-to-stock, Make-to-order, Engineer-to-order approaches..73
7.2.OEM with local print centre 74
7.3.Customer with OEM printers..76
7.4.OEM with certified external printing service providers 78
7.5.Customer with their own printers 80
7.6.Sub - Conclusion for Chapter 7..81

8. Use Cases...**83**
8.1.Use Case 1..83
8.2.Use Case 2..88
8.3. Sub – Conclusion for Chapter 8...90

9. Conclusion, Recommendations and Discussions....**91**
9.1.Conclusion..91
9.2.Limitations of the Study..94
9.3.Recommendations for further research..95
9.4.Discussions..96
9.5.Reflection..96
9.6.Feedback to the MOT Program...97

References...**98**
Appendices...**108**
Appendix 1: Interview Notes..108
Appendix 2: Use cases discussion questions...139
Appendix 3: AM Technologies and Materials..141
Appendix 4: AM and Supply chain...147
Appendix 5: Industry use cases...149

List of Tables

SL No.	Description	Page No
1.	Inclusion and exclusion criteria	14
2.	Spare parts for logistics and maintenance	19
3.	Rail spare parts for logistics and maintenance	19
4.	Approaches to spare parts management	30
5.	ASTM terminology for AM technologies	32
6.	ABS and PLA Properties	33
7.	Nylon PA 11 and PA 12 properties	33
8.	Properties of metals in 3D printing	33
9.	Responses for AM technology, advantages and drawbacks	46
10.	Usage of AM materials as stated by interviewees	50
11.	AM benefits for spare parts	52
12.	Challenges to AM adoption in spare parts	52
13.	Increased Responsiveness	54
14.	Minimized supply disruption	56
15.	Cost optimization	57
16.	Part complexity	59
17.	Sustainability	61
18.	AM technology specifications	63
19.	AHP	67
20.	Determining the weights with AHP	67
21.	PROMETHEE	68
22.	Normalizing the matrix with PROMETHEE	68
23.	Determining the deviation by pairwise comparison	68
24.	Calculation of preference function and determining the multi-criteria preference index	69
25.	Calculation of leaving flow and entering flow	69
26.	Full ranking with PROMETHEE	69
27.	Business Models Description	81
28.	AHP Criteria – Use case 1	84
29.	Criteria Weights - Use case 1	84
30.	PROMETHEE - Use case 1	85
31.	Normalizing the matrix – Use case 1	85
32.	Pairwise comparison – Use case 1	86
33.	Multi-criteria preference index – Use case 1	86
34.	Calculation of the leaving flow and entering flow – Use case 1	87
35.	Full ranking - Use case 1	88
36.	AHP – Use case 2	89
37.	Criteria Weights using AHP - Use case 2	89

List of Figures

SL. No.	Description	Page No.
1.1	Atos SOFIA features	5
1.2	Thesis Structure	8
2.1	Design Objective	9
2.2	Support Process	10
2.3	Flow of activity	11
3.1	Distribution Network Structures	20
3.2	Spare part supply chain activities	21
3.3	Spare part logistics model	21
3.4	Automotive aftermarket	22
3.5	Aircraft industry supply chain	22
3.6	Aircraft spare parts activities	23
3.7	Classification based on sales life cycle	27
5.1	Support Process	45
5.2	AM technology preference among interviewees	47
5.3	AM technology recent market study	47
5.4	AM technology by application	48
5.5	Technology acceptance model	53
5.6	Intermittent and lumpy demand patterns	55
7.1	Business model components	71
7.2	Customer Order Decoupling Point	73
7.3	OEM with local print center	74
7.4	Customers with OEM printers	76
7.5	OEM with certified external printing service providers	78
7.6	Customers with their own printers	80
9.1	Support Process	91

[This page left blank intentionally]

1. Introduction

To fuel economic growth and continuous worldwide development, technological change is needed as it gives rise to new organizational structures, methods and products (Dicken, 2011). Technological innovations along with new manufacturing techniques would indeed create more jobs and bring about positive changes to the society. So far, the world has witnessed the impact created by those technological and manufacturing innovations through the respective industrial revolutions that have taken place. Through the first industrial revolution in the late 18th century, society witnessed the use and growth of machines powered by steam power in manufacturing. Carrying forward the mechanization of manufacturing, increasing use of steam power, the second industrial revolution in the late 19th century oversaw the usage of petroleum, telegraph, electrification and the division of labour (Durão et al., 2016). The third industrial revolution in the 1970's was marked by massive advances in Information Technology (IT) and automation. These three industrial revolutions have led to improvements in production lead times, higher productivity and reduction in manufacturing costs. The breakthroughs achieved here have propelled further advancements in Information and Communication Technologies (ICT) which brings together processes, people and resources and makes the production environment more flexible, signalling the beginning of Industry 4.0 (Durao et al., 2016).

Industry 4.0 focuses more on the creation of complex, customised products and enablement of smart factories (Durao et al., 2016). Industry 4.0 can be visualized as a connected enterprise leading to the integration of processes, suppliers and customers end-to-end. One important innovation that would indeed help in creation of complex and customised products is 3D printing. Unlike the conventional subtractive manufacturing methods where an object is produced by removing the material from the workpiece, 3D printing is an Additive Manufacturing (AM) technique where digital technology is used to generate products layer-by-layer using 3D computer aided design (CAD) files. The AM process firstly starts with the creation of a 3D CAD model comprising all the product details and dimensions. The process is followed by slicing of the 3D model into 2D cross-sectional layers using slicing software. Finally, the 2D layers are fed into the 3D printing machine one after the other. The final object is produced by building a new layer on top of the previous layer (Khajavi et al., 2014). AM initially evolved during the 1980's in the USA when it was being used for production of product prototypes. This technology is constantly evolving in sync with the growth in information technology and emergence of new materials for 3D printing. Gradually, many more AM technologies developed such as Selective Laser Sintering, Stereolithography, Binder Jetting, Fused Deposition Modelling and Inkjet Bioprinting. These new AM techniques have enabled not only the production of prototypes, but also fully functional products. According to the 3D Hubs (2020) report, the market for 3D printing stands at 15.4 billion USD in 2019 and is expected to grow to 35 billion USD in 2024.

Holmström et al. (2010) highlight the benefits and the possible opportunities of AM where no tooling is required, small batches of complex products can be produced economically, capability of quick - design changes and the possibility of shorter lead times and lower inventory. In addition to this, the study by Lindemann et al. (2015) emphasises the benefits of AM on the overall lifecycle costs of parts.

Due to the above characteristics, AM has the ability to disrupt supply chains, logistics and business processes (Rylands et al., 2016, Durach et al., 2017 & Meier, 2020). The DHL 2016 report explains how supply chains are being changed with certain use cases in the areas of spare part production by Mercedes Trucks, direct part production in the healthcare sector (prosthetics), 3D printing by Adidas to produce custom made shoes (Heutger & Kückelhaus, 2016). Previous studies by Sasson & Johnson (2016) and Campbell (2011) point out the possible disruptive changes that could be made such as lesser supply chain complexity, new business models, economic impact by creating new jobs and reduction in the offshoring of jobs from developed countries to developing countries. In addition to this, Holzmann et al., (2019) investigated the business model patterns followed by 3D printer manufacturers and concluded that there is a positive relation between business models and technology. Rayna & Striukova (2016) discuss 3D printing processes around four key business model components – value proposition, value creation, value capture and value delivery. The above studies and statistics on AM business model innovation and the growth of this disruptive technology should push manufacturers, engineering firms to integrate AM into their business models, which would eventually help them stay competitive and offer value to clients.

Among all the areas suitable for AM, spare part production is the one that's caught the attention of the manufacturing as well as the technology industry. The spare parts constitute the aftersales market which is of strategic importance to many companies. According to Wagner et al. (2012) spare parts account for roughly 25% of the total sales and 50% of total profits of firms globally. So, firms have become aware of the impact of the aftersales market on their respective profits and revenues. Forecasting for the spare parts market is difficult due to its high unpredictability rate. Due to the shortened product lifecycles, increased product variety and rising competition, there is a need to ensure sufficient spare parts supply to keep the products functional over their lifetime and serve customers (Li et al., 2017)(Durao et al., 2016). Moreover, geographically dispersed markets force companies to set up service locations with inventory across the globe to serve customers. With diversifying customer needs, product variety is increased and more will be the quantity of spare parts to be held in stock. Therefore, if firms are good in managing their spare parts inventory, they would benefit from increased customer loyalty, higher customer perceived value, better corporate image, higher revenues and eventually higher profits.

To satisfy customer expectations and minimize demand uncertainty, firms must often setup warehouses near demand locations to store and manage the high levels of inventory. This leads to high inventory storage costs, rental warehousing costs and carries with it the risk of obsolescence. Khajavi et al., (2014) investigated different production scenarios to provide spare parts on-demand at a low cost for the F-18 super hornet jet. They found that the distributed AM production scenario would be better than the centralized AM production scenario in the long run as it would be less capital intensive, have shorter production cycles and be more autonomous. Firms are often forced nowadays to make a choice between being responsive, that is getting closer to the customer or being cost-efficient (Gunasekaran & Cheng, 2008).

Additive manufacturing could help possibly in solving these issues related to spare parts management, which is why its garnered attention from manufacturing companies. The initial setup costs in Additive Manufacturing are lesser than the Traditional Manufacturing setup costs due to the absence of expensive jigs, fixtures, moulds, forms and punches (Berman, 2012; Petrovic et al., 2011). Additive manufacturing is preferable mostly when the batch sizes are small due to low start-up costs (Berman,2012; Reeves et al., 2010)(Reeves et al., 2010). When batch sizes are large, traditional manufacturing is preferred due to a lower cost per unit. The study by Campbell et al. (2011) says that the AM technology has the potential to minimize high levels of inventory and costs related to storing that inventory. On-demand printing provides firms the capability to print a range of spare parts on demand, without the risk of obsolescence. Liu et al. (2013) discuss the centralized and distributed AM scenarios with the traditional scenario, and assess that the AM technology can move production closer to the customer and reduce the amount of safety inventory. By adopting AM, firms could benefit from better production lead times and delivery lead times, efficiency improvements in terms of costs reduction throughout the supply chain.

1.1. Company Description

The Master Thesis has been carried out at Atos SE. Atos, a European company headquartered in Bezons, France is a digital leader worldwide specialising in information technology (IT) services and consulting. With a revenue of 11.2 billion euros, 105,000 employees across 73 countries in 2020, Atos continues to grow and offer solutions in the areas of big data, cloud computing, cyber security, industrial automation and internet of things. Atos' industry expertise lies across several domains such as Manufacturing, Defence, Life Sciences and Healthcare, Banking and Financial Services, Media and Telecommunications. Some of Atos' major partners include Siemens, SAP, Microsoft, IBM, Amazon Web Services and Google cloud.

The thesis project focusses on the manufacturing industry, specifically additive manufacturing. In the manufacturing industry, Atos has been involved in use cases across the automotive, aerospace, processing and consumer goods industry and helped various clients to achieve operational excellence, create new business models and maximized overall customer satisfaction. Apart from being used only in prototyping, AM is evolving at a fast pace now to production of end components and spare parts as well. The penetration is still not very high and firms are still identifying business use cases for these respective applications. Through observations in market trends indicating the shift from Traditional Manufacturing (TM) to AM in prototyping and design all the way to production, Atos intends to leverage the opportunity to industrialize AM across various sectors. Atos experts along with other industry professionals believe that this industrialization can be fostered through evolution in printer technology that produce quality products with less rework; affordable printers that make the process economical and materials that provide good physical and mechanical properties. Adding on to this, customers are demanding more individualized products with specific requirements, signalling the trend of customization. Customers in the aircraft, automotive and rail industries are sensing the importance of AM and want to print spare parts on demand. Keeping the demands in mind, Atos senses the need to manage the network of OEMs, OEM-owned printer shops, certified printer providers and customers and protect the IP of the OEM-owned designs. To address these respective needs, Atos has developed the SOFIA (Solution for Industrialization of Additive Manufacturing) solutions described below as they sense a booming market for AM in end products and spare parts, which is expected to reach 26 billion euros globally by the end of 2021 and grow beyond that. Atos overall approach to industrialize AM includes the applications of IT, Engineering, Analytics and IoT across the product life cycle. The SOFIA offerings are:

- M4AM (Methodology for Additive Manufacturing) – helps companies, designers, mechanical engineers to select the right AM technology and calculate costs. M4AM helps evaluate the feasibility of an existing part to be manufactured by AM in an economic way. The M4AM integrates the economic, technical and IT aspects of AM across the complete project lifecycle. It incorporates the relevant industry standards.

- Additive IT Platform (AIP) – The AIP helps manage the AM ecosystem of an OEM and its partners, enables collaboration for the purpose of distributed manufacturing. It integrates with enterprise systems (ERP, PLM) and assures secure transactions with the incorporation of blockchain technology to protect the IP of OEMs. AIP monitors workflows throughout the production process.

- Predictive Monitoring System (PMS) – uses analytics for the prediction and monitoring of anomalies in the printing process. The purpose of the PMS is to ensure quality and ease the certification of parts.

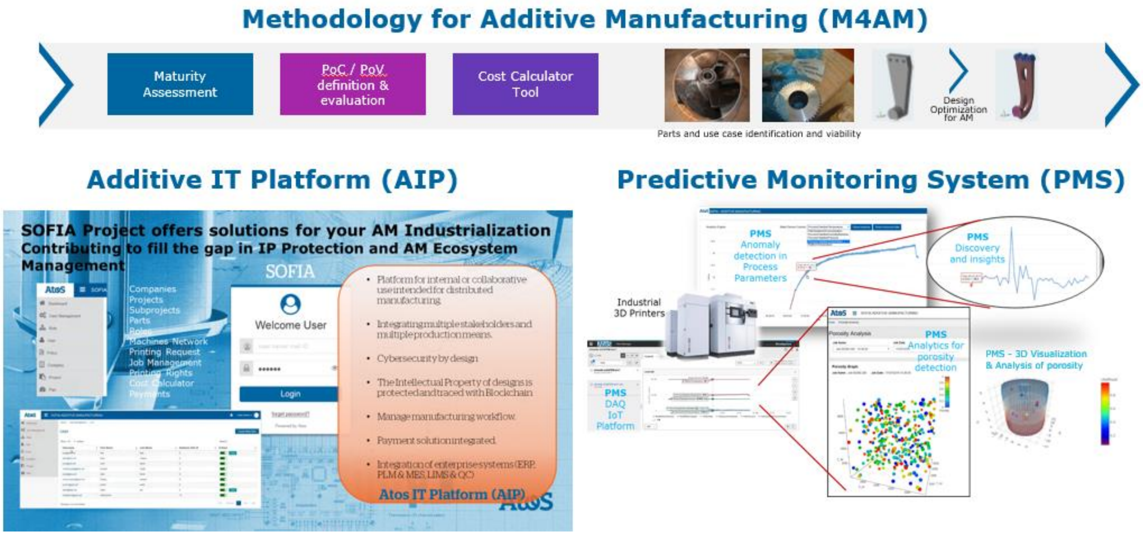


Figure 1.1: Atos SOFIA features (Atos)

With respect to the spare parts domain, Atos has identified use cases in the aerospace, automotive, energy & utilities and industrial equipment sectors where its solutions can be applied to bring about possible benefits such as reduced part inventory, lower storage costs, faster time to service, better supply chain responsiveness and improved traceability across the supply chain. Atos aims to identify the technical and economic criteria for selecting spare parts to be produced by AM and explore various business models to print and deliver the spare parts. A market study is needed regarding the commonly used AM technologies, materials, product quality factors and the cost factors driving AM adoption for spare parts. This serves as the overall motivation for the thesis project.

1.2. Problem Statement

From the observations in the previous two sub - sections, it is evident that AM technologies have the capability to add immense value to manufacturing firms' after - market business. They could be used not only for spare parts, but also for part prototyping and manufacture of end products. Although the technical and economic benefits of AM are well known, it is not easy for firms to select parts that are suitable for AM. Normally, firms would possess massive varieties of spare parts in their respective assortments. Along with this, the objectives of firms with respect to spare parts management vary. To classify and select spare parts for AM based on company objectives, technical and economic criteria is quite a challenge.

One motivation for this research is the limited study done on the perceived usefulness of AM technology in the spare parts domain. A study by Miladinov (2018) discusses the perceived usefulness of AM technologies more in the general sense without much focus on spare parts by highlighting factors such as compatibility, experimentation and observability. Research by Knulst (2016) includes 3D printed marine spare parts but does not measure the perceived usefulness of AM technology on spare parts through any performance parameters. Therefore, this study aims to describe the perceived usefulness of AM technology in spare parts (sectors of automotive, aerospace, rail, naval, equipment machinery etc.) with the spare part criteria from the producer as well as consumer perspective.

Research conducted previously related to AM in spare parts focuses on the benefits that AM could bring on spare part supply chains, and the technology specific advantages and limitations. Khajavi et al. (2014) explains the scenarios of distributed production and centralized production of spare parts in the aircraft industry and the economic benefits each scenario could bring about. Studies by Khajavi et al. (2014), Sasson & Johnson (2016), Berman (2012) and Petrovic et al. (2011) speak broadly about how advantageous AM could be by highlighting the advantages of 3D printing over traditional manufacturing. Studies by Bacchetti & Saccani (2012), Wahba et al. (2012), Ramanathan (2006), Bacchetti et al. (2010) Eaves & Kingsman (2004) discuss in detail the ABC classification method for classifying spare parts and the part characteristics such as part value, part volume, lead time, supply uncertainty etc. These studies do provide valuable information, but however do not help much to select spare parts specifically for AM. From the entire literature, only two papers address selection of parts for AM. Lindemann et al. (2015) suggested a bottom-up approach for the identification of parts that could be produced with AM, considering the entire lifecycle of parts. The study by Lindemann et al. (2015) specifically investigated parts that had to be redesigned and again produced by AM. This approach relies on the expertise of practitioners who may be technical experts but lack knowledge of logistics and supply chain or the other way round. This may lead to avoidance of certain parts which maybe highly AM capable. Moreover, this bottom-up approach will be better suited only for a few parts and not massive sets of parts. To overcome this drawback, Knofius et al. (2016) came up with a top-down approach starting with the company objectives. The AHP method used by Knofius et al. (2016) helps in identifying suitable parts for AM based on certain technical and economic criteria. So far, this has been the only Multi Criteria Decision Making (MCDM) method present in the literature to identify spare part candidates for AM. This MCDM method however needs to be supported by other MCDM methods in order to help firms select spare parts priority wise for AM, which serves as another motivation for this research study.

With respect to AM business models in spare parts, previous research is limited. Öberg et al. (2018) explain business models in the form of certain roles that a supplier, manufacturer or logistics provider could take upon the incorporation of AM. Studies conducted by Rayna & Striukova (2016) and Holzmann et al. (2019) explain the stages of AM adoption and its effects on business model components. Business model components were broken down into value proposition, value creation, value delivery, value capture and value communication and further quantified. The environmental, economic and social impact of AM on business models is discussed by Godina et al. (2020), through the use of the balanced scorecard. These studies speak about AM in general and do not take spare parts into account. Cardeal et al. (2020) evaluates the AM sustainability impact in aircraft maintenance through the Business Model Canvas which is indeed valuable for this research.

González-Varona et al. (2020) goes a step further and explores business models in spare parts logistics with a focus on small and medium enterprises (SMEs). This study provides a good starting point for the realization of AM - based business models in spare parts. However, the study only compares the AM - based business model with the traditional business model of spare parts. There could be various business models possible upon the incorporation of AM which has not been considered. Therefore, this calls for the need to study the various business models in the spare parts industry upon the incorporation of AM.

1.3. Thesis Objective

1.3.1. Scientific Contribution and Deliverable

Several studies show the advantages and limitations of AM Technology. Only two studies discuss the selection of parts for AM, out of which one study Knofius et al. (2016) is focused exclusively on spare parts. This study explains only one MCDM approach that is AHP. Regarding the perceived usefulness of AM technology for spare parts, very few studies are present which discuss AM in general and do not quantify the performance parameters for perceived usefulness. With respect to business models, few studies are present which either show the comparison between AM and TM for spare parts, or discuss AM from a broad perspective without much focus on spare parts. Therefore, the overall thesis objective (deliverable) is an approach to facilitate companies in their awareness and discussion of application possibilities for AM in spare parts. The thesis objective can be achieved by conducting a market study, answering the research questions on perceived usefulness, spare parts selection and business models, and developing a support process (design objective) as explained in chapter 2.

1.4. Structure of the thesis

The thesis project report is structured as follows as shown in figure 1.3. Chapter 1 contains the introduction, company description, problem statement and the thesis objective. Chapter 2 titled 'Thesis Project Methodology' describes the research questions, data collection procedure, sampling and the data analysis procedure followed to achieve the thesis objective. Chapter 3 titled 'Background' explains the literature study done on the spare parts business and additive manufacturing technology in detail. Chapter 4 contains the empirical findings, meaning the information obtained from the interviews and chapter 5 titled 'Analysis' combines the interview information and the scientific literature study. Chapters 6 and 7 explains the MCDM Tools and the business models in detail. Chapters 8 and 9 gives explanation of the use cases and contains the conclusion, limitations, recommendations and discussions of the study.

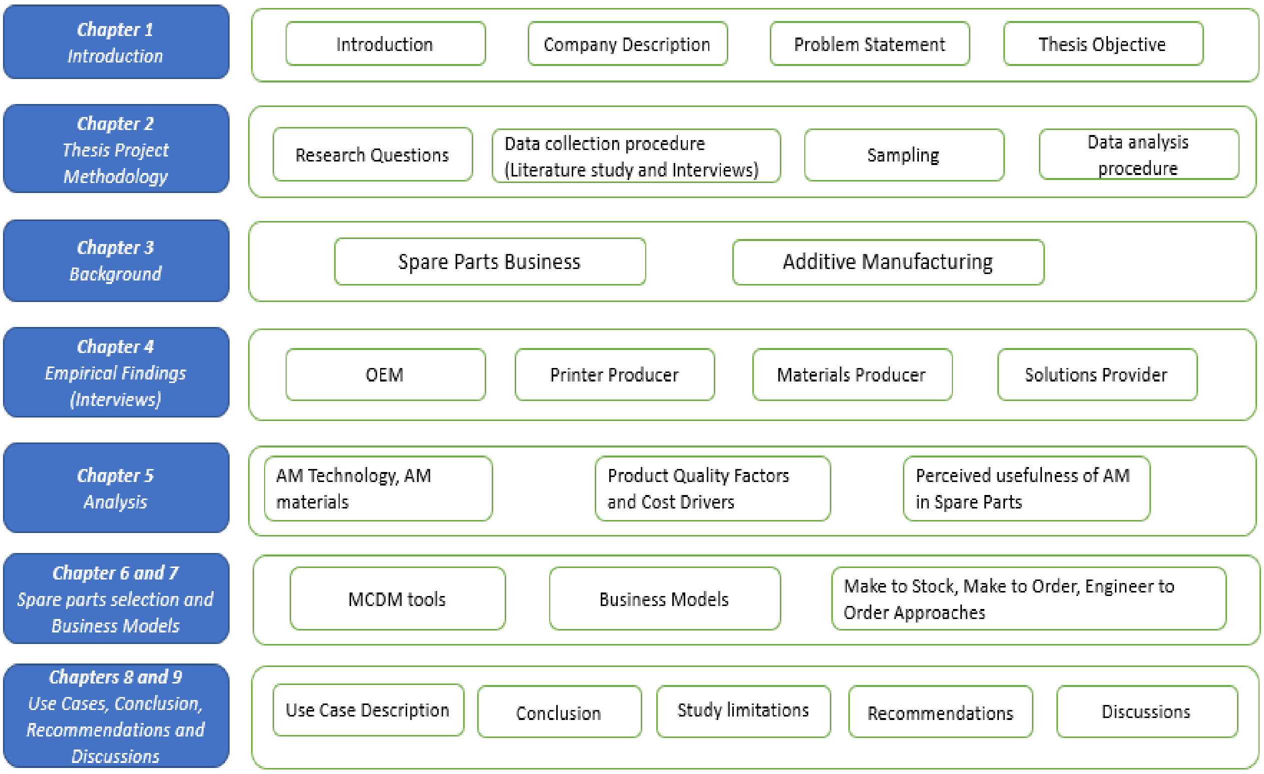


Figure 1.2: Thesis Structure (own illustration)

2. Thesis Project Methodology

The thesis objective stated in the previous chapter consists of a market study, research questions and a design objective (support process). The market study is not explained here, but explained in chapters 3 and 5. This chapter describes the research questions that need to be answered and the support process to be developed. The information obtained by answering the research questions will be used to develop the support process. The flow of activity is described considering the steps followed and the approaches used. Furthermore, this chapter explains the overall methodology followed in the thesis and describes the choices that have been made. The process of data collection and data analysis is explained in this chapter along with the advantages and limitations of the methods used to collect the data.

2.1. Design Objective and Research Questions

The design objective of this Master Thesis is stated as below:

"To develop a support process for machine users and machine producers (OEMs and their suppliers) to make the right selection of spare parts for AM and decide on the appropriate business models to produce the spare parts by AM."

The support process consists of the inputs as shown in the figure 2.1 below:

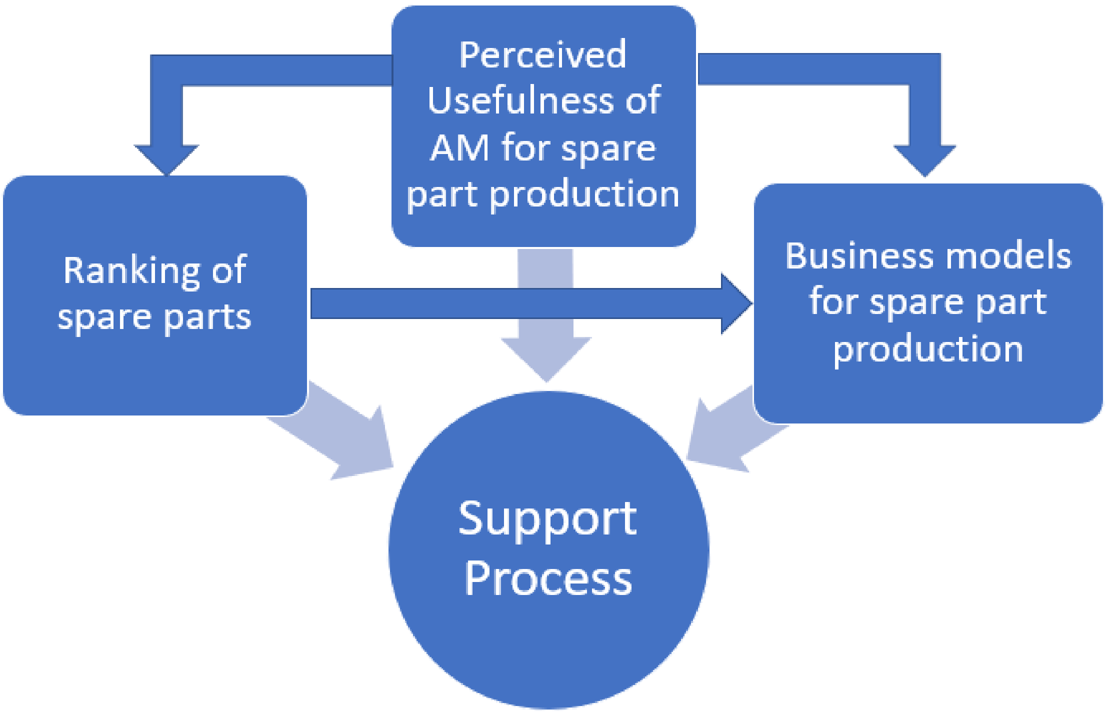


Figure 2.1: Design Objective (own illustration)

Firstly, the design objective stated above needs to be broken down into sub - objectives to be achievable:

1) Description of perceived usefulness of AM technology in spare parts using spare part criteria
2) Development of a spare part selection tool (ranking of spare parts) for AM based on spare part criteria
3) Description of the AM - enabled business models for spare part production

Secondly, the following research questions need to be answered for developing the support process, for which a 25-week Master Thesis Project has been carried out:

1) What could be the criteria to describe the perceived usefulness of AM for those producing spare parts?
2) Based on the criteria, how could spare parts be selected to be produced by AM?
3) What could be the possible business models to produce the spare parts with AM, given the spare part criteria?

The support process would be useful for firms managing spare parts that have still not adopted AM or have adopted AM to a small extent (mainly for prototyping and not much with respect to part production) and foresee massive potential in AM to print on-demand and seek to optimize costs associated with it. The support process is shown below in the figure:

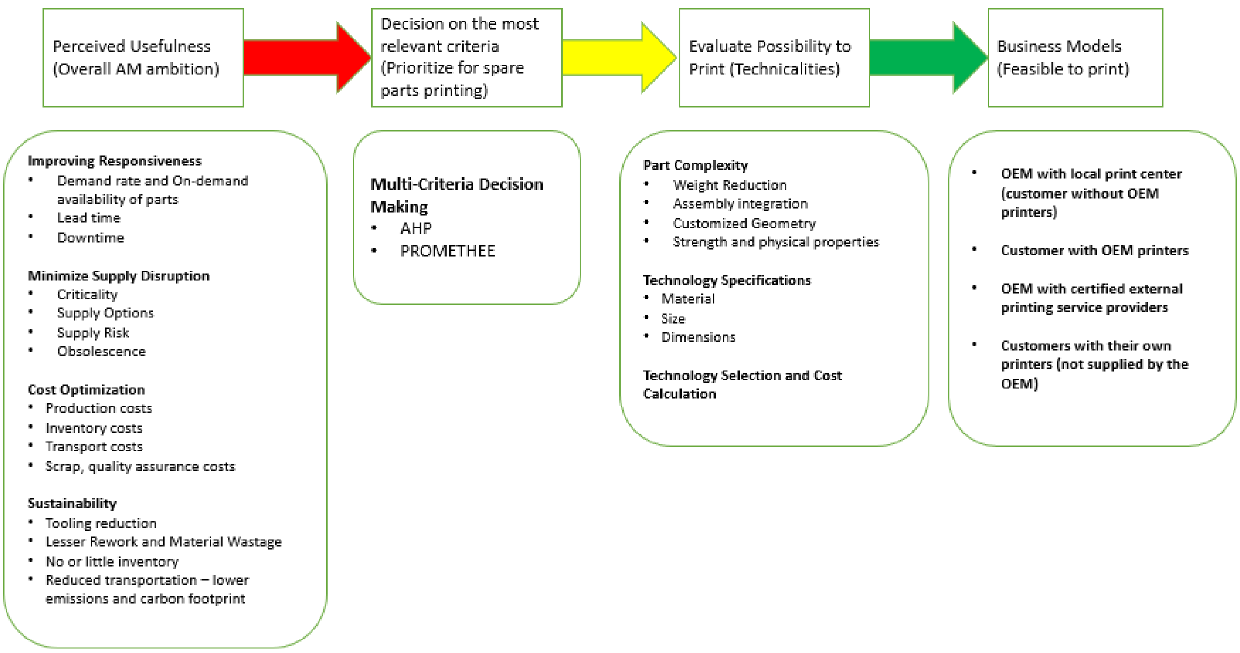


Figure 2.2: Support Process

To design the support process, a pragmatic approach has been used. This means the design is not based on any existing methods in theory, but is more practical and realistic. Firstly, the research questions were framed and put in order. Connections have been made between the research questions. The overall AM ambition starting with the economic criteria has been listed first followed by the MCDM tools to help organizations decide on the most important economic criteria. The technical criteria have been described after the MCDM tools because it is important to consider all the technical criteria for AM production without ignoring any. The final part explains the feasible business models to carry out printing for the selected spare parts (based on technical and economic criteria). The business models would help OEMs decide on whether to print on – site or outsource the printing activity.

2.2. Flow of Activity

The flow of activity is described by the figure 2.3 as shown below. The figure briefly describes the steps followed and the approaches used for each step to achieve the design objective. This is used to achieve not only the design objective, but also the overall thesis objective. Firstly, studies will be carried out on the spare parts business, AM technology and its applications in the spare parts industry with the help of scientific literature, industry use cases, consulting reports and news databases. Following this, research questions 1,2 and 3 will be answered using interviews, scientific literature, company documents and MCDM tools.

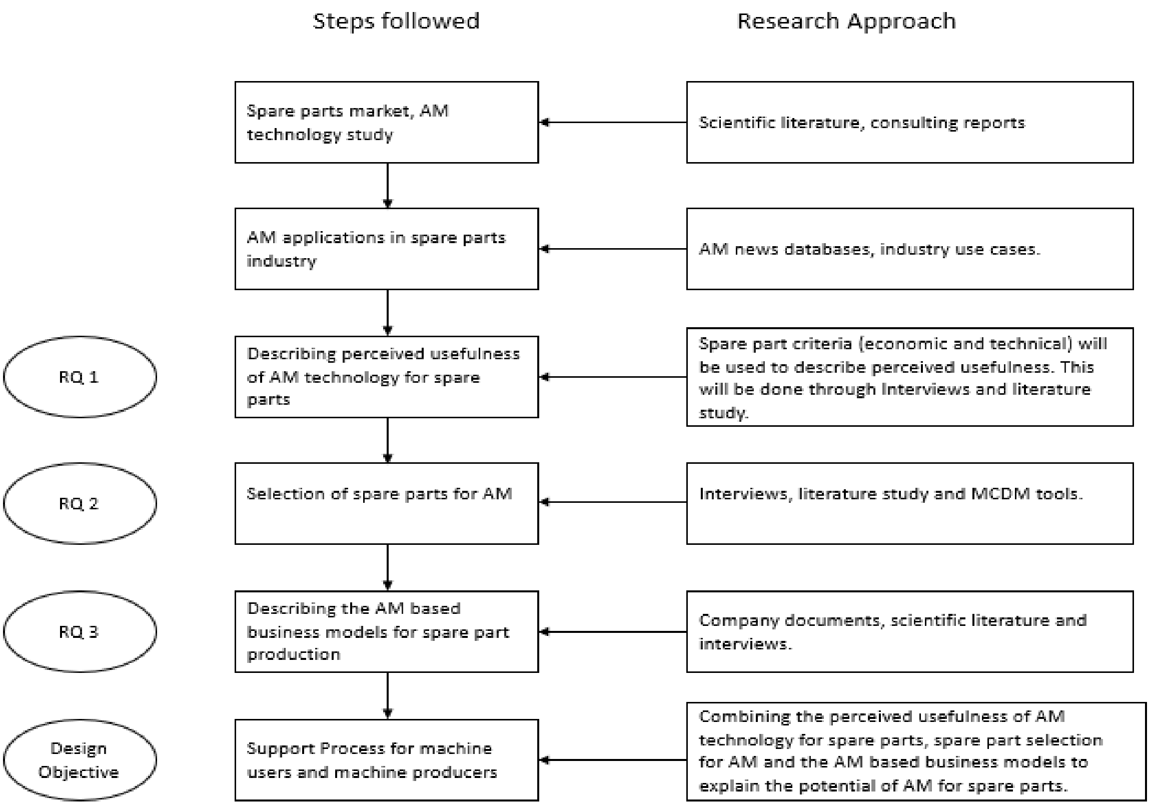


Figure 2.3: Flow of activity (own illustration)

2.3. Research Process

There are two ways of reasoning in the research process. They can be either inductive or deductive. Inductive reasoning is a process where certain phenomena is observed, based upon which appropriate conclusions are derived in a generalised manner (Sekaran & Bougie, 2016). In contrast, deductive reasoning works the opposite, that is from the more generic to the specific (Sekaran & Bougie, 2016). Deductive reasoning starts with a general theory, following which hypotheses is formed, and tested using a research method to confirm or refute the theory. According to Sekaran & Bougie (2016), deductive reasoning is predominant in quantitative approaches and inductive reasoning is mostly used in qualitative or exploratory approaches. This study follows the process of inductive reasoning.

2.4. Research Method

To fulfil the objective of the thesis, it is necessary to decide and pick the relevant tools for collecting and analysing data. As the thesis project is exploratory in nature, qualitative approach will be used. Therefore, qualitative data will be collected and worked upon. Qualitative approach often requires the active involvement of the researcher who not only gathers the information, but also interprets it for his specific research purpose (Easterby-Smith et al., 2015). It comes with an advantage of providing plenty of information to achieve in-depth understanding of a particular topic. However, qualitative research limits the number of participants in the study and makes it challenging to aggregate the collected data and make comparisons (Easterby-Smith et al., 2015).

2.5. Data Collection

To carry out this project, data and information will be collected through two approaches namely literature review and interviews. The procedure followed for reviewing the literature and conducting interviews is explained in the sub - sections below.

2.5.1. Literature Review Procedure

As put forth by Sekaran & Bougie (2016), literature review is the process of selecting documents that contain information, data, ideas written on the topic from a definite standpoint to satisfy a purpose or convey opinions on the topic, and evaluating the relevance of the documents for the research being conducted. Literature review helps the researcher to view a problem from a specific angle and develop useful insights on the research topic. Moreover, literature review helps the researcher to get familiar with the subject terminology and the methods used by others to carry out research. Through this, our research findings can be related to others' findings and valuable conclusions can be drawn. The literature review is accompanied by disadvantages such as the researcher's inability to access certain information which may lead to unnecessary time being spent on reviewing the literature.

The literature search process began with Google where I obtained news articles and industry white papers published by companies. Following this, I referred the TU Delft recommended databases namely Google Scholar, Scopus, Science Direct and Web of Science to improve the searches. By using keywords and the required filters, the relevant papers were found and number of citations of work till date were noted down. Also, the most recently published papers were considered from the recommended databases as the adoption of AM is relatively a new topic. The AM news databases and consulting reports as recommended by Atos were searched in order to gather the ongoing market trends of AM in production and future expectations.

To know the impact of AM on various industries and its supply chains, initially the keywords such as "additive manufacturing AND impacts", "additive manufacturing AND supply chain" were used. This displayed many articles. These articles highlighted the general keywords used for search which are important for future searches. Once the scope was refined to the spare parts domain, I searched for relevant articles where AM could be applied using the keywords:

"Spare parts" AND "supply chain management"

"Additive manufacturing" OR "3D printing" OR "distributed manufacturing" AND "spare parts"

"Additive manufacturing" AND "spare parts" AND "supply chain"

"Additive manufacturing" AND "spare parts" AND "business models"

"Additive manufacturing" AND "competitive strategy" AND "spare parts"

"Additive manufacturing" AND "spare parts" AND "perceived usefulness"

The filters 'Article' and 'Abstract' were applied and the above keywords were used in combination with each other and separately by themselves. The Boolean operators "AND", "OR" helped in achieving better search results and narrowing down the search. The selection was based on the following criteria as shown in the table below.

Table 1: Inclusion and Exclusion Criteria (own illustration)

Research Component	Inclusion Criteria	Exclusion Criteria
Technology	Additive Manufacturing Technologies	Traditional or subtractive forms of manufacturing
Scope	Prototypes, End products, tool production, Spare parts – Automotive, aerospace, rail, marine, energy and machinery	Other AM applications – construction, food processing
Time period	From 2000 onwards	Studies conducted before 2000.
Publication and Search recommendation	TU Delft recommended databases, English language.	
Area of research	Business, management, engineering, supply chain	Mechanical engineering, material science, computer science

Only articles pertaining to AM technologies in the manufacturing domain be it prototyping, tool production, end products and spare parts have been considered. Any of the other AM applications have been excluded. The main research areas considered are business, management, engineering and supply chain as the research objective is to study the future increased adoption of AM from a business and technology perspective.

2.5.2. Interviews

This sub - section gives a description of the second approach used, the interviews. It was decided to go for semi - structured interviews as the application of AM in spare parts is fairly new and requires in-depth information for research. This approach would help cover multiple areas (Gill et al., 2008). In a semi - structured interview, a set of pre-defined topics are used to guide the interview in the right direction and achieve the overall purpose of gathering relevant information. Semi - structured interviews also bring new issues to light by the interviewees, giving more insights to the researcher. The procedure used for interviews is explained with the following steps:

- First upon a literature study, interview questions were prepared. This was done by me with the help of my project supervisors at Atos.
- A list of Atos' clients and partners were highlighted for participation in the study.
- Employees from these respective companies were contacted through Atos, seeking their interest to participate in the study. The purpose of the research study was explained to them via email.
- Upon agreement to participate in the interviews, the interview questions were sent in advance to the interview candidates to make them familiar with the research topic. The consent form was also sent via email along with the interview questions. The consent form clearly mentioned that the responses would be kept confidential, summary of the data analysis will be mailed and results will be published anonymously.

- Every interview began with an introduction. Then questions were asked to the interviewees, responses were noted down. Clarifications or queries were made by both parties on the spot, either immediately after the question or after the response.
- The interviewees were thanked for their participation in the research and informed that any further queries or communication would be done through email.

Due to the Covid-19 pandemic and respondents being located at different locations across Europe, it was not possible to conduct face-to-face interviews. All interviews were conducted through video conferencing with Microsoft Teams.

2.6. Sampling

For the purpose of data collection, it is important to select the right set of elements. The process of selecting the right individuals, objects, or events as representatives for the entire population is known as Sampling (Sekaran & Bougie, 2016, p.235). Rather than selecting people who are easily available, it is important to target people or groups who are well versed with AM technologies and the spare parts business for this project. Therefore, it is suitable to use a nonprobability sampling technique called Judgement Sampling where interviewees are selected based on their expertise (Sekaran & Bougie, 2016). Judgement sampling is the process of choosing subjects who are in the best position to provide the relevant information needed (Sekaran & Bougie, 2016). Certain criteria were set to select subjects for the research study. The companies should be either Original Equipment Manufacturers (OEMs), printer producers, AM material producers or AM Solutions providers. With respect to OEMs, they could belong to the sectors of aerospace, automotive, machinery, rail or naval.

2.7. Data Analysis

Upon listening to the responses of the interviewees during the interviews, firstly notes were prepared. The prepared notes were translated into text digitally and sent to the respondents for verification. After having been verified, the text was organised carefully for each respondent belonging to a particular sector as shown in Chapter 4 (Empirical findings). Furthermore, the commonalities and differences have been observed and supported by scientific literature as shown in Chapter 5 (Analysis).

2.7.1. MCDM Tools

The MCDM tools that is AHP and PROMETHEE have been used for data analysis mainly to answer the second research question pertaining to selecting spare parts for AM production as shown in Section 2.1.

Selecting spare parts for AM is quite a challenge due to the different technical and economic criteria. The objectives with respect to spare parts management across firms could vary. To achieve those objectives, firms often must involve many stakeholders, consider multiple criteria and make trade-offs among them. This makes it a multi-criteria decision-making problem and that is why the MCDM approach has been taken into consideration. MCDM methods such as Multi-attribute Utility Theory (MAUT), Analytical Hierarchy Process (AHP) and Fuzzy Set Theory, ELECTRE and PROMETHEE were studied in the literature. MAUT, Fuzzy set theory and ELECTRE have not been considered due to the following reasons (Velasquez & Hester, 2013):

- They are highly data intensive meaning they need a lot of input to be developed.
- Many trial simulations need to be conducted before usage.
- It is difficult to explain the processes and the outcomes in general terms.

As defined by Saaty (1987), the Analytical Hierarchy Process (AHP) is a measurement procedure conducted through pairwise comparisons based on the opinion of experts. AHP helps measure intangible concepts in numerical terms (Saaty, 1987). AHP is one among the most used MCDM methods, which contains advantages and drawbacks. AHP has been chosen in this study because it is very user-friendly meaning that the pairwise comparisons make it easy for decision makers/stakeholders to weigh the criteria and decide on the available alternatives. Irrespective of the number of objectives to be achieved and the number of alternatives considered, AHP can handle as many as possible, indicating that it is scalable (Velasquez & Hester, 2013). The AHP is not very data intensive. It requires only numbers to carry out pairwise comparisons. However, if the decision problem is very big and must be broken down into many subsystems, AHP can be very lengthy and time consuming. The scale used in AHP can make it difficult for the user to decide which criteria or alternative is more important than the other. This would require careful judgement. Inconsistencies can occur because comparisons between concepts will have to be made and no single concept can be studied in detail (Velasquez & Hester, 2013). AHP is used in numerous decision-making areas such as project selection, resource management, political strategy etc.

PROMETHEE is an MCDM method which stands for Preference Ranking Organisation for Enrichment Evaluation. The advantage is that this method is easy to use. It helps obtain partial ranking (PROMETHEE 1) as well as complete ranking (PROMETHEE 2) of the alternatives. According to Abdullah et al. (2019) it is advantageous due to its success in real life decision-making problems. Previously, both PROMETHEE 1 and 2 have been used to evaluate performance in schools evaluate pipeline routes for transporting oil and gas and predict bankruptcy (Murat et al.,2015; Tavana et. al, 2013). The drawback of PROMETHEE is that it does not provide a clear method to assign weights (Velasquez & Hester, 2013).
This chapter explains the set of research questions to be answered and the steps followed to achieve the design objective and the overall thesis objective in sections 2.1 and 2.2. The sources of data collection that is literature study and interviews, procedures followed to collect data and the data analysis process have been described here in sections 2.5, 2.6 and 2.7, setting the basis for the following chapters. This is needed before the description of the literature study, observations and analysis. The next chapter helps explore the literature study on spare parts and additive manufacturing.

3. Background – Spare Parts and Additive Manufacturing

The purpose of this chapter is to acquaint the reader with the knowledge of spare parts and additive manufacturing technologies which is relevant for the development of the thesis project. The chapter is structured starting with supply chain management (SCM) first before describing the overall spare parts business and the AM technologies. This is done because SCM brings to light issues such as shorter product lifecycles and demand uncertainty, performance metrics like flexibility and reliability, relevant to the business of spare parts. By managing the spare parts supply chains with effective strategies, these issues could be possibly addressed by firms to achieve higher customer satisfaction and greater profitability. Following SCM, spare parts have been defined and classified. The spare parts supply chains within the sectors of automotive and aerospace have been explained due to the literature available to describe them and the existence of possibilities for AM applications. The current status and future growth of the spare parts market (including events like the covid-19 pandemic) has been described to indicate opportunities for businesses to apply technologies (AM and others) for effectively strategizing aftermarket offerings. After the spare parts market study, the attributes of spare parts such as demand rates, variety & response time and classification criteria such as lead time, supply uncertainty etc. have been explained as its very important for firms to focus on these challenging criteria and not overlook them. Moreover, these criteria have been chosen as AM could help in overcoming them and has discussed in detail in chapter 5 (perceived usefulness of AM). Lastly this chapter discusses the AM technologies and its advantages and drawbacks.

3.1. Supply Chain Management

Shortening product lifecycles and increasing competition over the last two decades has forced firms to rethink their supply chain practices and improve upon them. The term 'Supply Chain Management' was seen as logistics within the company and outside, ranging from customers to suppliers (Lambert & Cooper, 2000). Logistics has always been an integral part of supply chain management. The overarching objective of every firm across the sectors of Manufacturing, Information Technology, Healthcare, Finance, Consumer Goods, Electronics etc., is to create maximum value for stakeholders across the supply chain, starting from the supplier all the way to the customer. To stay competitive and reach high levels of profitability, the sequence and flow of activities and information is crucial (Lambert and Cooper, 2000). According to Perumal (2006), a sound supply chain strategy ensures and strengthens the business strategy.

Companies often want to minimize costs, scale-up profits and increase market share. But more often than not, reducing costs comes with increased risk (Albastroiu, 2012). Therefore, a firm's supply chain strategy should be a core part of the overall business strategy. The costs of the processes incurred within the company internally and the revenues received externally through clients must be considered in the supply chain strategy. With technology constantly evolving, firms often have to improve their supply chain strategies, to be more effective in meeting new customer needs and unmet demand situations by delivering good quality products or services. Supply chain management brings to light performance parameters such as flexibility and reliability that are important for firms to consistently achieve. Moreover, these parameters are relevant from the context of managing spare parts supply chains because uncertainties occur often due to varying product lifecycles for which spare parts would be needed to keep the products functional. Supply chain flexibility mostly measures the firm's ability to react quickly to demand uncertainties. Flexibility is assessed by levers such as volume, delivery and adaptation flexibility (Genevois et al., 2014). Therefore, the spare parts market and its management along with the usage of technology could be valuable contributors to firms' supply chain strategy to achieve high flexibility and reliability.

3.2. Spare Parts

Spare Part is a duplicate/interchangeable part that can be used to repair and replace a damaged or lost part in a machine. Spare parts are also referred to as repair parts, replacement parts and service parts. Capital spare parts are different, meaning they have a very long service life and minimal chances of failure. If they fail by chance, huge machine downtimes would occur. Some examples of spare parts are buffer box in trains; main bearings and thrust blocks in ships; brake calliper, shock absorbers and fuel pumps in cars; valve block in aircrafts.

In logistics and maintenance, spare parts are grouped into three categories which are Rotables, Repairables and Consumables (shown in Table 2). Rotables are parts that can be restored to a serviceable condition at an affordable cost. The scrap rate is very low for rotables. There is always a usage-based maintenance strategy for rotables, indicating that they are tracked and traced regularly. In usage-based maintenance, the usage of a part is measured and maintenance is carried out when a threshold level has been reached (Arts, 2013). For example, in aircrafts the landing gear usage is measured by the number of landings. Certain resources are dedicated towards maintaining rotable parts. The examples for Rotables include fuel pumps, hydraulic pumps in aircrafts, rolling stock bogies in trains. Rotable parts are more common in aircrafts than in any other modes of transport. In aircrafts, repairables are similar to rotables, but have a scrap rate of 25% (IATA, 2009). Repairables are usually worthy of repair from a cost perspective, enabling affordable maintenance. Unlike rotables, there is no usage-based maintenance strategy for repairables (Arts, 2013). A compressor is an example of repairable. For repairables, condition-based maintenance strategy is used, meaning the condition of a part/component is periodically checked and maintenance is carried out. For example, the number and length of cracks on a metal part could be used as a condition to repair the part. Consumables are parts which are scrapped completely once they have been utilised. Consumables are freshly bought from suppliers and never repaired. The scrap rate of 100% is the highest for consumables. Consumables generally do not cost much and examples are gaskets, fasteners.

For aircrafts, managing consumables is equally important as rotables and repairables, failing which the aircraft would be grounded. In automotive and rail industry, there exists repairables and consumables. According to Dongdong & Xingwu (2018) in automotive sector, the spare parts are further divided into consumable parts (probability of fault = 100%, very high frequency of replacement), wear parts (probability of fault = 100%, not so high frequency of replacement), insurance parts (probability of fault = 20% - 100%, will be used after 5 years) and accident parts (will never be used except when there are quality issues, design flaws, accidents). Regarding the rail industry as shown in Table 3, spare parts are mainly studied on the basis of criticality, value usage and lead times (Çelebi et al., 2008).

Table 2: Spare parts for logistics and maintenance (own illustration)

Spare Parts for Logistics and Maintenance	Description
Rotables	Can be restored to a serviceable condition at an affordable cost. Very low scrap rate. Usage-based maintenance strategy - rotables are tracked and traced regularly Examples: Fuel pumps, hydraulic pumps in aircrafts; rolling stock bogie in trains
Repairables	Similar to rotables, but have a 25% scrap rate. Economically worthy of repair. No maintenance strategy for repairables – not tracked and traced. Condition - based maintenance strategy is followed. Example: Aircraft compressor
Consumables	Scrapped completely once they have been utilised. Consumables are freshly bought from suppliers and never repaired. They have a scrap rate of 100%. Example: Fasteners, gaskets

Table 3: Rail spare parts for logistics and maintenance (Celebi et al., 2008)

1) Criticality	1a) Stock Out Penalty – situations that occur when an item that's required is not available 1b) Commonality – how many times it is used and in how many different vehicles it is used 1c) Substitutability – if close substitute parts are available, better the flexibility and responsiveness, reducing the criticality of the original part	Stock out penalty: High – spare parts need to supplied immediately and failure needs to be corrected quickly. Moderate – temporary arrangements can be made to control failure for a short time period, following which spare parts need to be supplied. Low – failure is not very critical; spares can be supplied after a long time.
2) Value usage	Measured by the product of annual usage quantity and average unit prices of the parts.	
3) Lead times	Time elapsed since placing the order of raw materials to the supplier, receiving and producing the parts and delivering it to the customer.	In maintenance, lead time is very important. Longer lead times could interrupt activity, leading to higher expenditure and financial losses.

This sub-section describes what spare parts are and how they are grouped in various sectors. The following sub-sections 3.2.1 and 3.2.2 briefly explain how spare parts supply chains are managed in the sectors of automotive and aerospace.

3.2.1. Automotive Industry Spare Parts Supply Chain

A study conducted by Deloitte explains that most automotive OEMs (both Chinese and worldwide) adopt a network structure for the distribution of spare parts (Shiu et al., 2013). Among the OEMs surveyed, majority of them chose to adopt the two-layer network structure (shown in figure 3.1) consisting of a central warehouse and regional distribution centres (RDCs). Few respondents (small scale OEMs) preferred the single layer network structure which allows direct distribution from the central warehouse to the dealer. This model might be cost effective but however is slow in terms of the time taken to respond to customer demand.

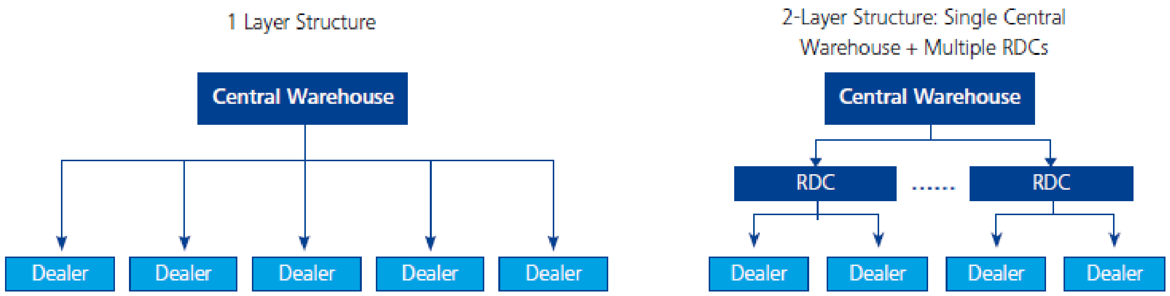


Figure 3.1: Distribution Network Structures (Shiu et al., 2013)

The study goes on to explain the models adopted by OEMs, namely the buyout model and the self-run model. In the buyout model, the OEMs utilize the services of professional spare parts wholesalers and retailers to sell and distribute spare parts across the regions. The buyout model transfers inventory management activities downstream and helps minimize inventory costs, making it more cost effective for the OEM. However, this model is not very responsive to changes in customer demand. In the self-run model, the RDCs are built by the OEMs. The operations of the RDC and distribution activities are either managed by the OEM or outsourced to third party logistics (3PL) providers. This self-run model is better responsive to customer demand and due to tighter network control, service levels are maintained. An example of Ford Motors is taken for the redesign of its spare part distribution network in this study. Initially, Ford had 1 central warehouse, 8 regional warehouses and adopted a pull deployment strategy with a safe inventory level. Ford then redesigned its spare part distribution network by constructing 23 distribution centres where 19 were for fast-moving parts, 3 for bulk parts and 1 for slow-moving parts. The spare parts are transported to the RDCs in cross-docking model. The figure 3.2 below highlights the supply chain for a finished vehicle and its spare parts. Previous models dealt with mostly the distribution activities. This diagram considers the raw material supply, manufacturing operations and distribution activities.

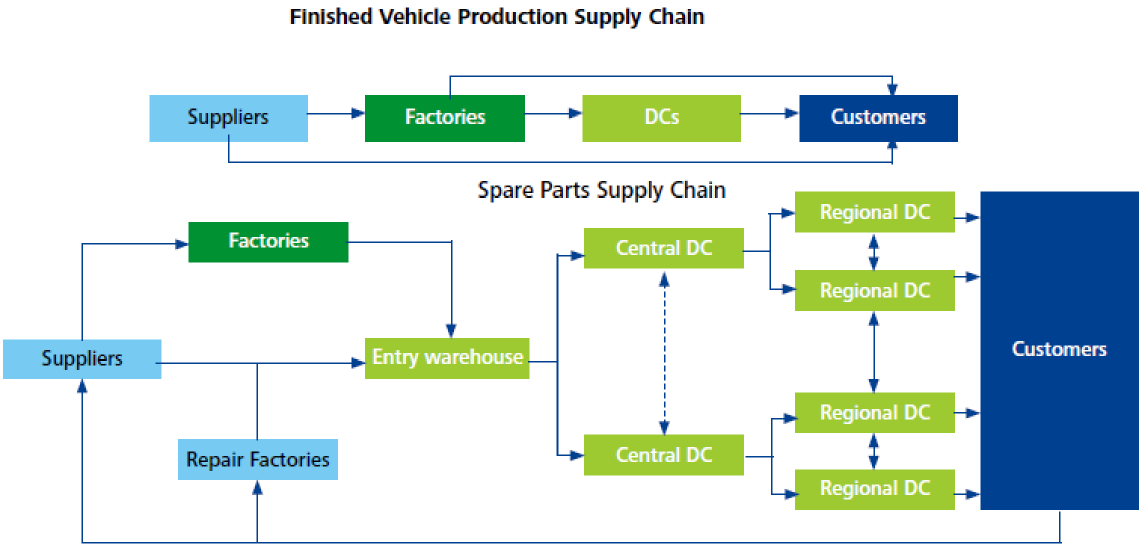


Figure 3.2: Spare Parts Supply Chain Activities (Shiu et al., 2013)

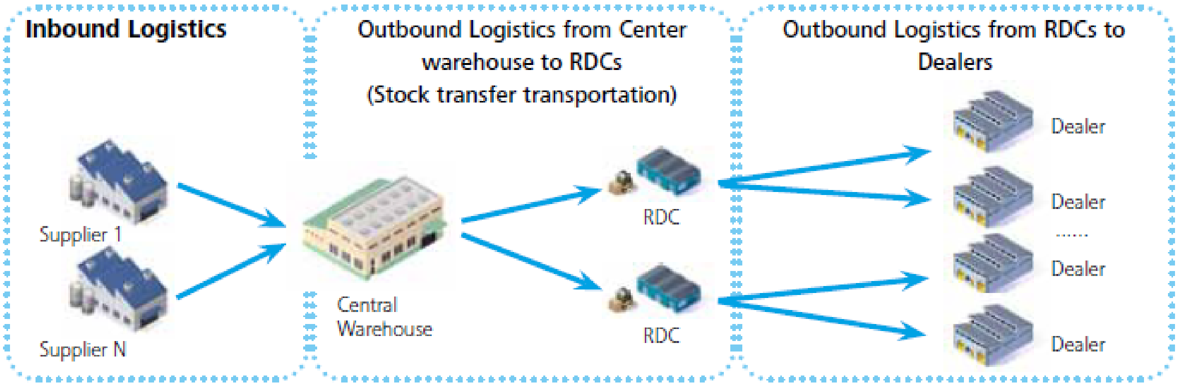


Figure 3.3: Spare Parts Logistics Model (Shiu et al., 2013)

The spare parts logistics model has been shown in Figure 3.3. According to the figure, the inbound logistics activity to deliver the parts to the OEM's warehouse is carried out by the supplier. According to the study, the OEMs do not have good control over inbound logistics. Even though some OEMs have adopted the milk-run mode, challenges do exist such as effective collaboration between the purchasing plan and supplier production plan, lean logistics capabilities of 3PLs, standardization of logistics equipment and transportation vehicles. The OEMs have good control over the outbound logistics from central warehouse to RDC's, where good efficiency and quality of transport is ensured. The OEMs normally outsource these activities to 3PL providers. RDCs carry out the outbound logistics activities to dealers. The LTL (less than truckload) model is adopted by the RDCs.

A study by McKinsey describes the structure of the automotive market that is expected in the future as shown in the figure 3.4 below (Kempf et al., 2017). Compared to the previous study, this study throws light on online distributors (e-commerce firms like eBay, Amazon etc) who could be used for parts distribution and intermediaries such as leasing companies, routing portals and automobile clubs who could be the new set of end users. The study highlights that most of the aftermarket suppliers currently are operating in the independent aftermarket via the OEM channel and in future it is expected that e-commerce businesses and workshops (OEM owned, franchised, independent garages etc) would dominate. Therefore, direct distribution is favoured according to this study.

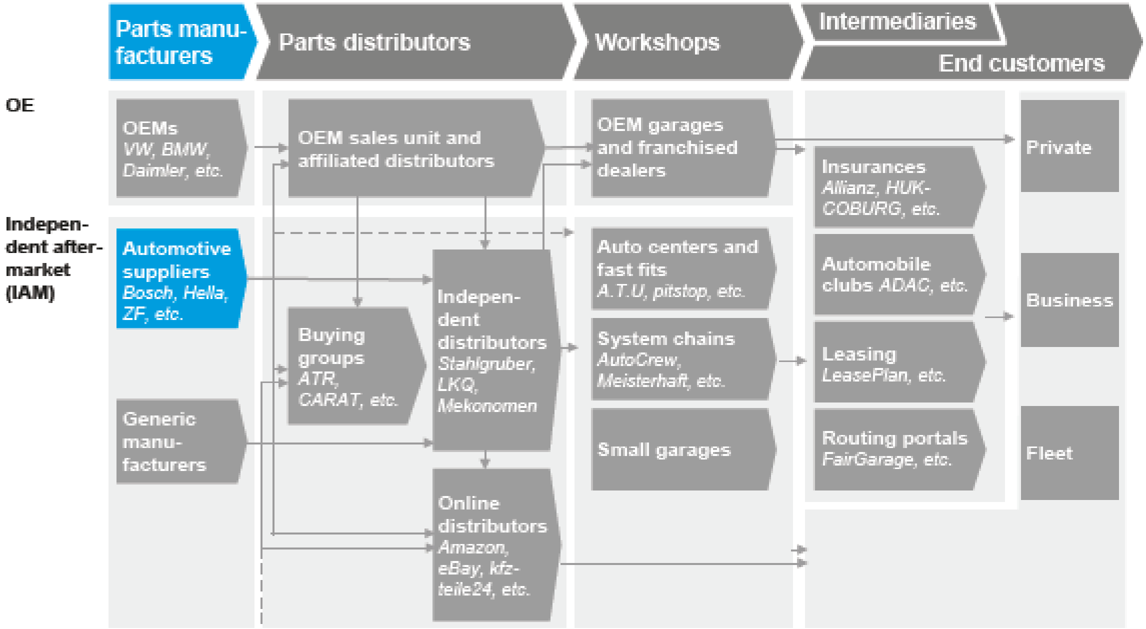


Figure 3.4: Automotive aftermarket (Kempf et al., 2017)

3.2.2. Aircraft Industry Spare Parts Supply Chain

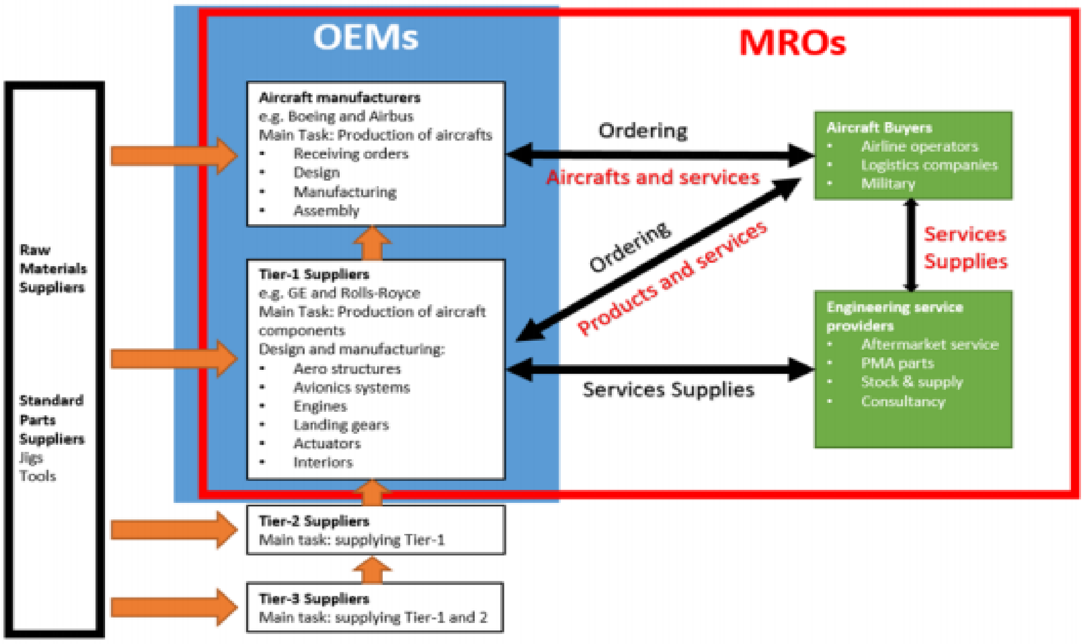


Figure 3.5: Aircraft industry supply chain (Singamneni et al., 2019)

The figure 3.5 above shows the generic supply chain structure of an aircraft industry. The suppliers across tiers 1,2 and 3 supply the aircraft manufacturers with components and subassemblies. The aircraft OEMs carry out the production of aircrafts upon receiving the orders from suppliers and customers (Singamneni et al., 2019). The overall design, production and assembly is carried out by the OEM. The customers are the commercial airline companies, military and logistics firms. The MRO companies exist to provide services. MRO companies could be part of OEMs or exist independently. MROs need to ensure frequent quality inspections and line maintenance to keep the aircraft in flying condition.

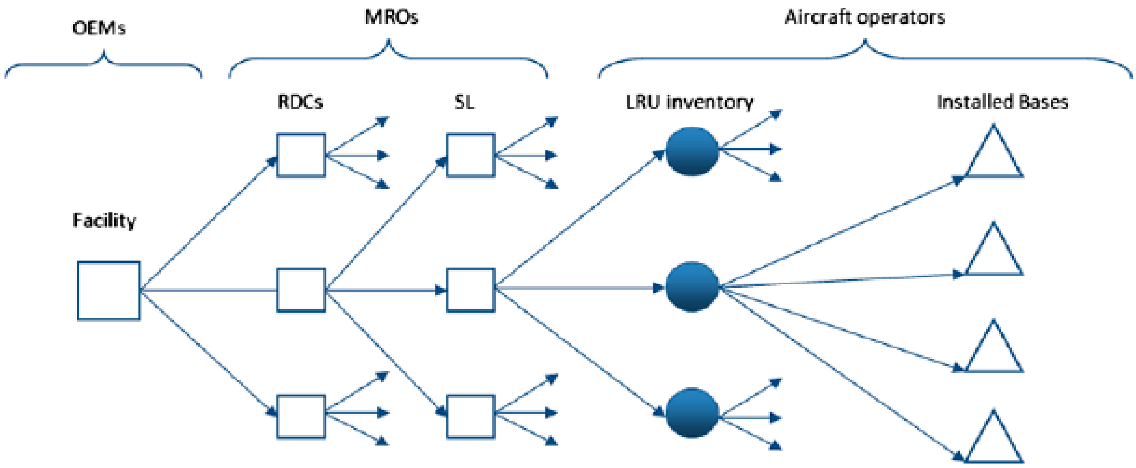


Figure 3.6: Aircraft Spare Parts Activities (Liu et al. 2013)

The aircraft spare parts supply chain can be depicted as shown in figure 3.6. The OEM produces the spare parts and supplies it to the RDCs. The RDCs are owned by the MRO companies. The RDCs distribute the spare parts to various service locations. In the service locations, the maintenance and repair of sub-components is carried out. The line replacement units located near the aircraft operators store the inventory of fully functional and to-be-repaired sub-assemblies. Once the assemblies are fully repaired and functional, they are taken to the installed base.

3.2.3. Spare Parts Market

The preceding sub – section explained the supply chain structures generally followed for managing spare parts. The spare parts market affects the supply chain structure, meaning that predictable demand could be handled easily, compared to situations when the demand is unpredictable. Therefore, successively a market study for spare parts is described along with the spare part attributes which could help strategize the supply chain that may impact firm revenues and profits.

The last few decades have seen the emphasis being placed on customer retention which is a critical source of business for companies. Product firms have slightly tweaked themselves by incorporating a service-oriented approach along with its already existing product-oriented approach, for the purpose of customer retention and customer acquisition. By stressing on customer relations management, firms could differentiate themselves from competitors and gain a good corporate image (Brax, 2005). According to Mandina & Karisambudzi (2016), it is lesser in terms of operational costs to maintain relationships with existing customers than acquiring new ones. Therefore, maintaining customer relationships is very important.

The aftersales market which includes spare parts could be a possible aid to firms for building customer relationships. Aftersales services foster interaction with customers and maintain long-lasting relations, thereby helping firms to leverage on the possible benefits (Brax, 2005). Cohen & Agrawal (2006) describe in their study that the market for aftersales in the automotive, machinery and IT sectors would be at least 4-5 times larger than the finished goods market. As mentioned previously, the aftersales market accounts for 50% of firms' total profits globally (Wagner, Jönke & Eisingerich, 2012). A focussed spare parts management strategy could be a differentiation point and account for the possible losses made on finished goods (Bacchetti, 2010). The decreasing revenues on the sales of finished goods present an opportunity for firms to place big bets and up their game in the aftersales market (Bacchetti, 2010).

In 2014, a study on the dynamics of the automobile aftersales market in Europe conducted by Boston Consulting Group (BCG) in collaboration with the European Automobile Manufacturers Association (ACEA) reveals that the competition is intense, forcing the manufacturers (OEM network) to come up with new service offerings to counter the independent service providers. The study includes the following countries – UK, France, Germany, Poland and Spain. The independent service providers consist of repair shops and garages offering services and selling spare parts, without any contractual obligations with Vehicle Manufacturers (Frowein et al., 2014). According to the study report, the automotive after-market sales grew from 115 billion euros in 2010 to 121 billion euros in 2012. The number of cars on the road increased and so did the expenditure on accident repairs, spare parts. Worldwide 60 million cars are produced each year, each vehicle lasting for an average of 11.4 years approximately (Reeves & Mendis, 2015).

To assess the automotive aftermarket prospective future outlook, McKinsey conducted a study with European Association of Automotive Suppliers (CLEPA) in 2017 (Kempf et al., 2017). They expect disruptive changes in the aftermarket due to increasing adoption of technological innovation, changing customer expectations and emerging markets. In 2015, the maintenance, repair of vehicles along with the retail business of vehicle parts constitute for about 760 billion USD worldwide, 20% of overall automotive revenues. The forecast for the aftermarket in 2030 is expected to be approximately 1200 billion euros, signalling a growth of roughly 3% per annum. Emerging markets like China, India and the Rest of Asia would account for a bulk of the automotive aftermarket revenues, whereas Europe and North America would decline. Business model evolution is expected to take place through direct distribution models and e-commerce. This along with further digitization will enable the aftermarket players to get closer to the customer. According to the recent 2021 Global Automotive Aftermarket Report by Grand View Research (2021), the automotive aftermarket was valued at 390 billion in 2020, projected to be $408 billion at the end of 2021 and expected to grow at a CAGR of 3.8% to reach approximately $530 billion by 2028. This massive growth is favoured by digitization of part delivery sales and services along with the creation of online portals for distributing these parts or components. The key value chain enablers are the part suppliers (OEMs or their subcontractors, 3rd party repair shops) and service enablers. The Genuine parts produced by OEMs or their respective subcontractors accounted for about 52% market share, offering the best quality and warranty although coming at a high price. The certified parts segment (parts produced by 3rd party repair shops, certified by OEMs) is also very attractive due to its cost-effectiveness. Uncertified parts too have a liking among certain customers due to low costs, but however they cannot carry any warranty and are not approved by the carmaker. The parts considered in this study are replacement parts such as brake parts, filters, body parts, tires, exhaust components, turbochargers etc. The growth in the automotive aftermarket has however been hindered by the Covid-19 pandemic. In June 2020, a survey was conducted by FIGIEFA, a European trade organisation to investigate the impact of Covid-19 on the operations of automotive spare part distributors. They found that despite most of these companies being allowed to conduct activity with limitations from March 2020, a massive decline in overall sales was reported. More than half of the respondents reported 50% losses, 30% of the respondents reported a decline of two-thirds in sales (FIGIEFA, 2020). Moreover, a study by Bain & Company projected a decline of 15% in auto part sales for 2020 and expect the sales to be 4-8% lower than forecasts till the end of 2025 (Zayer & Hoffmann, 2020).

Not only in the automotive industry is aftermarket growth expected, but also in the aircraft industry. According to Oliver Wyman, the expenditure on Maintenance, Repair and Operations (MRO) is projected to increase to 116 billion USD by 2029, from 81 billion in 2019. However, the Covid-19 pandemic has wreaked massive havoc in the aircraft industry. Another report by Oliver Wyman highlighted that the overall expenditure on MRO would decrease by at least 55% from 2020 onwards (Cooper et al., 2019). They predict that by 2022, once flying resumes, airlines would rely more on USM (used serviceable material) than OEM produced parts to cut production and material costs. Boeing entered the USM market in 2019 to supply affordable spare parts to its customers. Furthermore, the article by Cummins, (2020) expresses that airlines would need spare parts and MRO at a higher scale in the long run, due to the fact that they are in a cash crunch and cannot afford new aircrafts. To maintain the aircrafts in good condition, it would be economically feasible to use spare parts from defunct aircrafts. Although passenger flying would be minimum, aircrafts would be needed to transport essential medical supplies during such public health emergencies. So, cargo flights are definitely necessary. The Asia Pacific region held the highest market share for commercial aircraft aftermarket parts in 2020 (Mordor Intelligence, 2020). In the same year, the Asia Pacific region alone had 8000 commercial aircrafts in service. With this, the average age of all these aircrafts is expected to increase, indicating that more part replacements and maintenance is required. Boeing has partnered with suppliers like MRO HAECO, KAEMS etc for spare part supplies. In February 2020, Israel's El-Al airlines set up a partnership with AJW group for aircraft MRO activities.

All these studies and reports present massive opportunities for businesses to carefully strategize, plan in the event of disruptions like the Covid-19 pandemic and expand their aftermarket service offerings. Quite often the aftermarket spare parts or replacement parts have specific characteristics or attributes which makes it challenging for firms to focus on. Despite the proven benefits of cost reduction, quick response time, faster lead time and quick delivery, firms often overlook or ignore the spare parts business and don't adapt their management strategies (Bacchetti & Saccani, 2012).

3.2.4. Spare Part Attributes

Certain attributes of spare parts such as Demand Rate, Resupply Lead Time, Safety Stock Costs, and Response Time make spare parts management challenging for firms (Knofius et al., 2016). Firms in the areas of automotive, aerospace, energy & utilities and industrial machinery where spare part usage is frequent, are often exposed to a complex environment where customer expectations vary, part sizes are large and varied, demand patterns fluctuate constantly (Wahba et al., 2012; Bacchetti & Saccani, 2012; Syntetos & Boylan, 2001).

One major attribute of spare parts is the demand uncertainty explained by the unpredictable demand rate and high volatility (Baccetti & Saccani, 2012; Khajavi et al., 2014). The factors of intermittent demand and variation is explained here. In certain cases, finished products dot sell completely and excess stock of spare parts is carried over. In other cases, demand for products would be very high and firms would struggle to meet the demand due to shortage of supply of spare parts. This explains situations where demand for spare parts is highly unexpected (Cohen et al, 2006). Moreover, the demand uncertainty is amplified nowadays, when new products are constantly introduced to the market with short product lifecycles (Khajavi et al., 2014).

Secondly, the extensive variety of parts in a spare part assortment make the process of managing spare parts more difficult. The study by Khajavi et al. (2014) states that the pressing need to support older generation products with the existing ones adds to the quantity of items that need to be held in stock. For example, in the automotive industry, the mechanical components like brake, gearbox last long but the electronic components don’t last long enough. So, the firm would have to maintain different set of spare parts corresponding to the product lifecycles (Knofius et al., 2016). Moreover, the aftersales market is an unpredictable marketplace where they must manage nearly 20 times more stock keeping units (SKU’s) than the production department (Cohen & Agrawal, 2006).

Thirdly, the response time factor which customers give high weightage to is important for the firm (Knofius et al., 2016). If any industrial equipment that’s needed for daily operations gets damaged, high costs would be incurred along with equipment downtime. In this situation, the client would expect the damaged spare part in the machine to be replaced quickly. Also, the client would expect top quality and good service. The transportation modes chosen by the firm would affect response time (Knofius et al., 2016).

Nowadays, managing spare parts to deliver high customer service is becoming a challenge due to the constant introduction of new products and different variants in the market. The objective of spare parts management is to ensure sufficient availability of spare parts with low costs and minimum investment. The stocking of high inventory of spare parts would ensure that the time constraints are met with respect to production. However, this could lead to higher inventory costs in the warehouse due to hold-ups that occur when the quantity of spare parts received is more than the demand for those products which require the spare parts. As mentioned previously, spare parts management must respond to the ever-changing expectations of customers and address the problem of demand fluctuations. The main issue is with the management of slow moving, high value spare parts mentioned by Knofius et al. (2016) which poses a challenge for effective inventory management. This could lead to high safety stock costs. Added to this is the issue of product obsolescence due to the low turnover rate of slow-moving spare parts, which forces companies to think whether to maintain inventory of those respective spare parts or not (Khajavi et al., 2014). If they do, then they would be able to ensure high customer service although at extra costs. If they don't, then they risk losing customers. This explains the trade-off that companies must make (Wahba et al., 2012).

3.2.5. Classification of Spare Parts

Large sizes of spare parts inventory are indeed very complex to manage as each of them would serve different purposes (Bacchetti & Sacchani, 2012). To overcome some of the issues stated previously in sub-section 3.2.4, spare parts need to be classified or categorised according to the purposes they serve. Classifying the spare parts helps in better organisational decision making. Classification is done either on a single criterion or multi-criterion basis (Wahba et. al., 2012) as some spare parts might fall into one or more criteria. One of the most important classification methods is the ABC analysis. This quantitative method is based on the Pareto principle that categorizes items into very important (A), moderately important (B), relatively important (C). The drawback of ABC analysis is that it is effective for maximum two criteria (Ramanathan, 2006). For multi – criteria (more than two criteria) classification, the Analytical Hierarchy Process (AHP) would be very useful. The AHP method breaks down goals into criteria, sub criteria and alternatives to guide decision making (Ramanathan, 2006).

Van der Auweraer et al. (2017) classified spare parts based on the Sales Life Cycle. As shown in figure 3.7, the phases of the Sales Life Cycle are divided into the Initial phase, Mature phase and the End-of-Life phase. In the initial phase, the products are introduced into the market, demand for spare parts is low. This is where the installed base and the new product sales grow. In the Mature phase, the installed base reaches the maximum and the new product sales slump. The demand for spare parts increases here and reaches a maximum at the end of the mature phase. In the end-of-life phase, the spare parts demand decreases.

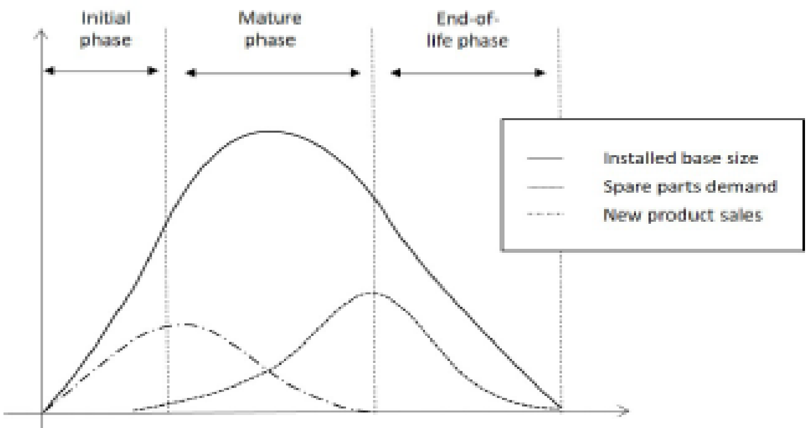


Figure 3.7: Classification based on Sales Life Cycle (Van der Auweraer et al., 2017)

Spare parts can be classified according to supply uncertainty and lead time. The lead time is considered when deciding whether to keep spare part inventory or not. If the response lead time is more than the replenishment lead time, then it's not required to keep inventory (Bacchetti et al., 2010). The lead time factor at times could be more critical than all the other supply chain factors.

From the customer point of view, demand volume and demand value are critical factors. The number of customers and demand directly accounts for the frequency of spare parts. The frequency indicates the rate at which spare parts are consumed that help in spare part classification (Wahba et al., 2012). Customers may need spare parts sometimes on a regular basis (every 1-2 years) and sporadically rest of the time (once every 4-5 years approximately), creating a slow - moving demand pattern. This creates variability of demand which could impact lead times (Eaves & Kingsman, 2004). Due to demand variability, forecasting becomes difficult, resulting in spare parts being held in stock as protection against high costs that would occur if an item was required and not immediately available.

Part criticality can help determine the market demand for parts. The effect that an individual part could have on a product functionality reflects its criticality. A part can be considered a critical one if it serves a critical purpose in an operation (Wahba et al., 2012). If the part is highly critical meaning that its necessary for a critical operation, it could lead to higher losses or shutdown if it fails or breaks. This would prove to be very costly and impact service levels. Therefore, a certain amount of safety stock needs to be maintained to satisfy customer demand and attain high service level (Bacchetti et al., 2010).

Part value is a common classification criterion used in spare parts management. High value parts are generally not preferred to stock in the supply chain (Jouni et al., 2011). However, spare part stocks must be held if the products which require the spare parts are not produced on demand to fulfil lead times, responsiveness and maintain customer satisfaction.

3.3. Potential for AM in Spare Parts

The above observations made in the aftermarket business along with part attributes indicate strong potential for technological innovation in the spare parts sector, in the form of Additive Manufacturing. In 2017, Geissbauer, Wunderlin & Lehr (2017) from Price Waterhouse Coopers conducted a survey among suppliers (including OEMs and 3rd party suppliers) and buyers of spare parts in Germany which highlights a few important findings. They are:

- Spare part suppliers are not meeting the needs of customers, 50% of these customers are looking to adopt AM to print parts on their own.
- Within the next 5 years, 85% of suppliers would incorporate AM to complement their existing manufacturing processes.
- Within 10 years, these suppliers would save costs of up to 3 billion euros annually.
- Companies are still not aware of the potential of AM and companies that invest in AM early on will have a competitive advantage.

Adding on to this, Reeves & Mendis (2015) highlight the compelling drivers for AM adoption among various stakeholders in the supply chain. For an OEM, AM could eliminate the need to hold excess stock and dispose them at the end of vehicle's life. For third – party suppliers of tools, AM could help reduce investments on custom tooling. From the perspective of a vehicle owner, AM could enable on-demand part production even after the completion of the warranty period.

The EY report by Thewihsen et al. (2016) explains business trends and technology improvements in favour of AM adoption mostly by aerospace and automotive industries. The notable business trends are individualization, sustainability; technology improvements are lightweight materials, better materials management. The report consists of use cases such as General Electric (aerospace) adopting AM for production of fuel nozzles, and BMW using AM for producing the water pump wheel. Complementing this report is another report by 3D Hubs, describing the use cases of AM adoption in 2019. In the aerospace industry, Collins Aerospace and Marshall Aerospace adopted AM for MRO activities (3D Hubs, 2020). BMW's competitors Audi and Volkswagen too adopted AM for part production. In the railway industry, UK Trains started 3D printing obsolete components. 3D Hubs forecasts the 3D printing market to touch $35 billion approximately in 2024, up from $12.1 billion in 2019.

An article by Stone (2021) highlights the importance of 3D printing to reduce inventory costs, emphasising on how holding costs (occur for long times, 5-10 years) and transportation costs to deliver the part to the customer location could be minimized. The problems that occur in managing long-tails (further discussed in chapter 5, section 5.5.1) and part obsolescence drives the need for digital inventory of spare parts (Gupta, 2020). The high volume of slow-moving spare parts with intermittent demand are described as 'long-tail' components (Topan & Bayindir, 2012). Looking back at figure 3.7 in the products' end-of-life phase, the existence of long-tail spare parts could be common due to the reduction in the installed base size and constant variation in demand for spare parts. Obsolete parts are difficult for manufacturers to produce in short periods of time. The inability to produce affects customer satisfaction and aftersales service. With digital inventory, parts can be produced on-demand near the customer location in faster time. The need to hold excess physical inventory (includes unused parts) could be minimized using 3D printing.

Even though 3D printing can produce on-demand and help reduce inventory, it raises concerns with respect to costs, quality and speed. At low cost, economies of scale, traditional manufacturing is more preferred. The speed the 3D printing process at the moment varies from a few hours to a few days, implying that a trade-off needs to be made between holding inventory (in conventional production) and printing on demand. Whether the 3D printed part would possess good quality (strength and other physical properties) as compared to the conventionally produced part or not is of paramount importance. Moreover, it is difficult for firms to decide the approach for spare parts management. When a car model is introduced into the market, it normally lasts for 5-7 years till a newer model is introduced. The demand for this new model and its respective spare parts will be high till the newer model is introduced. In this phase, it would be ideal to conventionally produce the spare parts as they are in high demand and possibly high frequency, meaning that a make-to-stock (MTS) approach would be suitable (shown in table 4). MTS approach is characterized by short lead times, high inventory costs and low flexibility. Once the newer car model is introduced, the demand for the existing model would reduce and so would the demand for its spare parts. The demand for these older spare parts would follow irregular, inconsistent patterns which when stored in inventory, could lead to high storage costs. Forecasting for spare parts in such a scenario would be difficult. This is when 3D printing would be advised in order to produce on-demand and minimize inventory, favouring a make-to-order (MTO) approach. MTO approach is characterized by longer lead times, low inventory costs and high flexibility. However, 3D printing could offer faster lead times, thereby favouring the MTO approach for spare parts with uncertain demand. These approaches are discussed in detail with respect to the business models in chapter 7. It is difficult to rely completely on either of the approaches. Hence, a hybrid approach consisting of both is preferable. For example, Daimler EvoBus prints approximately 2000 spare parts out of over 320,000. Most of these parts are replacement and obsolete parts. These parts also have certain customer specifications, so they need to be customized. Also, Deutsche Bahn prints obsolete parts to keep their older generation trains running (Naramore, 2020). Both these examples present the hybrid use of MTS and MTO approaches. The next section explains Additive Manufacturing (3D Printing) in detail.

Table 4: Approaches to Spare Parts Management (own illustration)

Approaches to Spare Parts Management	Description
Make-to-Stock (MTS)	Suitable for high demand, high frequency parts Push system – production follows replenishment policy Short lead times, high inventory costs, low flexibility (customization)
Make-to-Order (MTO) and Engineer-to-Order (ETO)	Suitable for uncertain/intermittent demand parts of small lot sizes Pull system – driven by customer demand. Once customer orders are placed, only then products/parts are made Longer lead times, low inventory costs, high flexibility

3.4. Additive Manufacturing

Additive Manufacturing or 3D printing initially evolved during the 1980's in the USA when it was being used for production of product prototypes. This technology is constantly evolving in sync with the growth in information technology and emergence of new materials for 3D printing. Post the loss of patent protection in 2009, many firms entered the AM market fostering advancements in the manufacturing sectors of military, automotive and aerospace with a wider range of materials, lower production costs and new technologies (Khajavi et al., 2014). This oversaw the development of AM technologies such as Selective Laser Sintering, Stereolithography, Powder Bed Fusion, Fused Deposition Modelling and Inkjet Bioprinting. These new AM techniques have enabled not only the production of prototypes, but also fully functional products. For example, AM has had a positive effect on the hearing aid industry, aircraft industry and the dental industry (Khajavi, Partanen, 2014). Previous research by (Holmström et al., 2010) shows that 3D printing is beneficial in the spare parts industry as no tooling is required, small batches of complex products can be produced economically and shorter lead times and lower inventory are possible. In addition to this, the study by Lindemann et. al. (2015) emphasises the benefits of AM on the overall lifecycle costs of parts. The AM machines together with advances in parameters such as speed, reliability, cost, material availability has the potential to influence spare part producers' strategic innovation decisions. The DHL 2016 report shows the evidence of major corporate firms adopting 3D printing, firstly with Daimler Trucks launching its 3D printed spare parts service and the start-up 'Carbon' founded by GE, BMW and Nikon and HP's 3D printing initiative (Heutger & Kückelhaus, 2016).

Most often in previous research, literature and industry terms, 3D printing is coined in different forms. In the early stages where it was used for designing and developing prototypes, it was labelled as Rapid Prototyping. But now, the technology has advanced beyond just prototypes to end products. The other terms used in literature are 'Rapid Manufacturing', 'Distributed manufacturing' and Direct Digital Manufacturing. The term that is the most accepted today and laid down by the American Society for Testing and Materials (ASTM) is 'Additive Manufacturing'.

3.4.1. Additive Manufacturing Technology

Additive manufacturing is a combination of processes that utilize many technologies to build up products layer by layer. As agreed by ASTM international, some of the AM processes that are widely available and commonly used in the industry are material extrusion, binder jetting, vat polymerization and powder bed fusion, directed energy deposition, sheet lamination and material jetting. The table 5 below gives a simple description of the different AM technologies used in industry today. The detailed description of these technologies can be found in appendix 3.

Table 5: ASTM Terminology for AM technologies (ASTM International, 2013)

Technology	Description
Binder Jetting	An additive manufacturing process in which a liquid bonding agent is selectively deposited to join powder materials.
Directed Energy Deposition	An additive manufacturing process in which focused thermal energy is used to fuse materials by melting as they are being deposited. DISCUSSION — *"Focused thermal energy" means that an energy source (e.g., laser, electron beam, or plasma arc) is focused to melt the materials being deposited.*
Material Extrusion	An additive manufacturing process in which material is selectively dispensed through a nozzle or orifice.
Material Jetting	An additive manufacturing process in which droplets of build material are selectively deposited. DISCUSSION—*Example materials include photopolymer and wax.*
Powder Bed Fusion	An additive manufacturing process in which thermal energy selectively fuses regions of a powder bed.
Sheet Lamination	An additive manufacturing process in which sheets of material are bonded to form an object.
Vat Photopolymerization	An additive manufacturing process in which liquid photopolymer in a vat is selectively cured by light-activated polymerization.

3.4.2. AM Materials

To enable the usage of AM technology and to obtain the desired set of properties with the end product, the right kind of materials need to be used. Also, advancements in materials are needed to further the development of AM. This subsection will describe the commonly used materials in AM for production of prototypes and end products. The properties of polymers such as ABS, PLA, PA11, PA12 and metals such as Aluminium, Titanium and Stainless Steel are given in the tables 6,7 and 8 below. The detailed description of each of these materials is described in appendix 3.

Table 6: ABS and PLA properties (Oosthuizen et al., 2013)

			Materials	
Properties	Units	ASTM	PLA	ABS
Tensile Strength	MPa	D638-03	59	40
Elongation at Break	%	D638-05	7	50
Modulus of Elasticity	MPa	D638-04	3750	2600-3000
Izod Impact Strength	J/m	D256-06	26	34
Density	kg/mm3		0.00105	0.00125

Table 7: Nylon PA11 and PA12 Properties (EOS, 2021b)

		Properties				
		Tensile Modulus (MPa)	Tensile Strength (MPa)	Elongation at Break	Melting Temperature (degree Celsius)	Density (kg/m3)
Nylon	PA11	1600	48	45%	201	990
	PA12	1650	48	18%	176	930

Table 8: Properties of Metals in 3D printing (EOS, 2021)

		Properties		
		Ultimate Tensile Strength (MPa)	Yield Strength (MPa)	Elongation at Break
Metals	Aluminium	460	245	5%
	Titanium	1055	945	13%
	Stainless Steel	590	500	47%

3.4.3. AM versus Traditional Manufacturing

Even though additive manufacturing can provide companies with several new opportunities and benefits which are difficult to obtain in traditional manufacturing, studies conducted previously have shown that there are still drawbacks with AM technologies. So, producing all sorts of items using AM is still not possible (Lindemann et al., 2015). In the following sub-sections, benefits and drawbacks of 3D printing are illustrated.

AM Benefits

Some of the AM benefits that have been found in the literature and elaborated upon here are:

- Ability to produce in small quantities
- Reduction in unit costs
- Design Freedom
- Increased complexity
- Environmentally friendly

Firstly, it would be very difficult to produce small batches of parts using the traditional manufacturing methods. To produce new designs or parts frequent tool changes, expensive tools, jigs and fixtures, moulds are required (Khajavi et al., 2014). This consumes plenty of resources like time and money and makes it difficult to economically produce small batches of parts. The fixed costs of AM processes are relatively low except the machine costs, and it does not require expensive tooling to produce new designs. As the need for tooling is eliminated, production lead times and costs in the initial stages of the product development cycle are reduced (Khajavi et al., 2014; Holmström et al., 2010). Also, with AM the safety stock of tools and raw materials is eliminated. Regarding AM, the unit cost is the same irrespective of the number of items of each design that are produced. In traditional manufacturing, it would be costly to customize products and mass production would be cheaper. Highly customized and low volume parts can be economically produced with AM (Khajavi et al., 2014; Sasson & Johnson, 2016).

Secondly, AM offers more design freedom compared to traditional manufacturing which is needed today as product designs continue becoming complex with various shapes, sizes and structure (Chua & Leong, 2015). How much ever complex the product is, it can be designed three dimensionally on a computer and fed into the AM machine for production (Campbell et al., 2011). In AM, multiple parts or subassemblies can be printed as one entire piece at once. In traditional manufacturing, each product is broken down into sub-parts and manufactured separately. This would require a large amount of tooling, moulds, jigs and fixtures as mentioned before. The technology however has certain limitations with respect to strength of products produced especially by binder jetting and material extrusion (Berman, 2012) (Petrovic et al., 2011).

Moreover, in AM complex geometries can be produced and the production process is the same no matter how complex the product (Petrovic et al., 2011). It is not costly due to the product complexity. Adding on to this, due to less tooling and assemblies required, the number of items to be kept in stock is lesser. Therefore, AM can withstand the risk of product obsolescence (Berman, 2012). Less labour is required in AM production processes, which implies labour costs can be reduced (Chua & Leong, 2015).

Most importantly, AM can help companies minimize their environmental impact. AM facilitates the use of 3D design files for prototypes that can be done digitally. Even a prototype in traditional manufacturing would require tools, jigs and fixtures and all these can be eliminated with digital design files. Distributed production with AM that would take place closer to the consumer can help reduce the carbon emissions caused by vehicular pollution. With traditional manufacturing, there be plenty of material waste in the production processes. This can be minimized with AM.

AM Drawbacks

Some of the AM drawbacks that have been found in the literature and elaborated upon here are:

- Limited material availability
- Reliability (includes production speed, part strength and surface finish)
- High procurement, maintenance and energy costs
- Limited AM awareness among the workforce

With benefits also lie limitations of AM technologies, which could be either technical or economical. The most often listed technical limitations are material availability, production speed, part strength and surface finish (Berman, 2012). The economic limitations are costs of energy, labour, materials and machine procurement (Khajavi et al., 2014).

The major issue holding up the increased adoption of AM is the range of available materials. In comparison to Traditional Manufacturing (TM), the number of materials available is limited. Research is being carried out on materials and the material availability is steadily increasing. The expansion of the range of suitable materials for AM is extremely necessary (Campbell, 2011). Also, many AM machines are suitable only for specific types of materials. AM machines can print either plastic or metal products, not both. Lack of material flexibility and integration is a problem with AM production. Integrating a variety of materials in a single machine is necessary (Heutger & Kückelhaus, 2016). Moreover, there are no globally defined standards for the development, qualification and standardization of materials for AM suitability (Binkhuysen et al., 2020). There are a few listed quality specifications, but again only a few materials can be processed within those respective specifications. So, certain materials that could qualify for AM usage are not due to lack of standardization. From an environmental perspective AM is far more advantageous than TM, but certain polymer materials cannot be recycled (Binkhuysen et al., 2020). However, most of the metals in AM can be recycled.

With evolution in production technologies, AM technologies especially have minimized production, product changeover and handling times. AM offers the possibility of flexible production. However, these AM technologies are costly and are not 100% reliable. Therefore, reliability is a challenge (Binkhuysen et al., 2020). Due to the elimination of the need to separately assemble each part, AM saves lot of time and is faster. Also, complex parts could be produced as a single assembly in AM. Yet, the quality specifications and the surface requirements put forth by manufacturers restrict the use of AM (Binkhuysen et al., 2020). To meet these requirements, tolerance limits and obtain perfect surface finish, AM products need pre-processing (prototypes) and post-processing. These processes could impact costs and time. The materials such as polymers in this sense are very good as they need limited post-production, but metals need post-production finishing so that the part dimensions are within the specified tolerances. Some AM processes possess the problem of non-uniform part strength. Sometimes, the part strength would be strong in the X and Y direction and as the layers are built one on top of the other in the Z direction, the bonds could be weak (Campbell et. al, 2011). The part application and the usage requirements help decide whether the part is suitable for AM or not. If the part must be used frequently and possesses limited strength, producing it with AM implies that frequent changes or rework is needed, which does not make sense economically. Binkhuysen et al. (2020) explain with an example of a mounting bracket that just replicating a part that was conventionally manufactured by AM isn't enough as different design principles exist for different manufacturing processes. For an AM technology to be purposeful (improving performance) and its capabilities to be utilised, it is important for designers to select appropriate part designs.

Although AM helps save costs related to additional tooling and moulds etc., it would be quite costly to produce parts in large quantities (mass production) due to the high raw material costs. AM would be best suited for personalised high value products where strong emphasis is placed on supply chain responsiveness, and in situations where supply of low quantity parts is critical and inventory costs need to be controlled. The procurement costs for an AM machine depending on the technology are quite high compared to conventional machines (Chua & Leong, 2015). With the procurement costs, maintenance and energy costs are incurred to keep the machine functioning throughout its life. Adding to this, there is the challenge of limited capabilities and awareness among the workforces. For example, specialised technicians trained in processes such as moulding or welding, would find it difficult to assimilate the knowledge of AM technologies. Therefore, the workforce personnel need to be trained regarding 3D modelling and design software and AM machine technicalities, implying that labour and training costs are high.

3.5. Chapter 3 Sub - Conclusion

This chapter helped explore the spare parts business that is constantly growing and could be a key contributor to firms' revenues and profits. The spare parts supply chains have been studied to visualize the activities that normally occur and witness how AM could make an impact on those activities (see appendix 4). The common attributes used for classifying spare parts such as demand rate, supply uncertainty, response times, part value, demand volume and demand value as stated in sub-sections 3.2.4 and 3.2.5 have been described. The nature of the spare parts business and the spare part attributes complicate spare parts management but present many opportunities to utilize new Industry 4.0 technologies like AM. Moreover, the covid-19 pandemic that led to lockdowns being enforced and disruption of economic activity has accelerated the need to adopt AM. AM could help in such unpredictable situations and companies adopting it would gain competitive advantage. The evidence for this is presented in the consulting reports of McKinsey, Deloitte, EY and PWC and scientific literature cited in this chapter (Reeves & Mendis, 2015, Khajavi et al., 2014; Sasson & Johnson, 2016; Chua & Leong, 2015) along with the industry use cases (see appendix 5). Following this, the AM technologies and the materials used have been described in sub - sections 3.4.1 and 3.4.2. AM has been compared to conventional manufacturing and its benefits and limitations have been listed in sub-section 3.4.2. The important benefits of AM are the possibility to produce small lot sizes, lesser unit costs, design freedom, parts of higher complexity and environmental friendliness. The limitations are limited material availability, reliability, high procurement, maintenance and energy costs, low AM awareness among the workforce. This provides the foundation for Chapter 4 where AM technologies and the spare parts domain have been further discussed with interviewees, factors important to each of them have been listed.

4. Empirical Findings (Interview Observations)

This chapter presents findings from the conducted interviews. The questions asked to the interviewees are similar in most cases, with minor differences due to the industry segment they represent. The firms consulted for the research study include an OEM, a printer producer, a materials producer and two solutions providers. The interviewees from these firms requested anonymity. Therefore, their names, designations and companies they represent are not described here. These details are known to the researcher and the thesis supervisors. The following sub-sections give an overview of the firms' businesses and describe their responses. The responses have been structured into AM Technology and Spare Parts. The interview questions have been attached in appendix 1.

4.1. OEM (Firm 1)

One OEM that was consulted for the research study is an equipment producer for the pharmaceutical packaging and cosmetic industries based in Italy. Their pharmaceutical equipment ranges across categories like Liquids (Aseptic filling), Powders, Creams, Labelling & Serialization and Secondary Packaging. In the liquids category, they manufacture aseptic liquid filling machines for injectable drugs and syringe handling machines. Their machines (processing, sachet filling & closing, jar filling, strip packing) are highly recognised in the powder and cream segment that demands strict adherence to regulations. Regarding the labelling, serialization and secondary packaging their machines cater to carton labelling, coding and serialization, tray forming, wrapping, case-packing and palletizing. They produce a vast range of machines pertaining to these operations in the pharmaceutical industry. Their machines consist of diverse sets of simple and complex parts.

AM Technology

Firstly, the respondent was asked about the technologies they are currently using to produce the parts, assemblies that constitute their machines. The technologies used by them are predominantly the 5-axis CNC machining technology along with the advanced laser cutting and sheet metal machines. When asked specifically about AM, the opinion was that research activities are being carried out on potential AM applications and they have adopted AM on a small scale. The respondent reasoned out that they use AM mainly for difficult parts that cannot be made and are not economical through the conventional processes. The AM technologies they mainly use are FDM, SLA and DMLS. Specifically, FDM was preferred for small size plastic parts and prototypes with less complex designs, which could be printed at a fast speed at lower costs. SLA technology was chosen by the company for complex plastic parts that demanded good surface finish, intricate features and accuracy with respect to dimensions and tolerances. For metal parts that are highly complex with geometries difficult to produce using conventional production, DMLS was chosen. The materials used are ABS, Nylon (both PA 11 and PA 12) for plastic parts, Aluminium and Stainless Steel for metal parts. Currently, AM has been applied by them largely for prototyping and very minimally for end products and spare parts. Regarding possible improvements that could be made through AM, the KPIs which they felt could be impacted are lead times, lot sizes, production costs, transportation costs and design complexity.

Moreover, the enablement of on-site and on-demand production were listed along with the precious factors that could make the whole supply chain sustainable and enhance customization. As customization is one of their core strengths, the respondent felt AM is very relevant for their business in future. Overall, the company intends to complement their traditional manufacturing processes with AM.

Spare Parts

Secondly, discussions went on about the spare parts business. The number of spare parts they manage is approximately 20,000 and this contributes to a maximum of 10% revenue for the company. The respondent reflected that their spare parts can be managed with the existing business model, however it would get difficult in the long run due to rising inventory and warehouse costs. For this reason, the respondent felt 3D Printing would be helpful. The company follows a made-to-stock as well as a made-to-order approach for spare parts.

4.2. Printer Producer (Firm 2)

A German company that produces 3D printing machines and materials was consulted for the research study. This firm caters to aerospace, automotive, medical and electronic industries. The company feels that the use cases of spare parts is very interesting and therefore agreed to participate in the study.

AM Technology

The company works mostly on SLS technology for production of both plastic and metal components. When asked the reason for using SLS, the respondent mentioned that the technology is very good in terms of the quality of the product produced with multiple lasers that can fuse the powder at a fast - scanning speed, implying that the productivity is high. Compared to the other techniques, SLS offers a consistent surface finish. Factors such as the ability to produce functional parts with highly complex geometry and the non-requirement of support structures were highlighted for SLS. SLS can be used for functional prototypes and end-use products. The respondent highlighted the growth of industrial AM would be driven by Laser AM technologies like SLS and electron beam technologies. The materials for AM were briefly discussed. It was found that the company uses Nylon (Polyamide 11 and 12) for polymer AM applications and Aluminium, Stainless steel and Titanium for metal AM. The respondent explained that the materials market now is dominated by a few players but expects the market to grow due to the scale of investments and innovations going on.

The factors affecting product quality were briefly discussed. Material was found to be a paramount factor that helps achieve good strength and mechanical properties. Along with materials, the other factors were the production technique, machine stability, ability of the software to monitor the process and provide relevant data to control the process. Also, the skills of the operator to monitor and make the changes are important.

The cost factors driving AM adoption were elaborated upon. The respondent felt that most of the costs (roughly 60%) could be attributed to post-processing, machine procurement and maintenance and the remaining would account for the material, labour and energy costs. It was reflected that AM is still not cheaper than conventional manufacturing, and AM is suitable when specific goals such as design complexity need to be achieved.

Spare Parts

Following the discussion on AM technology, the spare parts topic was discussed. Regarding the benefits of AM for spare parts, the respondent listed digital inventory and on-site production as the factors to help overcome the high costs associated with storing inventory in the warehouse. Adding on, the ability of AM to help mitigate demand uncertainty and product obsolescence were listed. Moreover, when a spare part is immediately needed for the functioning of an equipment or a component, AM would be helpful. To increase the adoption of AM in spare parts, the OEMs, design owners need to readily agree to offer their designs to customers for printing. This could lead to issues of IP infringement.

4.3. Materials Producer (Firm 3)

A chemical producing company from Germany which produces powders, filaments, photopolymers and inks that can be used in different AM processes was approached for the research study. They find spare parts management to be challenging at all stages of manufacturing, storage and shipping. At the moment, they are helping to solve the manufacturing challenge by producing materials for spare part applications, focused mainly on automotive industry. They are expanding their services portfolio to the aircraft industry as well.

AM Technology

The discussion began with the AM technologies the company is using currently to produce products. The respondent explained that they have adopted the SLS, SLA and FFF techniques for polymer applications, and for metal applications FFF and SLS techniques. The reason for adopting these techniques was that they can produce at a high speed and obtain the desired product quality. There was no specific reason for each technique, but an overall reason as to why they use these techniques was provided. To drive industrial growth of AM, the respondent listed SLS, SLA and HP Multi-jet fusion to be the main technology candidates. The design complexity and product quality could be better achieved in future with these techniques. The materials used by the firm were discussed next. The respondent listed ABS, PLA, PA 11 and PA 12 for polymer applications; metal filament (stainless steel) composites for metal applications. Regarding the status of the global AM materials market, the respondent explained that there are niche players currently who offer materials for specific applications. The respondent expects the market to grow in future with increasing research being carried out on metal and polymer applications. There are significant opportunities for growth in the materials market and the respondent expects that competition would increase in future with more players entering the market. Apart from the materials they use themselves, the respondent listed PA 11 and PA 12 to be used commonly in PBF technology and ABS, PLA and metal filaments to be used in Vat Polymerisation.

Regarding the benefits of AM technology, the respondent firstly listed the possibility of producing small lot sizes and achieving customization with AM. Further, the respondent mentioned that materials can be used in different ways to achieve the desired behaviour in the final product, meaning they could be combined with other materials in different proportions. Also, the sustainability benefit of AM was highlighted, indicating that certain raw materials like powders can be reused and need not be disposed.

Next, the respondent was asked to highlight the factors affecting AM product quality. The respondent mentioned material to be the main factor affecting product quality. For achieving good strength and mechanical properties, it is important that materials are used in correct proportion and combined as composites when required. Adding on, the respondent expressed that the machine is very important, meaning that it should be stable and reliable. Furthermore, the respondent spoke about the software used in the machine that would definitely help in ensuring quality. The main challenge to product quality is the machine stability. Adjustments should be made available to react in real-time, as quickly as possible.

The cost factors affecting AM adoption as put forth by the respondent were machine and material costs that account totally for 70%, and the rest would be attributed to labour and energy. The respondent reflected that currently AM is very expensive and it makes sense to use it only when small lot sizes and high variety is desired. Adding on, the respondent expressed that even today in most cases, conventional manufacturing make sense as it is more economical. The respondent explained that costs per part in AM would reduce if material costs decrease and processing speeds improve.

Spare Parts

When the applicability of AM for spare part production was discussed, the respondent found the use cases of Daimler Evobus and Deutsche Bahn to be very interesting as AM enables storing inventory online, indicating that in the long run inventory need not be stored in warehouses and possibly warehouses could be eliminated. Therefore, costs associated with warehousing can be reduced and products do not have to travel long distances from factory to the customer. So, transportation could be made more sustainable and economical. Moreover, the respondent highlighted the ability of AM to help in reacting to sudden demand changes through on-demand, decentralized production. Furthermore, in situations where short lead times are desired and equipment downtimes are not tolerated, the respondent expressed that AM would be suitable.

The respondent mentioned that the main challenge for AM adoption in spare parts is that AM produced parts should possess comparable strength and physical properties as the conventionally produced parts. Further, the respondent highlighted that the processes used by customers must comply with the AM production quality standards followed in industry.

4.4. Solutions Providers (Firms 4 and 5)

Two solutions providers in the AM domain were consulted due to their extensive AM knowledge and their interest in the spare parts business which is growing and could potentially be an area of application. One company helps manage digital supply chains of manufacturing companies by addressing security, IP, authenticity and traceability needs. The other company provides a platform to upload design files, make modifications, select the materials and select the appropriate producer.

AM Technology

Respondents from both firms explained that the market for AM technology is constantly growing and significant investments are being made for innovation and R&D on 3D printing technologies. They highlighted that Powder Bed Fusion techniques like SLS has grown significantly and become very important in a short period of time for both metal and plastic applications. With respect to SLS, factors such as consistent surface finish, creation of highly complex geometry, less dependence on support structures and high process productivity were listed. The other techniques that have seen rising adoption are the HP multi-jet fusion technology (Binder jetting technique) due to the high precision it offers and photopolymerization techniques like SLA.

Coming to benefits offered by AM, the respondents felt that the following are important. Firstly, the possibility of producing parts as and when customers need it at their respective locations along with the ability to produce in small quantities economically. Secondly, what is important is the concept of distributed manufacturing that helps minimize inventory and logistics costs.

When asked about the materials for AM, both respondents highlighted that plenty of R&D and innovation is going on in the AM materials market, be it plastic-based AM or metal-based AM. One company explained there are there are limited players in the market now, indicating the market for AM materials is niche compared to Traditional Manufacturing. The materials that are commonly preferred were picked by one respondent as follows: Filaments - ABS and PLA; Powders - Polyamide 11 and 12; Metals - Aluminium, Titanium and Stainless Steel. The other respondent chose not to comment on the materials as their organization isn’t associated with it.

The possibilities to produce a product with certain materials were discussed. Both the respondents felt that it is possible to produce both prototypes and end products with plastics and metals. The aircraft, automotive and defence industries have displayed the capability to produce both prototypes and end products. However, they feel that there are challenges. Now it is difficult to achieve the physical and mechanical properties in all the metal components that are AM produced. Also, they mentioned that AM stands a good chance in specific applications where precision, complexity and less weight is desired. When the product quality topic was discussed, the following were explained by them. Firstly, both felt that the chosen materials matter very much across the entire product lifecycle. It is indeed important to have the right material. Secondly along with materials, the technology and the machines used matter a lot. The software used throughout the lifecycle impacts quality. The software could be sensitive sometimes and managing the entire process workflow is challenging. Thirdly, the workers need to be trained to use the software and operate the machines. Regarding the challenges to product quality, both respondents explained that the physical properties of the AM materials, stability and repeatability of the AM processes and the post-processing operations matter a lot.

Regarding the cost drivers, both respondents agreed that equal investments need to be made in materials, machine, labour and processes. One of the respondents went on to explain that AM helps minimize tooling costs and the number of parts to be printed does not matter in AM.

Spare Parts

Pertaining to spare parts, the respondents listed some benefits of AM. The possibility to produce on-site, near the customer would help save logistics costs. Also, tooling and moulding costs can be minimized. In certain situations, suppliers would require manufacturers to sign a contract for a specified quantity of spare parts. Only then will the suppliers produce and deliver the spare parts to the manufacturer. Thereby, the manufacturer will end up procuring a huge quantity of spare parts and incur high warehousing costs. AM could help cut down on these storage costs. Moreover, when a spare part is immediately needed for the functioning of an equipment or a component or when products become obsolete, AM would be helpful.

When the respondents were asked about what needs to be done in order to increase the adoption of AM by the spare parts sector, one respondent said that producers need to think about managing spare parts for products to keep them functional over the service life. The other respondent said that investments need to be made in hardware, software and materials and the processes should be repeatable in the long run. Also, this respondent highlighted that the AM technology awareness for spare parts is low. So, AM knowledge should be disseminated to all employees across organisations. Along with this, OEMs should be willing to share their digital files with customers or external partners.

4.5. Chapter 4 Sub – Conclusion

This chapter explained in detail what the respondents think about AM for their respective businesses. The AM technologies and materials which they favour for the growth of their businesses and the reasons for it have been highlighted. For my study, it is important to understand which of the AM technologies would be favoured for industrial adoption (for end products and spare parts) given the advantages and limitations. Therefore, each respondent was asked to list the technology they are using and the technologies that are being used in the market, and describe the benefits or drawbacks they are experiencing. Moreover, issues like cost drivers and product quality driving AM adoption have been listed here. Respondents' insights on the KPIs that could be improved (lead times, inventory costs, obsolescence etc) in the spare parts business with AM have been noted. These have been analysed further in the successive chapter.

5. Analysis of Interviews and Literature Study

This chapter explains the market study by consolidating the findings from the interviews (as discussed in the previous chapter) on AM Technology, Materials, Factors affecting AM Product Quality, Cost drivers for AM adoption, benefits and challenges to AM in spare parts and supports it with scientific literature and industry use cases (sections 5.1 – 5.4). The industry use cases have been described in detail, which can be found in appendix 5. The support process which is relevant to this chapter is explained in figure 5.1 shown below. The perceived usefulness as shown in the figure are described in this chapter starting from section 5.5 onwards.

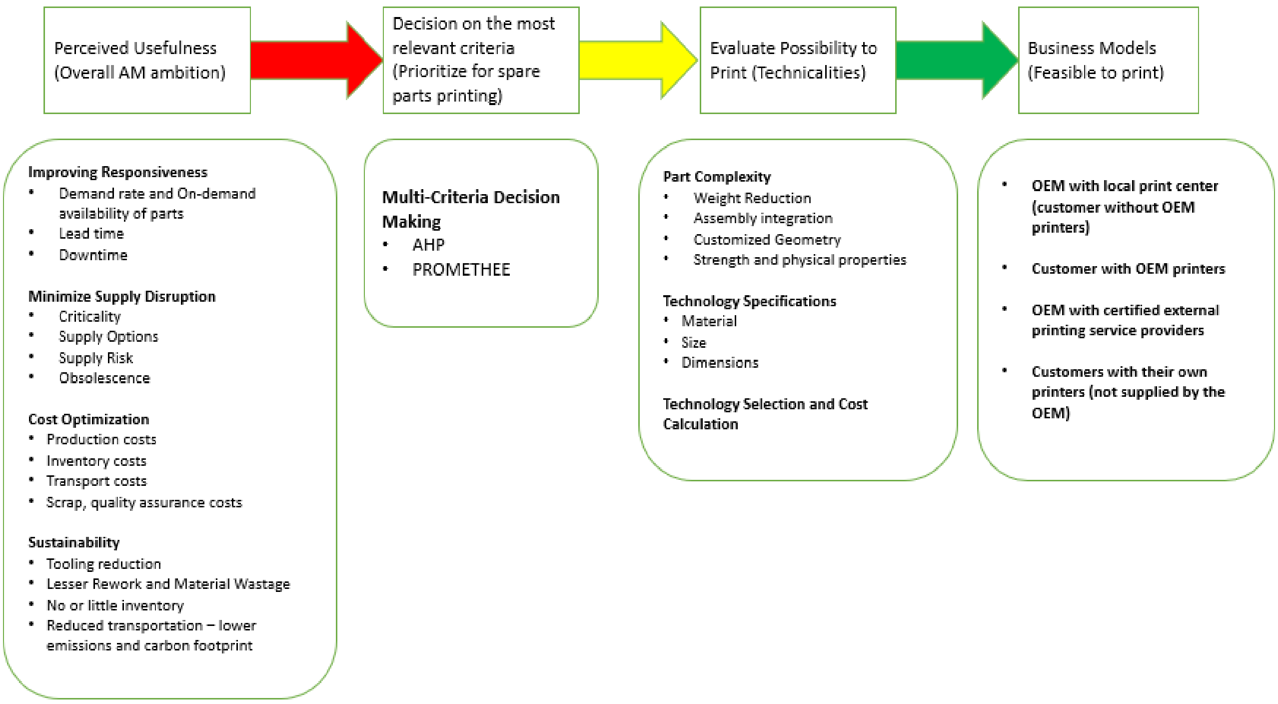


Figure 5.1: Support Process (own illustration)

5.1. AM Technology

The responses from the interviewees (firms listed previously in chapter 4) indicate a high preference (Figure 5.2) for Powder Bed Fusion techniques such as Selective Laser Sintering (SLS) and Direct Metal Laser Sintering (DMLS) to carry out AM production activities for both metal and polymer - based applications. The overall opinion expressed was that PBF technology is driving the industrial adoption of AM due to its ability to produce complex designs, high accuracy, non-requirement of support structures etc. The most recent scientific study carried out by Vafadar et al. (2021) on metal AM technologies shows that 54% of the metal AM market is dominated by PBF technology (see Figure 5.3).

Table 9: Responses for AM Technology, advantages and drawbacks of each technology (own illustration)

AM Technology	Participant Responses (Out of 5 participants)	Advantages	Drawbacks
FDM or FFF	2	Fast speed, Low costs	Low Accuracy, Poor Surface Finish
SLA	4	Good surface finish, Intricacy, Accuracy	Small Build Chambers, Low Material Compatibility, High Cost of Photopolymer
SLS and DMLS (PBF)	5	Highly Complex Geometry and Designs, Absence of Support Structures, High Process Productivity, Consistent Surface Finish	Post Processing is required, Skilled Workforce is necessary, High overall costs
Multi Jet Fusion (Binder jetting)	1	High Precision, Cost effective, Fast speed	Poor Mechanical Properties

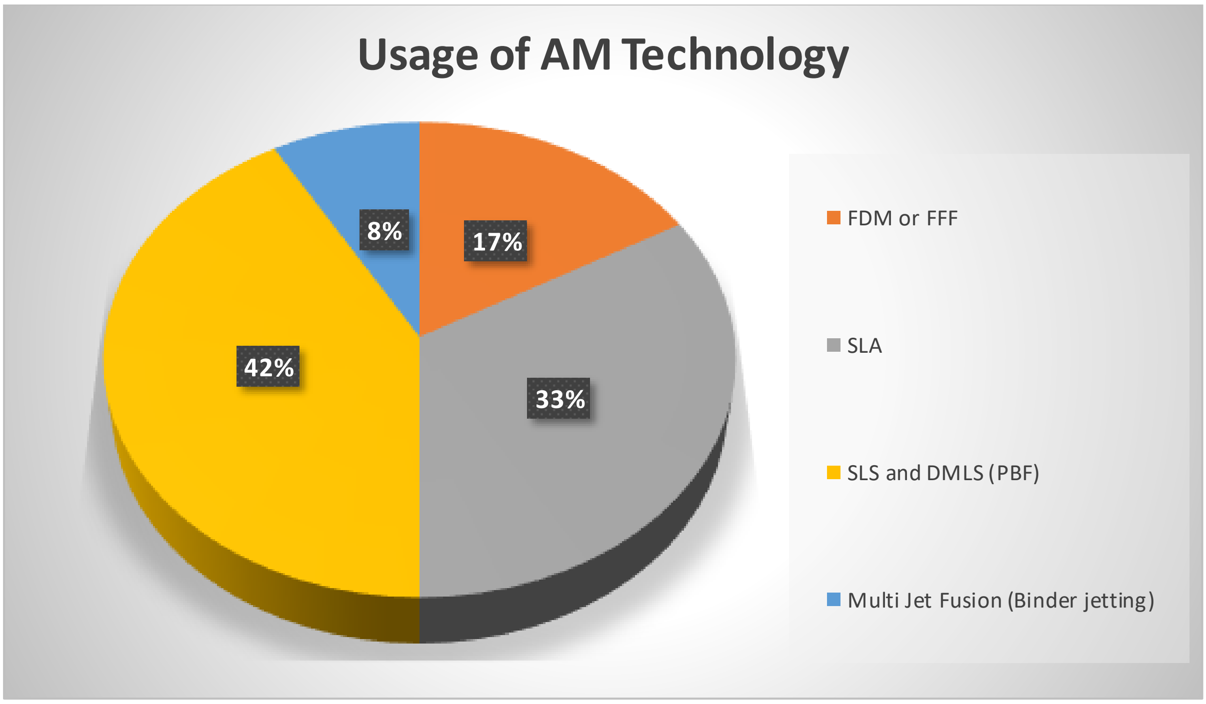


Figure 5.2: AM Technology Preference among Interviewees (own illustration)

-

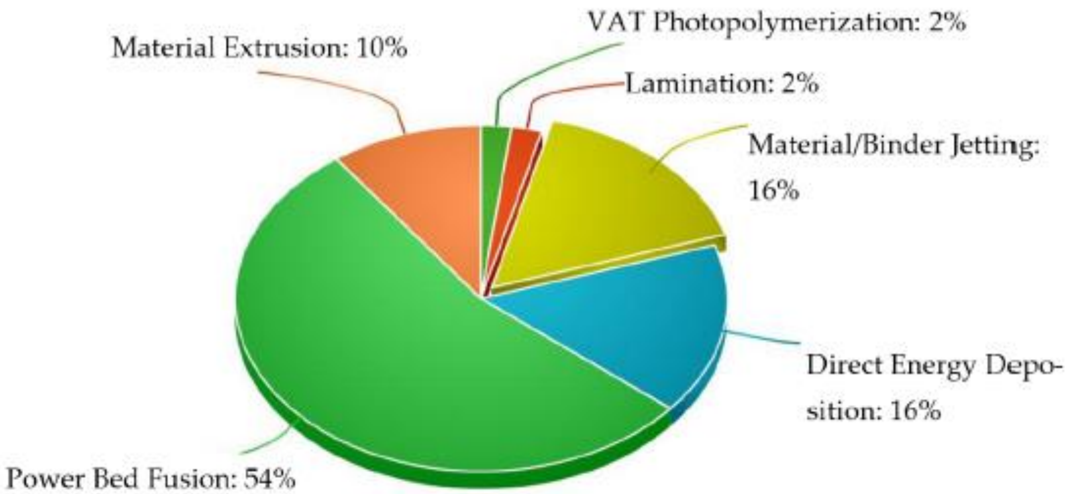


Figure 5.3: AM technology recent market study (Vafadar et al., 2021)

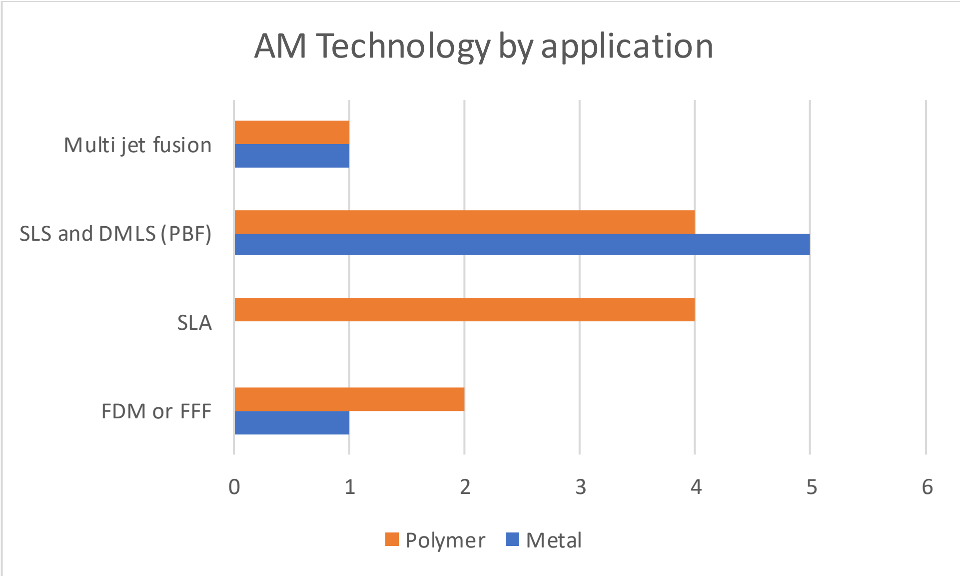


Figure 5.4: AM Technology by application (Listed by interviewees)

Adding on to the benefits listed by the interviewees in Table 9, Chen et al. (2017), Abdulhameed et al. (2019) & Vafadar et al. (2021) highlight benefits of PBF such as high processing speed, high material compatibility, high strength and mechanical properties, non – requirement of support structures, dimensional accuracy of +/- 0.3mm and tolerance (+/-) 0.05 – 2.5 mm. These authors provide a list of drawbacks of PBF like its high costs, size limitation, distortion and surface finish which depends on the powder grain size. Nath & Nilufar (2020) and Alghamdi et al. (2021) illustrate the use of PBF for polymer - based applications, namely SLS. Due to the absence of support structures and high speed, SLS is preferred for polymer applications. There exist many use cases for PBF like BMW (metal), Bugatti (metal), Rolls Royce, Daimler EvoBus (polymer SLS), Mercedes Benz Cars (metal), Audi (metal), Ford and Porsche (Laser Metal Fusion). The highly noted ones are Daimler Evobus using EOS SLS Technology to print spare parts (polymer type) and Mercedes Benz using polymer PBF for spark plug holder and sunroof rollers for some of its cars, Bugatti using PBF (SLM process) to print the brake calliper, Porsche using Mahle's Laser Metal Fusion (PBF) to print the engine piston, Audi using metal PBF to produce spare parts like water connecting pipes for the W12 engine. BMW and Rolls Royce already uses PBF technology to produce metal parts. In the aircraft sector, the notable use cases are Safran which desired to utilize metal PBF (SLM process) in the gearbox to reduce the number of assembly parts from 12 to 2, GE Additive procured highly advanced laser AM machines to produce the Leap engine fuel nozzle for use in civil aircraft. This AM produced fuel nozzle has replaced an assembly of 20 components with one single component with lesser cost, lower weight and better performance. NASA utilised the SLM process to produce the metal rocket injector, bringing down the number of parts from 115 to 2. Liebherr Aerospace additively produced (EOS SLS process) the nose landing gear and the valve block for Airbus, achieving a weight reduction of approximately 30%, stiffness of over 100% and performance comparable to the conventionally produced one. Along with the above PBF techniques, there exists another PBF Technique called Electron Beam Melting which has not been listed by the interviewees, but has been embraced by the aircraft industry with big players like Sciaky and Rolls Royce.

The next technology in preference was Vat Polymerization, namely SLA (see table 9 and figure 5.2). Stereolithography (SLA) was listed by the interviewees mainly for polymer – based applications (Figure 5.4). Frandsen et al. (2020), Nath & Nilufar (2020) and Chiririwa (2021) illustrate the benefits of SLA like consistent surface finish, high accuracy, low energy consumption and quick processing speed which makes it ideal for polymer applications. According to the figure 5.3 above, the use of SLA for metal applications is limited due to the low strength of the parts produced and high post processing time. Metallic parts are not made using SLA, but parts with metal content (metallic parts with photopolymer resins) are made. This combination helps in achieving better thermal and mechanical properties with SLA Vafadar et al. (2021). The SLA use cases include Ford that adopted Formlabs SLA to replace broken push buttons from electronic devices, General Motors and Fiat Chrysler for tooling and parts (Boissonneault, 2021).

The fused deposition modelling (FDM) technique based on material extrusion does not have much prominence among the interviewees. The purpose for using FDM is mainly for small & simple parts and the low cost of the overall process. The HP multi-jet fusion technique (binder jetting) has only been spoken about by one participant. According to the recent study as shown in figure (Vafadar et al. 2021), Material Extrusion accounts for 10% and Binder Jetting accounts for 16%, indicating that both techniques have a lot of potential for future growth. This is visible with many use cases. Pertaining to FDM, there are certain use cases with Volkswagen, General Motors, Lamborghini, Continental AG and BAE systems. Starting from the design of the corrado adapter, Volkswagen has gone on to produce high performance parts with structural requirements like gearshift knobs and mirror mounts. The FDM Machines helped Volkswagen save $160,000 in tooling costs in 2016, which is expected to increase every year. In 2018, Volkswagen set a goal to produce at least 100,000 spare parts every year. Lamborghini and General Motors have used Stratasys FDM technology for prototyping and tooling. Continental AG recently partnered with Stratasys to use their FDM technology for producing gluing jigs and X-ray guides. BAE systems too uses Stratasys FDM for producing aircraft ground equipment parts. Marshall Aerospace has adopted FDM to produce spare parts such as air conditioner ducts, knife holders and switches. Regarding HP Multi jet fusion, BMW has adopted it for producing the guide rail for the i8 roadster (polymer MJF) and Rolls Royce has adopted the same (polymer MJF) for its interiors. Volkswagen intends to use the HP MJF technology for its mass-produced vehicles. General Motors partnership with HP and GKN Powders for the goes a long way in the industrialization of the HP MJF technology (Boissonneault, 2021).

The Directed Energy Deposition technique (LMD, LENS etc) was not listed by any interviewee. However, it does have increasing adoption particularly in the aircraft industry. Some of the advantages of DED are high deposition rates at low-resolution, high-density parts with strong mechanical properties, possibility to use for MRO operations, large size complex parts etc. Some of the use cases of DED are Marshall Space Flight Centre producing the nozzles for rocket engine applications, Norsk Titanium producing components for the Boeing 787 Dreamliner, European Aviation Safety Agency for MRO activities due to its high accuracy (Yusuf et al., 2019).

5.2. AM Materials

Along with AM technologies, questions were put forth to respondents regarding the materials they use in their respective AM activities. For polymer applications, Nylon PA11 & PA12, ABS and PLA were listed. For metal applications, Aluminium, Titanium and Stainless Steel were listed. The advantages and drawbacks of each of these materials have been taken from the literature and are listed below in table 10. Also, it is important to note the AM technologies supporting the use of these materials.

Table 10: Usage of AM Materials as stated by the interviewees (own illustration)

Materials	Participant Responses (Out of 5 participants)	Advantages	Drawbacks	Supporting Technologies
Polyamides (PA 11 and PA 12)	4	High Chemical and Mechanical Resistance, High Shock Resistance, Strong, Rigid and Flexible	Low Stiffness and Heat Resistance, Low Resistance to UV light, Needs drying before processing	FDM, SLS, Multi-jet fusion
ABS	3	High rigidity, good impact resistance even at low temperatures, good abrasion and strain resistance	Scratches easily, Poor solvent resistance, can suffer from stress cracking in the presence of some greases	FDM, SLS
PLA	2	Biodegradable, consistent, good part stiffness, cost-effective	Low heat resistance, can fail under high pressure	FDM
Aluminium	3	High load bearing capacity, Low weight and good corrosion resistance	Low melting point, lower heat resistance compared to Titanium	SLS, DMLS, FDM, SLA, EBM, DED
Titanium	3	Low specific weight, biocompatibility, high corrosion resistance and ductility	Higher cost compared to stainless steel and Aluminium	SLS, DMLS, EBM, DED
Stainless Steel	3	Hardness, ductility, high corrosion resistance and high fatigue resistance		SLS, DMLS, FDM, EBM, Multi-jet Fusion

5.3. Factors affecting AM product quality and Cost drivers for AM adoption

The factors affecting AM product quality listed by the interviewees are Materials, Machines & Production Technology, Software Monitoring and Worker Knowledge. The cost drivers mentioned by them are materials, machines, labour, energy and post-processing.

The materials available for metal applications are increasing, however today they are in limited number (Vafadar et al., 2021). Some of them are Copper, Aluminium alloys, Stainless Steel, Titanium alloys, Nickel alloys and Inconel. Research is being carried out on nanomaterials and metal composites. In metal AM, a lot of potential exists to achieve design complexity and good strength and other physical properties. But in many situations, the material properties change post production, the behaviour of the materials vary under different loads and distorted geometry occurs (Kok, Y. et al., 2018, Kumar, H.A. et al., 2019 & Seifi, et. al., 2017). Often post processing is required in metal AM to detect and eliminate voids and porosity, ensure that the part deviation from actual size and geometry is minimal. The cost of metal powders ranges from \$350-\$550 per kg, indicating that metal AM material costs are very high (Gregurić, 2019). For polymer applications, materials are available in plenty but they need to reinforced with fibres like Kevlar, Carbon fibre and Glass fibre to achieve the required strength for use in load bearing applications (Nath & Nilufar, 2020). Often, the polymer printed parts by themselves are weak compared to the conventionally produced ones. Nylon PA12 powders cost between \$45 - \$75 per kg and PLA filaments cost between \$20 - \$70 per kg, indicating that polymer AM material costs are affordable (Gregurić, 2019).

The machines, production technology, software and worker knowledge were given equal importance along with materials. Regarding machine, the maximum build volume restricts the sizes of parts that could be printed. The ability of the machine to withstand heavy loads over long periods (machine stability) is to be considered. The product quality varies according to the machine stability and the selected technology. For example, PBF techniques require post processing to achieve good product quality. Furthermore, the software used across all AM machines must aid manufacturers in build planning, build monitoring and feedback control to ensure machines' repeatability, consistency with respect to geometry, surface finish and physical properties (Wing et al., 2017). According to Vafadar et al., (2021) the machine costs today are very high ranging from \$115,000 to \$1.9 million. Added costs with regard to post-processing, repairs & maintenance, electrical works and heat furnaces need to be taken into account. Post-processing operations normally performed are washing, sintering, heat treatment, cold rolling and laser processing. Moreover today, investments need to be made in training workers on AM processes, materials, software and safety standards. To further the awareness of AM and increase its adoption, educational institutes like MIT, University of Texas; industry players like Stratasys are organizing training courses (Pei, E. & Loh, G.H., 2019 & Simpson, T.W. et al., 2017)

5.4. AM for Spare Parts

When the interview participants were asked about the benefits that AM could bring about for spare parts, the following benefits were stated by them as shown in the table 11. These will be further explained in detail in the Perceived Usefulness section.

Table 11: AM benefits for spare parts (own illustration)

Benefits of AM for spare parts	Participant Responses (Out of 5 participants)
Part Complexity	1
Part Criticality	3
Production on demand (Address Demand Uncertainty)	4
Mitigate Product Obsolescence	2
Cost Reduction (includes production, inventory and transport costs)	5
Total number of participants in the study	5

The challenges to AM adoption for producing spare parts as put forth by the interview respondents are shown in the table below:

Table 12: Challenges to AM adoption in spare parts (own illustration)

Challenges to AM adoption in spare parts	Participant Responses (Out of 5 participants)
Technology Awareness	1
IP Issues	2
Cost and ROI Considerations	2
Strength and other physical properties	2
Total number of participants in the study	5

Technology awareness, costs and ROI, strength and other physical properties have been discussed previously. Among the participants, the willingness of the design owner to provide the design file to the customer due to IP concerns was common. The study by Widmer & Rajan (2016) from Deloitte on 3D printing IP issues throws light on liability where questions arise to how the customers could claim compensation in case of a failed product or faulty design, whether to blame the design owner or the printer service provider. In case of Atos however, due to the AIP blockchain platform, these issues would be minimized.

5.5. Perceived Usefulness of AM

Upon completion of the discussions on AM technologies, materials, factors affecting AM product quality, cost drivers and the application of AM in spare parts, the perceived usefulness of AM for spare parts was discussed. To introduce perceived usefulness to the reader, it is best to elaborate the technology acceptance model first.

According to Davis (1996), the users' intention to use a technology is the best predictor of the actual technology usage. In the Technology Acceptance Model (TAM), the users' intention to use a technology is measured by Perceived Usefulness, Perceived Ease of Use and the external variables affecting these measures. These measures have been validated in many studies (Hsu & Lin, 2008). When the TAM is applied to organizations, many variables need to be considered than when it's applied to individuals. In organizations, decision making involves many individuals who possess different ideas and opinions. Decisions are often made taking into account the feedback of all members. Especially when new technologies like AM need to be applied in an organization, time must be allocated for group meetings to discuss the possible effects of AM adoption, along with financial support which is required to procure resources (machines, material, software) and labour to ensure smooth adoption. Many industrial organisations have utilised TAM successfully to predict technology adoption (Chatzoglou et. al., 2010, Kim, 2009 and Yarbrough & Smith, 2007). The TAM can help organizations understand the variables affecting Perceived Usefulness and Perceived Ease of Use to carry forward the installation and application of a technology.

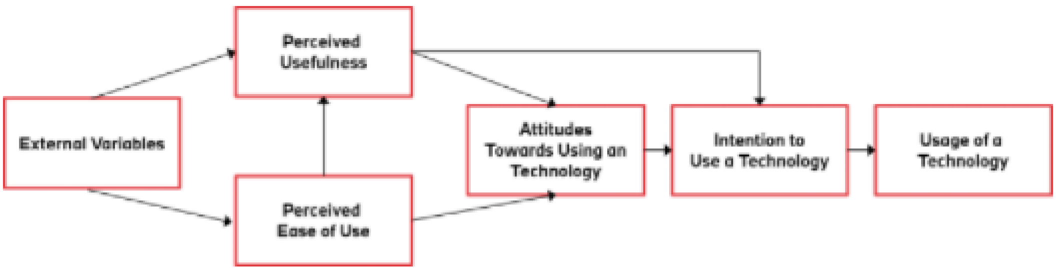


Figure 5.5: Technology Acceptance Model (Davis, 1996)

In this study, there will be focus on the perceived usefulness factor. Davis (1996) describes perceived usefulness as the degree to which a person trusts that a particular technology could enhance their work performance. Davis (1996) considered perceived usefulness to be a summation of all possible benefits or advantages that a technology could bring about. Venkatesh et al. (2003) and Davis (1989) used factors such as productivity increase, performance enhancement, speed of work and effectiveness to measure perceived usefulness. Regarding AM technology for spare parts, perceived usefulness has been explained by the following concepts:

- Increased Responsiveness
- Minimized Supply Disruption
- Cost Optimization
- Part Complexity

- Sustainability

The criteria for all the concepts of perceived usefulness have been chosen by the interviewees from the firms consulted for the study (same as chapter 4). Firm 1 corresponds to the OEM; Firm 2 corresponds to the printer producer; Firm 3 corresponds to the material producer; firms 4 & 5 correspond to the solutions providers.

5.5.1. Increased Responsiveness

The concept of increased responsiveness which is the ability of a producer (manufacturer/supplier) to react to uncertain situations such as sudden changes in demand or supply that may occur, at a fast rate to ensure customer satisfaction is explained by the criteria listed in table 13. The criteria are discussed in detail along with the application of AM to help fulfil the criteria and supported with industry examples.

Table 13: Increased Responsiveness (own illustration)

Increased Responsiveness	Firm 1	Firm 2	Firm 3	Firm 4	Firm 5
Safety stock and inventory					
Availability of parts (on demand)	X	X	X	X	X
Downtime		X	X		X
Demand rate			X		
Production and Delivery Lead time	X	X		X	X
Replenishment Lead time				X	X

5.5.1.1. Demand Rate and Availability of parts on-demand

Spare parts are sometimes observed to have unpredictable demand patterns which are intermittent and lumpy as shown in figure 5.6 (Boylan & Syntetos, 2010). Demand rates are mostly low and volatile for spare parts (Bacchetti & Sacchani, 2012). The slow-moving spare parts with intermittent demand are described as ‘long-tail’ components (Topan & Bayindir, 2012). The quantities of spare parts demanded will not be static but will vary highly. These demands could be seasonal as well. The demand seasonality together with the quantities or lot sizes can make spare parts management and forecasting more difficult. Adding on to this is the issue of demand uncertainty which is determined by how many of the finished products fail and at what frequency they fail (Khajavi et al., 2014). Factors like the extent of product usage, quality of maintenance offered, and the failure rate contribute to the demand uncertainty (Wagner et al., 2012). Most often, the demand for spare parts occurs in irregular intervals, which is always unexpected for any firm. Nowadays, these issues are amplified by the constant introduction of new products that have short lifecycles.

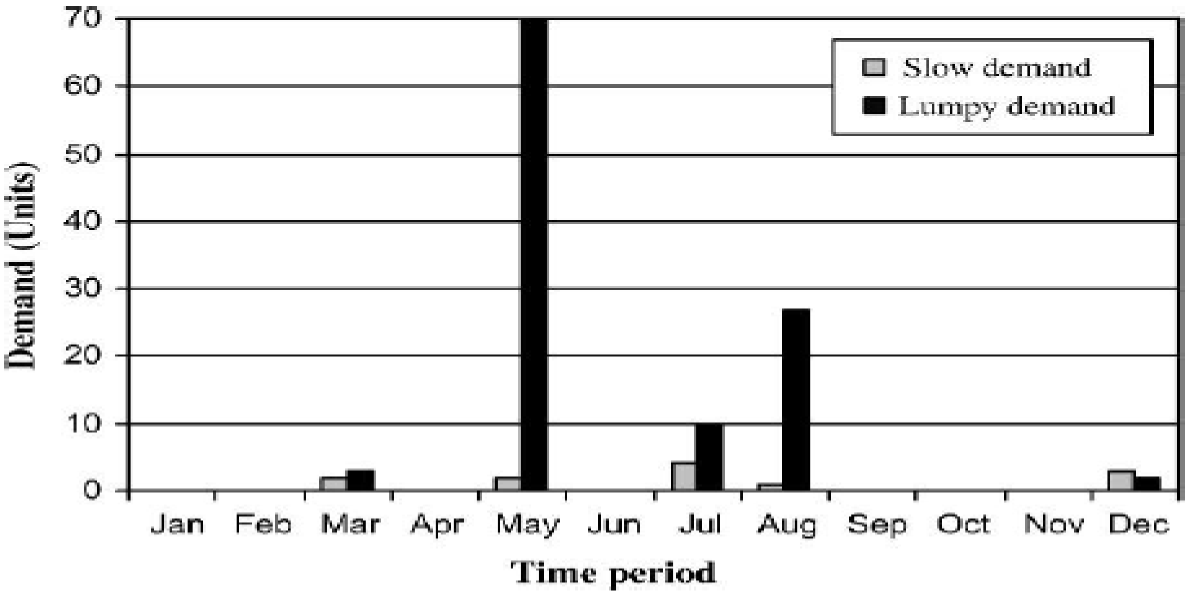


Figure 5.6: Intermittent and Lumpy Demand patterns (Boylan & Syntetos, 2010)

AM enables printing on demand, reducing the need to keep spare parts in stock (Berman, 2012). The demand rate fluctuations and the uncertainty mentioned above can be mitigated. According to the 2016 DHL study, firms in the future may not have to store spare parts in warehouses and incur high inventory storage costs (Heutger & Kückelhaus, 2016). When there is an urgent need to be fulfilled, the enablement of on-demand production through AM makes it possible to respond to unexpected demand. With this, firms can complement their existing make-to-stock strategy with the make-to-order strategy. Replacing the existing make-to-stock strategy entirely is still difficult.

5.5.1.2. Lead times and Downtime

Many a time, sub-parts and raw materials for assemblies are ordered/procured through external suppliers. The processing and assembly may take place across various units in the factory. This requires planning across all the factory departments while producing and delivering the final product. Sometimes, when the demand for certain products is very high, many components and assemblies get produced in batches to reduce the overall production cost. Due to the product demand being high, machines would get overloaded with capacity and this might to long waiting times (Knofius et al., 2016). Adding on to this, the tooling that is required in conventional production consumes significant time, impacting the production lead time (Hopkins & Dickens, 2003). In the conventional manufacturing scenario, when products are made and sold and need to be serviced after a certain usage period, the spare parts or replacement parts would take time to be produced and delivered to the customer as distances between the production facility and customers are large. Also, the suppliers would be geographically dispersed, leading to high replenishment lead time. In this situation, AM could be of good use because parts would be made on demand near the customer location with the available design files and delivered in much quicker time. AM has the potential to improve lead times (includes production, delivery and replenishment) and customer satisfaction. For example, Deutsche Bahn prints spare parts on demand and for certain parts like the steel sand box, lead time was reduced from 18 months to 3 weeks. Deutsche Bahn prints many other parts such as coat hooks, spare aluminium headrests and a spring-loaded locker assembly. Siemens Mobility was able to bring down the production lead time by about 95% with AM. Along with the lead time improvement, AM can help reducing the equipment downtimes due to the presence of various business models that make it possible to print spare parts near the customer, with the availability of appropriate technology and materials.

5.5.2. Minimized Supply Disruption

Minimized supply disruption has been explained using the criteria of criticality, supply options, supply risk and obsolescence as shown in Table 14. When these issues occur, AM could possibly help to mitigate them. Supply disruption mainly refers to breakdown in the production process (includes supply of raw materials) and delay in delivery of products to customers, which could lead to longer lead times and equipment downtimes. The supply disruption concept has been chosen because these scenarios arise in the traditional manufacturing scenario and cause problems. Moreover, the impact of disruption is accelerated and its effects have been seen in the covid-19 pandemic. In unpredictable times like these, factors like criticality, supply risk become problematic. This is where AM could be helpful in minimizing supply disruption.

Table 14: Minimized Supply Disruption (own illustration)

Minimized Supply Disruption	Firm 1	Firm 2	Firm 3	Firm 4	Firm 5
Criticality	X	X	X		
Supply options				X	
Supply risk		X		X	
Obsolescence	X		X		X

5.5.2.1. Criticality and Supply Options

Criticality refers to the effect that a part has on a system, when it gets worn out or breaks down (Jouni et al., 2011). According to Wahba et al. (2012), a part is considered critical if it is used for a specific purpose in a production process and can lead to equipment shutdown when it fails. The study by Molenaers et al. (2012) highlighted criteria for the criticality of spare parts such as Equipment criticality, probability of item failure, replenishment time, number of suppliers available and the availability of technical drawings. Based on this, spare parts were classified into the categories – Vital, Essential and Desirable. Furthermore, the levels of criticality for spare parts were discussed that is high, medium, low and no criticality. For items in the essential and durable categories, where the part failure can occur with 6 months or between 6 months to 1 year, replenishment time could range from 2 days to maximum 1 month, and the supply options could vary from just 1 to 3 suppliers to sometimes greater than 3 as well, AM would be helpful to address the immediate availability needed considering the duration of failure. The fact that failures occur in such short intervals of time reflect the need to have spare parts on-demand, failing which downtimes will occur causing dissatisfaction to customers. For items in the 'Vital' category, where supply options are limited to maximum 1 supplier, replenishment times are more than 1 month and technical specifications are not available, the need to use AM is equally justified. Moreover, for certain spare parts which belong to the high and medium levels of criticality where unavailability is mostly not desired, quick supply of materials is needed with almost zero risk, AM could be very useful. Therefore, the on-demand and on-location capability of AM could be used to respond quickly to part failures and address the problem of limited supply options in these situations. Additional supply options provided with AM could help in minimizing supply disruption.

5.5.2.2. Supply Risk and Obsolescence

Most often, OEMs/manufacturers are required to satisfy a minimum order quantity for spare parts, failing which suppliers would discontinue the supply of spare parts. If the demand overall is not very high, suppliers could also stop production of those spare parts. This could lead to massive supply risks. If OEMs produce spare parts on their own, the conventional mode of production would require them to produce in batches for higher cost efficiency. Due to innovations and short product life cycles in certain industries, new products constantly enter the market and many products get phased out. The demand for spare parts to keep these products functional is normally uncertain as discussed before. Firms may or may not be able to service the products which become obsolete over time, due to the discontinuation of spare parts production and supply. AM could provide the required flexibility to help deal with the issues of obsolescence and minimize supply risks.

5.5.3. Cost Optimization

The costs associated with 3D printing of spare parts have been broken down into production, quality assurance, scrap, inventory, safety stock and transportation costs as shown in table 15. They have been explained in detail below. AM could compensate for its high production costs by offering savings in terms of scrap, inventory, safety stock and transportation. As highlighted below in the use cases, firms currently intend to complement their conventional manufacturing processes with AM to reduce inventory & safety stock costs and improve lead times.

Table 15: Cost optimization (own illustration)

Cost optimization	Firm 1	Firm 2	Firm 3	Firm 4	Firm 5
Production and Post processing Cost	X	X	X	X	
Quality assurance related costs			X	X	
Cost for scrap		X		X	
Inventory costs	X	X	X	X	X
Safety stock costs	X			X	X
Transportation costs				X	

The aircraft, automotive and industrial equipment industry spending lots of money on Maintenance, Repair and Operations indicates the importance of the aftersales or spare parts market. Often these firms have to make trade-offs between being responsive or cost-effective. To balance both, firms end up accumulating a lot of inventory, almost equal to 10% of the revenue (Thomas & Gilbert, 2015). This adds up a lot to inventory and safety stock costs. When it comes to spare parts, the irregular demand or infrequent orders leads to excess accumulation of infrequent spare parts that consume physical storage space, incur high rental costs, taxes and insurance. Sometimes, demand can occur in big numbers for a particular set of parts for which excess safety stock should be maintained that again adds up to the overall inventory costs. To produce these respective parts on-demand through conventional production, it would be very costly and consume a lot of time. This is because raw materials will have to be ordered in fixed quantities from the suppliers, meaning that the excess raw material that's not used would be stored as inventory. Also, when these parts are produced in-house, many of them that are not sold will be stored. Here AM could provide the necessary ability to produce on-demand without storing inventory and therefore help in bringing down those inventory and safety stock costs.

Normally in many cases, raw materials and spare parts for assemblies are ordered through suppliers across the globe. The final assembly is done at one single facility. This inventory will have to be transported from the supplier location to the assembly facility, which incurs high costs. In case of any delays, extra transport costs are incurred. AM allows the building of an entire assembly at once, without having the need to order and receive parts from different locations to complete an assembly. This property of AM could help in inventory and transport costs. However, the strength and other physical properties of the parts produced through AM would be in question.

When it comes to production costs, machine, material and post-processing costs are the highest for AM (Thomas & Gilbert, 2015). Now, AM production is still costlier compared to conventional manufacturing. The benefit that AM provides with respect to assembly costs is the reduction in tooling and injection moulds. AM not only helps bring down assembly costs but also assembly time. AM provides an important benefit of reducing costs associated with scrap. In conventional manufacturing, scrap and rework can be very costly. When testing prototypes conventionally, there would be a lot of material wastage and costs associated to it. If firms are not ready to completely adopt AM, they could adopt AM for testing prototypes to save those material wastage costs. Costs for AM are expected to be more competitive in the future, with increased adoption, higher economies of scale and lower material costs. Moreover, quality assurance costs need to be considered when switching from one process to another.

Many firms (described in the following sentences, not interviewees) are showing the interest and realizing the importance of AM to minimize production, inventory and safety stock costs and lead times. Daimler began with the NextGenAM system to 3D print complex metal parts aiming to save at least 50% on production costs. Daimler is also exploring the digital inventory concept for spare parts to save on inventory and safety stock costs. Daimler EvoBus achieved faster lead times, reduced inventory and tooling costs with AM. Continental AG aims to use 3D printing on a larger scale for jigs and fixtures, complementing the conventional processes. In the aircraft industry, Satair, MTU aero engines and Liebherr were able to reduce the cost, production time per piece and overall lead time with AM. In the naval industry, the Singapore Government and firms like ThyssenKrupp have started storing spare parts inventory digitally and producing parts on-demand to cut inventory costs and improve lead time.

5.5.4. Part Complexity

Part complexity refers to the ability to create complex parts with varied geometry without any restrictions. This is normally not achievable in conventional production. The concept of part complexity which can be achieved through AM and is primarily desired in industries from a technical standpoint has been addressed using the criteria put forth in table 16. Weight reduction and assembly integration is preferred in the aircraft industry whereas the automotive industry mostly prefers the creation of difficult parts and customized geometry that can be made possible with AM. For AM production, parts' functionality and design needs to be considered, and complexity would not be an issue. AM enables design for function, which would normally be limited in conventional manufacturing. The part complexity has been achieved by Angel Trains for replacement parts by using Stratasys FDM Technology (Iftikhar, 2018). The materials used to make these replacement parts were highly wear resistant and compliant to fire safety standards. Another example is Bombardier Transportation which adopted AM to print spare parts on demand, and for complex parts like the air vent system for a train (Boissonneault, 2019d). By 3D printing the complex air vent system, Bombardier achieved weight reduction and met the rail certification standards. Adding on, Deutsche Bahn (DB) has printed spare parts like the steel sand box and coat hooks, and other parts such as headrests, fan propellors etc (3D Printing at DB | Deutsche Bahn AG, 2016). DB was able to achieve strength and physical properties comparable to conventional manufacturing and most importantly reduce lead times.

Table 16: Part Complexity (own illustration)

Part Complexity	Firm 1	Firm 2	Firm 3	Firm 4	Firm 5
Creation of functional parts that are normally difficult to create otherwise	X	X		X	X
Part or assembly integration	X			X	X
Weight reduction		X	X		
Customized geometry	X			X	
Strength and other mechanical properties				X	
Use of different materials		X			

5.5.4.1. Creation of difficult to create parts and Customized Geometry

One of the main benefits of AM is its ability to create complex parts that would normally be difficult with conventional production. Conventionally, it would be very time and effort consuming. AM offers the flexibility to use different AM technologies to create parts with complex geometries. Internal cavities, fillets can be created to reduce the weight of the part and distribute load uniformly across the part. In AM, there is limitation with respect to geometry. Whether the geometry is simple or complex, it can be 3D printed by feeding the design into the AM machine (Campbell et al., 2011). Spare parts of highly customized geometry existing in small quantities can be produced through AM. In AM, the cost of the production process is the same no matter how complex the product is and the number of parts to be printed (Petrovic et al., 2011). The automotive industry values the usefulness of AM for customized geometry and ability to produce difficult-to-create parts. Examples for this are explained by Volkswagen producing gearshift knobs and mirror mounts and Porsche producing engine pistons through AM. These are highly complex, high-performance parts which have been produced by Volkswagen and Porsche. By producing the rear dumper shield with AM, Chevrolet achieved higher design freedom and better aerodynamic performance for its Silverado off-road truck.

5.5.4.2. Weight Reduction and Assembly Integration

With more design freedom, the weight of the parts produced can be lowered. Custom producing complex parts conventionally is possible but would normally lead to higher weight and costs. In the automotive industry, Bugatti has been able to achieve weight reduction for some of its spare parts like the exhaust tailpipe, motor bracket, brake calliper and the spoiler bracket. Fiat Chrysler, Renault, Nissan were able to achieve part reduction, lighter weight and higher performance by adopting AM. Players in the aircraft industry highly value the usefulness of AM for weight reduction and assembly integration. Liebherr Aerospace produced the nose landing gear and the valve block for Airbus through AM which helped achieve weight reduction of maximum 35%, significant part reduction and performance equal to the conventionally produced one. Safran utilized the SLS AM Technology to produce the gearbox which helped in reducing the number of parts from 12 to 2, leading to effective assembly integration. GE Additive began to adopt AM for its GE9X engine titanium blades and witnessed a massive weight reduction of approximately 200 kgs and fuel savings of 10% over conventionally produced nickel blades. By using 3D printing with Nylon Polyamide-12, Marshall Aerospace achieved a weight reduction of approximately 65% for the ducting adapter.

5.5.4.3. Use of different materials and strength properties

Among the metals, Titanium, Steel, Aluminium, Nickel and their alloys have been used due to their high strength, hardness and corrosion resistance properties. With AM, these respective metals can be used to form complex products with good strength (Ngo et al., 2018). Quality wise, these metals when used in AM do present good quality compared to conventional production. However, porosity could be an issue that eventually results in crack propagation through the surface. Therefore, post processing heat treatment is necessary in AM to control porosity. These metals and alloys when processed in AM help achieve better functionality, part reduction and lesser material wastage. Polymers and composites are widely used in the AM industry due to their ability to accurately produce complex parts. Polymers alone won't offer high strength and flexibility. They are fused with composites. Thermoplastic polymers such as ABS, PLA and Polycarbonate are popular in 3D printing processes. The advantages of these polymers are that they are cost-effective, accurate for complex products, fast prototyping speed and can be used for customization (Ngo et al., 2018). The mechanical properties may be an issue.

5.5.5. Sustainability

Nowadays, manufacturing processes need to be more environment friendly and sustainable. AM definitely offers the possibility to make manufacturing more sustainable by utilizing less resources indicating the reduction in carbon emissions and greener environment. Hence sustainability has been chosen as one concept to measure the perceived usefulness of AM for spare parts. Sustainability has been described in this sub-section with the criteria listed in table 17.

Table 17: Sustainability (own illustration)

Sustainability	Firm 1	Firm 2	Firm 3	Firm 4	Firm 5
Reduction in tooling (jigs, fixtures and moulds)					
Lesser Material wastage		X	X	X	X
Less Rework				X	
Reduced or no transportation	X		X	X	
No or little inventory	X	X			

5.5.5.1. Tooling reduction

In injection moulding processes, costly moulds and tooling is required. Also, as tools get used and worn out, they often need to be replaced in conventional processes. This adds to the lead time and production costs. As discussed before, more than 85% of the costs for a conventionally produced part are incurred on tooling and injection moulds (Thomas & Gilbert, 2015). This isn't very economical for low volume part production that is needed today for making spare parts for which demands are mostly uncertain. For low volume, small part production, AM would be best suited as economies of scale are low and prototypes can be produced and tested without having the need to carry out tooling and retooling processes. Moreover, when the need arises for spare parts, it will be difficult to procure tools in a short time frame via conventional methods of production. So, AM helps reduce the over-dependence on tooling and is more self-reliant for producing difficult-to-produce, customized parts.

5.5.5.2. Lesser material wastage and rework

Most of the AM processes are less resource intensive and environment friendly. In AM, material is added layer-by-layer, meaning only whatever is needed for the part is used, unlike subtractive processes where material is removed to get the desired product leaving behind rest of the workpiece (Campbell et. al., 2011). AM offers the possibility of maximum utilization of material by reusing of powders, resins. These materials are 95-98% recyclable (Niaki et al., 2019). Old and obsolete material need not be disposed but can be recycled and reused. Conventional production methods generate a lot of material waste and scrap (Cotteleer & Joyce, 2014). According to (Achillas et al., 2014), in the aircraft industry, about 20 kg of material are required to produce 1 kg of end-product. So, the remaining 19 kg is waste that needs to be reprocessed or recycled. This presents an opportunity for AM usage. AM processes consume lesser energy and are leaner due to less resource requirements (Niaki et al., 2019). Rework in the conventional setup can be very costly. Tools will have to be set up and machines will have to run again. AM offers the possibility to design and test prototypes, without having the need to worry about rework.

5.5.5.3. Reduced transportation, No or little inventory

Most often production is carried out centrally at one facility. The raw materials, other subcomponents and spare parts are ordered through suppliers scattered across the globe. So, the distances are larger and the transportation of all these goods leads to more carbon emissions and higher pollution. Once they are shipped, they get stored as inventory in warehouses, consuming a lot of space and incurring high costs. AM could address this issue by decentralizing or distributing production, producing on-demand to cater to customer needs. This would help minimize the excess transport needed, save on carbon emissions and reduce the amount of inventory that needs to be stored.

5.6. AM Technology Specifications

Adding to the criteria listed in the previous sub-sections, it is important to be aware of the technology specifications such as the materials supported by each technology, the range of build sizes of the respective machines and the dimensional accuracy offered by each technology. It is briefly described in Table 18.

Table 18: AM Technology Specifications (Frandsen et al., 2020; Hubs, 2021)

AM Technology	Common Materials	Build Size	Dimensional Accuracy
SLS	Powders - Nylon PA 6, PA 11, PA 12, ABS	Average build size of 300*300*300 mm, can go up to 750*550*550 mm	Varies from + or - 0.3 mm
DMLS	Metal powders - mainly stainless steel and alloys	Maximum of 250*150*150 mm	Varies from + or - 0.1 mm
SLM	Metal powders - mainly aluminium and titanium	Maximum of 250*150*150 mm	Varies from + or - 0.1 mm
Binder Jetting	Stainless steel	Large sizes of 1800*1000*700 mm maximum	Varies from + or - 0.2 mm
SLA	Resins	Small sizes of 145*145*175 mm, large sizes of 1500*750*500 mm	Varies from +/- 0.01 mm to +/- 0.03 mm
FDM	ABS, PLA, Nylon PA 6, PA 11, PA 12	Desktop size of 200*200*200 mm, industrial FDM printer of 1000*1000*1000 mm	Varies from + or - 0.5 mm

5.7. Chapter 5 Sub – Conclusion

This chapter sums up the analysis conducted on AM Technologies, materials, factors affecting AM product quality, cost drivers for AM adoption and application of AM in spare parts. From sections 5.1 and 5.2, it was found that Powder Bed Fusion (PBF) is the most preferred technique for industrial AM adoption, for both metal and polymer applications. PBF supports the usage of many materials, indicating that it is very versatile. Other techniques mentioned such as SLA, FDM and HP Multi-jet fusion have been adopted but not as much as the PBF techniques. From section 5.3, the cost drivers driving AM adoption in spare parts were found to be machine, materials, post processing, labour and energy. The challenges to AM adoption (section 5.4) were found to be Technology awareness, Intellectual Property (IP) issues, costs and return on investment (ROI), strength and other physical properties. In section 5.5, the perceived usefulness of AM for spare parts was studied with concepts such as increased responsiveness, minimized supply disruption, cost optimization, part complexity and sustainability. The selection of spare parts for AM and the business models that enable spare part production will be discussed in the following chapters 6 and 7.

6. Selecting Spare Parts for AM

The purpose of this chapter is to elaborate on the MCDM tools for the selection of spare parts for AM. As mentioned in chapter 2, section 2.7.1, the MCDM tools used are AHP and PROMETHEE. This chapter explains the steps followed in both AHP and PROMETHEE for selecting spare parts for AM production. This is the decision - making (prioritizing the criteria for spare parts printing) part of the support process as shown in figure 5.1. The information obtained here could be used to answer the second research question as shown in chapter 2. The steps explained here will be applied in the use cases in chapter 8.

6.1. Explanation of steps in the MCDM Tools for selecting spare parts for AM

The MCDM tools that have been considered are AHP and PROMETHEE. This section will explain the steps followed in both the tools.

The steps followed in AHP are:

1) Defining the problem – begins with the goal at the topmost level followed by the criteria at the middle level and the alternatives at the bottom level.
2) Assessing the importance of criteria – decision maker needs to prioritize the given criteria using pairwise comparison. He needs to assess which criteria would be more/less important than the others. This is called weighting.
3) Assessing the importance of alternatives for each criterion – the alternatives are again compared using pairwise comparison to assess how well an alternative meets the mentioned criteria.
4) Obtaining an overall score for each alternative – the overall score is obtained by combining each individual option scores with the criterion weights.

The pairwise comparisons to assess the importance of criteria can be done using the scale put forth by Saaty (1987) where:

1 = Equal importance
3 = Moderate importance
5 = Essential or strong importance
7 = Very strong importance
9 = Extreme importance

2,4,6 and 8 are intermediate values.

The steps followed in PROMETHEE are (Abdullah et al., 2019):

1) Determining the criteria and the set of possible alternatives in a problem
2) Determining the weights of the criteria

NOTE: Here, the weights will be determined using the AHP.

3) Normalizing the decision matrix using the formula shown in the figure below

   For beneficial criteria: Rij = [Xij - min (Xij)] / [max (Xij) – min (Xij)]

   For non - beneficial criteria: Rij = [max (Xij) - Xij] / [max (Xij) – min (Xij)]

   Where i (number of alternatives) = 1, 2…, n and j (number of criteria) = 1, 2…, m

4) Determining the deviation by pairwise comparison as shown below

   Dj (a, b) = Gj(a) – Gj(b)

   Dj (a, b) = difference between the evaluations of alternative 'a' and alternative 'b' on each criterion.

5) Calculation of the preference function

   The preference function Pj (a, b) is calculated using the formula Pj (a, b) = Fj [dj (a,b)].
   Pj (a, b) = difference between the evaluations of one alternative with another alternative on each criterion. These values range from 0 to 1. The negative values obtained are equated to zero and the positive values are taken as it is.

6) Determine the multi-criteria preference index as shown below

   This is determined by multiplying the weights associated with each criterion and the values of the preference function obtained in the previous steps.

   Preference index = Σ Wj * Pj (a, b)

7) Obtain the preference order by full ranking

   Full ranking:
   ϕ(a+) - ϕ(a-) = ϕ(a)
   ϕ(a) = net outranking flow, ϕ(a+) = positive outranking flow (leaving flow), ϕ(a-) = negative outranking flow (entering flow)

In the interviews conducted, when respondents were asked questions with regard to applying AM for producing spare parts, the main objectives they listed were improving responsiveness and reducing costs. The criteria for improving responsiveness were on-demand availability, lead time and downtime. The criteria for reducing costs were production cost, inventory cost and transport cost. To show an example, the objective of improving responsiveness has been taken and shown in the tables below.

For prioritizing the objectives and weighing the criteria, the AHP has been used (shown in tables 19 and 20 below). The interviewees were asked to rate the criteria mentioned using the scale put forth by (Saaty, 1987). The interviewees rated the criteria in general as to what would be important for their spare parts business overall (shown in table 19). Then the weights were calculated (shown in table 20). The PROMETHEE has been shown in tables 21, 22, 23 and 24 according to the steps mentioned to obtain the ranking of spare parts (assumptions have been made). The spare parts 1, 2 and 3 have been listed (not by the interviewees, but on my own) to explain the working of the PROMETHEE tool. The number of spare parts that can be used could be many. For explaining the tool, only three parts have been considered. Also, all the values for downtime, on-demand availability and lead time for spare parts 1,2 and 3 in tables 21, 22, 23 and 24 have been assumed. These could vary across companies.

Table 19: AHP (own illustration)

Improving Responsiveness	Downtime	On-demand availability	Lead times
Downtime	1	7	5
On-demand availability	0.143	1	3
Lead times	0.2	0.33	1
SUM	1.343	8.33	9

Downtime with respect to on-demand availability = 7, indicating that on-demand availability with respect to downtime = 1/7 = 0.143
Downtime with respect to lead time = 5, indicating that lead time with respect to downtime = 1/5 = 0.2
On-demand availability with respect to lead time = 3, indicating that lead time with respect to downtime = 1/3 = 0.33. The sum is calculated column wise. For example, 1.343 = 1 + 0.143 + 0.2.

Table 20: Determining the weights with AHP (own illustration)

Improving Responsiveness	Downtime	On-demand availability	Lead times		Criteria weight
Downtime	0.744	0.840	0.55		0.7134
On-demand availability	0.1064	0.12	0.33		0.186
Lead times	0.149	0.0396	0.111		0.099

Here, the value of each cell is obtained by dividing the value listed in the previous table by the sum of the columns. For example, 1/1.343 = 0.744, 7/8.33 = 0.84 and 5/9 = 0.55. The criteria weight is calculated by the row-wise average that is (0.744+0.84+0.55)/3 = 0.7134.

Table 21: PROMETHEE (own illustration)

Improving Responsiveness	On-demand availability (number of parts)	Downtime (hrs)	Lead time(hrs)
Weights	0.186	0.7134	0.099
Spare part 1	50	25	24
Spare part 2	30	20	26
Spare part 3	40	10	48
Max	50	25	48
Min	30	10	24

Table 22: Normalizing the matrix with PROMETHEE (own illustration)

Spare part 1	0	1	0
Spare part 2	1	0.66	-0.9166
Spare part 3	0.5	0	1

Here step 3 of PROMETHEE is used:
For beneficial criteria: Rij = [Xij - min (Xij)] / [max (Xij) – min (Xij)]
For non - beneficial criteria: Rij = [max (Xij) - Xij] / [max (Xij) – min (Xij)]
Where i (number of alternatives) = 1, 2..., n and j (number of criteria) = 1, 2..., m

Here, the on-demand availability is considered the non-beneficial criteria as certain quantities of spare parts need to be produced by AM to achieve benefits like lower downtime and lower lead times. So, the beneficial criteria are downtime and lead times.

For example, if we consider spare part 2, the value '1' (1st column, 2nd row) is obtained by the equation [max (Xij) - Xij] / [max (Xij) – min (Xij)] = (50 - 30) / (50 - 30) = 1

Table 23: Determining the deviation by pairwise comparison as shown below (own illustration)

D(P1-P2)	-1	0.33	0.9166
D(P1-P3)	-0.5	1	-1
D(P2-P1)	1	-0.33	-0.9166
D(P2-P3)	0.5	0.66	-1.9166
D(P3-P1)	0.5	-1	1
D(P3-P2)	-0.5	-0.66	1.9166

Here step 4 of PROMETHEE is used:
Dj (a, b) = Gj(a) – Gj(b)

Dj (a, b) = difference between the evaluations of alternative ‘a’ and alternative ‘b’ on each criterion.
D(P1-P2) = 0 – 1 = -1, D(P1-P3) = 0 – 0.5 = - 0.5.

Table 24: Calculation of preference function and determining the multi-criteria preference index with PROMETHEE (own illustration)

D(P1-P2)	0	0.33	0.91	0.326
D(P1-P3)	0	1	0	0.713
D(P2-P1)	1	0	0	0.1866
D(P2-P3)	0.5	0.66	0	0.5642
D(P3-P1)	0.5	0	1	0.193
D(P3-P2)	0	0	1	0.099

Here steps 5 & 6 are used. The preference function Pj (a, b) = Fj [dj (a,b)]. Pj (a, b) = difference between the evaluations of one alternative with another alternative on each criterion. These values range from 0 to 1. The negative values obtained are equated to zero and the positive values are taken as it is.
Preference index = Σ Wj * Pj (a, b). The last column on the right side shows the preference index values.
For example, D(P1-P2) = (0.1866*0) + (0.7134*0.33) + (0.099*0.91) = 0.326. The weights 0.1866, 0.7134 and 0.099 have been found using AHP in table 20.

Table 25: Calculation of leaving flow and entering flow with PROMETHEE (own illustration)

	Spare Part 1	Spare Part 2	Spare Part 3	Leaving flow
Spare Part 1	0	0.3263	0.713	0.3466
Spare Part 2	0.1866	0	0.564	0.2502
Spare Part 3	0.1931	0.099	0	0.0976
Entering Flow	0.1266	0.142	0.426	

Table 26: Full ranking with PROMETHEE (own illustration)

	Leaving flow	Entering flow	Difference	Rank
Spare Part 1	0.3466	0.1266	0.22	1
Spare Part 2	0.250	0.142	0.108	2
Spare Part 3	0.0976	0.425	- 0.328	3

Here the full ranking is done using the formula:
$\phi(a+) - \phi(a-) = \phi(a)$
where $\phi(a)$ = net outranking flow, $\phi(a+)$ = positive outranking flow (leaving flow), $\phi(a-)$ = negative outranking flow (entering flow)

From table 24, the preference index values obtained have been used to calculate the leaving flow and the entering flow in table 25. For example, D(P1-P2) = 0.326 has been used in table 25 and similarly all other values have been used. The leaving flow is calculated by taking the average of the rows and the entering flow is calculated by taking the average of the columns. As shown in table 25, 0.3466 = (0+0.326+0.7134) / 3 and 0.1266 = (0+0.1866+0.193) / 3

The full ranking shown in table 26 is obtained by calculating the difference between the leaving flow and the entering flow for each spare part. The spare part with the highest value in the difference column is ranked first and subsequently the other spare parts are ranked.

6.2. Chapter 6 Sub - Conclusion

In this chapter, the MCDM tools that is AHP and PROMETHEE have been discussed to help qualify spare parts for AM. The steps employed in using both AHP and PROMETHEE have been described. The AHP tool helps firms clarify their objectives for AM production of spare parts and decide on the relevant criteria to achieve those objectives. The PROMETHEE tool helps prioritize the ranking of spare parts for AM production. Both the tools together could be used by firms with more objectives and criteria. These tools need to be tested by each firm specifically as its objectives would be very specific and the firm would possess varying quantities of spare parts. Both these MCDM tools have been further explained in chapter 8, use cases. The steps explained here will be applied in the use cases.

7. AM Business models for Spare Part Production

To produce spare parts by AM, the feasible business models need to be studied. They will be explained in this chapter. The information obtained here could be used to answer the third research question as shown in chapter 2. This forms part of the support process (shown in figure 5.1) which will help in deciding the feasible ways to print and deliver the spare parts to customers. The make-to-stock (MTS), make-to-order (MTO) and engineer-to-order (ETO) approaches as referred to in chapter 3, section 3.3 will be explained here in sub-section 7.1. Following this, the chapter will explain the four business models chosen that are – OEM with local print center (customer without OEM printers), customer with OEM printers, OEM with certified external printing providers and customers with their own printers (not supplied by the OEM) in sub-sections 7.2 – 7.5. The criteria such as costs, criticality, downtime, lead time and technology flexibility will be described for each of the business models. Moreover, these business models will be explained using the MTS, MTO and ETO approaches.

Firstly, the study on business models that have been done till recently will be explained to give the reader a clear picture. The stages of AM adoption that is Rapid Prototyping, Rapid Tooling, Direct Digital Manufacturing, Home Fabrication and its effects on the business model components have been articulated by Rayna & Striukova (2016). The key business model components are value proposition, value creation, value delivery, value capture and value communication as shown in the figure 7.1 below.

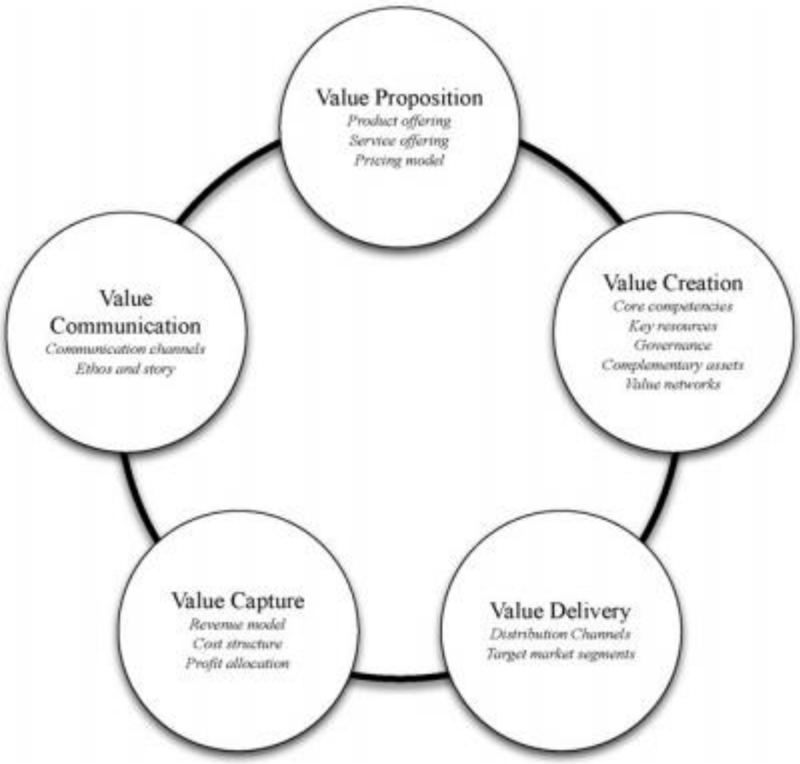


Figure 7.1: Business model components (Rayna & Striukova, 2016)

The authors provide insights that rapid prototyping and rapid tooling would have limited impact on business models whereas direct digital manufacturing and home fabrication would be disruptive as they increase value creation and value delivery. Holzmann et al., (2019) extend this research by applying the key business model components to 3D printer manufacturers to predict what kind of business models they would follow. Holzmann et al., (2019) broke down value proposition, value creation and value capture into measurable variables. Following this, they conducted a study with 3D printing manufacturers and concluded that they generally follow two models – "Technology expert model" or "Low - cost online model". Both these studies provide interesting information regarding business models enabled by 3D printing technologies.

Godina et al. (2020) studied the economic, social and environmental impact of AM on business models using the balanced scorecard approach. This approach would be helpful for firms in making better decisions and strategizing according to the external environment. Godina et al. (2020) say that the information regarding the impact is very scarce and the new AM business models are still at infancy. Thereby, this makes it difficult to predict the impact of AM on business models. Cardeal et al. (2020) went on to evaluate the economic, environmental and social impact of AM with the use of a Business Model Canvas for Sustainability. This study was focused on the aircraft MRO sector. Cardeal et al. (2020) claim that their study could be beneficial economically by producing lighter weight components with AM, acquiring raw materials like powders and filaments from few suppliers leading to a reduction in the number of suppliers and customers paying lesser prices due to lower carbon emissions. The study expresses the social benefits by highlighting that AM would decentralize production and help to better utilize the skills of the local workforce and lead to welfare due to safer manufacturing techniques. Environmentally AM would be friendly as it enables delivery on-demand, reducing the need to rely on transport modes that result in high carbon emissions. Also, the material usage improves with AM meaning lesser material waste during production which is very important in the aircraft industry. However, this approach needs to be practically applied and tested in other industries apart from aircrafts to be generalisable. González-Varona et al. (2020) compared the spare part business models of AM and TM and explained the potential benefits that an AM digital supply chain could bring about. This work is focused on small and medium enterprises (SMEs). They suggest that small and medium scale producers (including designers) of spare parts could reap the benefits without increasing logistics costs and printer shops close to the customer can satisfy the on-demand requirements. The fact that AM raw material suppliers are limited in number and not widely distributed adds to the drawback of the digital supply chain.

The business models that have been considered for the study are described in the sub-sections 7.2, 7.3, 7.4 and 7.5. Before the business models, the spare parts management approaches such as Make-to-stock (MTS), Make-to-order (MTO) and Engineer-to-order (ETO) as referred to in chapter 3, section 3.3 will be explained. This can be used to relate with the business models that will be described in the following sub-sections.

7.1. Make-to-stock, make-to-order and Engineer-to-order approaches

According to Olhager (2010), the customer order decoupling point (CODP) is the point in the product value chain, where the product is associated to a specific customer order. CODP separates the forecast - driven upstream activities (material flow, production, purchasing) from the order – driven downstream activities (customization, distribution and delivery). At this point, firms decide the quantity and schedule of materials/products to make and purchase. The CODP is the last point at which inventory is held and product specifications are finalised. Based on the CODP, different approaches such as MTS, MTO and ETO can be used for producing standardized and customized products.

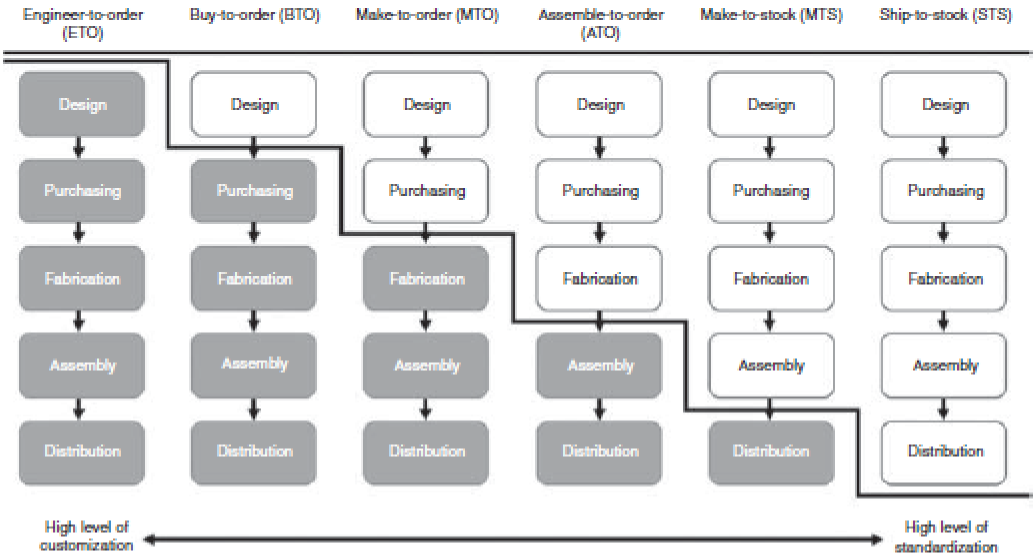


Figure 7.2: Customer order decoupling point (Ryan et al., 2017)

For the MTS approach as shown in figure 6.2, the CODP is located downstream meaning that customization is held up till the final point of assembly (Ryan et al., 2017). Basically, in MTS approach the focus is more on standardization than customization. In MTS, customer demand is fulfilled with stocked inventory of finished goods. MTS is a push system characterized by short lead times, higher storage costs and low customization flexibility (Peeters & van Ooijen, 2020). Moving on, for the MTO approach as shown in figure 6.2, the CODP is located more upstream indicating that the fabrication and assembly is postponed till customer orders arrive. The bill of materials (BOM) and specifications remain the same, but specific features are added to the product based on customer requirements. The BOM consists of raw materials, sub-components, sub-assemblies required to manufacture an end product. The MTO is a pull system, driven by customer demand. The ETO approach is similar to MTO where production begins only after customer orders arrive, but specifications are custom for each item. Products with very low frequency could be produced using ETO. The CODP is located fully upstream for the ETO approach. The AM production of spare parts generally favours the application of the MTO approach (Ryan et al., 2017). Firms could use these approaches to complement their existing MTS approaches for producing spare parts. From the figure, only MTS, MTO and ETO have been considered as these are relevant to AM production of spare parts. Due to the possibility of assembly integration with 3D printing, the fabrication and assembly could be combined as a single step.

The following subsections explain the business models along with the spare parts management approaches that could be used in each of them.

7.2. OEM with local print center (customer without OEM printers) – Model 1a

The OEM manages the Additive Manufacturing Platform (AM platform is common for all the business models described in sub-sections 7.2 - 7.5). The Additive Manufacturing platform helps OEMs carry out the following activities:

- Design parts for the equipment/assembly with CAD, slicing software
- Conduct test runs for the parts to finalize the part design
- Save the part design and configuration files for usage
- Upon customer order send the design file, monitor the payment transaction and manage the printing activity.

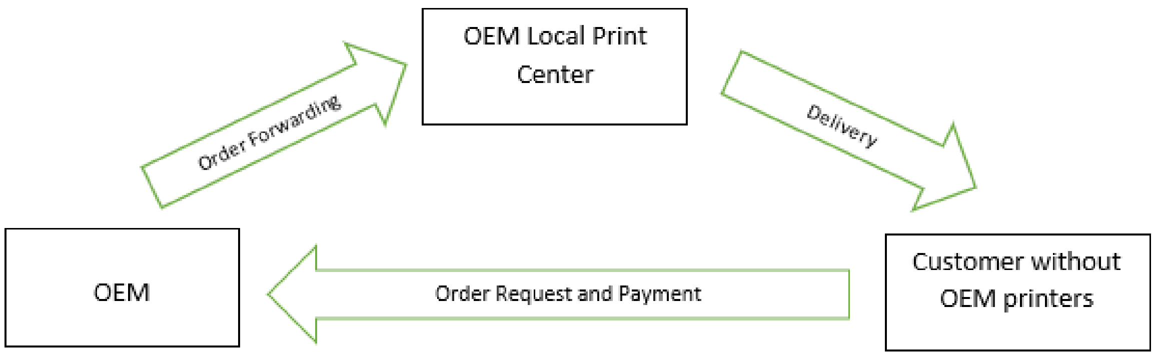


Figure 7.3: OEM with local print center (own illustration)

In this model, as shown in figure 6.3 the activities proceed as follows. First, the customer places an order request to the OEM for spare parts. Upon receiving the order request from the customer, the OEM checks its part library for the design files and approves the customer order. The OEM forwards the design files to its local print center and sends an invoice to the customer. The activity of IP protection for both design file and the physical part will be managed by the OEM. The OEM establishes the quality and compliance requirements of the printed parts, and the print centre ensures it. The OEM's local print center receives the order forwarded by the OEM and processes it. The material and machine selection for part printing is done on the platform managed by the OEM based on the order requirements. The printing setup activities such as the tooling, slicing the design file into layers and feeding into the printer to print the required parts is done by the print centre. The parts are printed and delivered to the customer by the print centre. Then, the customer makes the payment to the OEM for the design file and the physical part.

In this model, the costs incurred for the OEM is very high. Investments are needed for procuring the machines, maintenance within the premises (includes labour), material feed (powders, metal, filament) and operation (software). The printer facility costs such as rent, electricity etc., too needs to be covered by the OEM. This model could prove to be very capital intensive for the OEM, but for the customer it could be cost effective.

Moving on, the criticality refers to how urgently spare parts of good quality are needed to keep the equipment functional and mitigate equipment downtimes. The on - demand availability of parts will be ensured to a good extent in this model. For spare parts with high and medium levels of criticality where unavailability is not desired and quick supply is required, this model could be very useful. But due to the local print center's off-site presence, there could be chances of disruption in supply. For example, in the times of pandemic where strict lockdowns would be in place, this model could pose a problem of supply disruption. Logistics risks could exist in this model. The Criticality and Downtime factors are related to one another. When good quality spare parts are urgently required to keep the equipment functional and address downtimes, this model will ensure those spare parts are available and keep the downtimes low. Since OEMs have control over production, they can ensure quality.

The lead times in this model are low. The local print center's off-site presence and the limited technology availability may increase the lead time. Along with these, the certification process for specific, high-quality parts may take time, thereby increasing the lead time.

The technology flexibility offered in this model is low. The OEMs would invest only in certain technology, materials and machines to save on costs. Economically, it might not make sense for OEMs to invest in a range of technologies considering their already occurring high costs of machine procurement, maintenance, material feed, operation, rent and electricity.

Approaches used in Model 1a - OEM with local print center

For this model, where the OEM's local print center would carry out printer setup and printing activities, the MTO approach could be well suited for production of spare parts that are characterized by uncertain demand (includes phased - out models for which an installed base still exists). If the demand is about 10 parts per month or 100 parts per year approximately or less, the MTO approach would be helpful by saving material and its associated costs. This is a pull system generated by customer demand. The OEM would be in possession of the part designs. The OEM's print centre would be in possession of the raw material (powders, metal and filament) and the printing machine to be able to produce the parts when needed. With the MTO approach, the CODP is located upstream, meaning that the printing of spare parts can be postponed till customer orders arrive. The bill of materials (BOM) and product specifications possessed by the OEM will be the same. As per customer requirements, post - processing operations can be carried out on the parts to meet the strength requirements and obtain better surface finish. Due to the chances of the print centre being off – site, the print centre must ensure smooth delivery (minimal delivery lead time) to the customer by hiring a reputed third - party logistics provider (3PL). This will in turn help address criticality and minimize downtime. However, if there are spare parts which have predictable demand, meaning that the demand could be approximately 10 parts per week, 100 per month or more, then it might be useful to adopt the MTS approach. This indicates that the CODP for these parts would be located downstream, thereby ensuring that completed parts would be ready to be transported to the customer. This is a push system. The MTS approach would ensure sufficient raw material, safety stock (higher than 10 parts per week) and finished parts to be delivered to the customer on time. As this business model would incur high capital investment and machine depreciation for the OEM, the MTS approach could help in minimizing those costs by utilizing the machine to the fullest extent. The MTS approach can be viable for the OEM only when the demand for spare parts is predictable. Therefore, for this model it would be advisable to use a combination of the MTS and MTO approaches, considering the spare parts demand and the high capital investment costs for AM technology. As the OEM would invest in only one particular technology, custom made part designs cannot be produced, thereby ruling out the ETO approach.

7.3. Customer with OEM printers – Model 1b

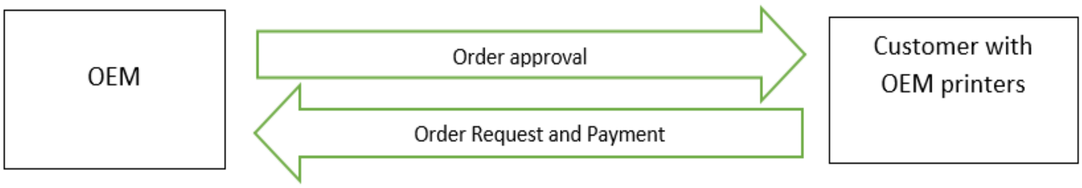


Figure 7.4: Customer with OEM printers (own illustration)

In this model, as shown in figure 6.4 the activities proceed as follows. First, the customer places an order request to the OEM for spare parts. Upon receiving the order request from the customer, the OEM checks its part library for the design files and approves the customer order. The OEM forwards the design files to the customer and sends an invoice along with the design files. Then, the customer makes the payment to the OEM for the design file. The activity of IP protection for both design file and the physical part will be managed by the OEM. The OEM establishes the quality and compliance requirements of the printed parts, and the customer ensures it. The customer receives the design files from the OEM upon payment. The instructions regarding materials and technology required for part printing is given to the customer by the OEM (platform). The printing setup activities and part printing is done on-site by the customer.

With this model, the costs incurred for the OEM is high. Investments are needed for procuring the machines and maintenance outside the OEM premises. The material feed, operation (software), personnel, rent and electricity costs would be borne by the customer and the OEM does not need to worry about it. This model could be capital intensive for the OEM given the machine procurement and maintenance costs. For the customer, this model could be more capital intensive than model 1a, due to the fact that he needs to bear the material, personnel and energy costs.

Regarding criticality, the customer has full control over production and can produce on-demand on - location in the lowest possible time. The on-demand availability of parts with good quality will be ensured to the best extent in this model. For spare parts with high and medium levels of criticality where unavailability is not desired and quick supply is required, this model could be the most useful. The chances of supply disruption and supply risk is very low. When good quality spare parts are urgently required to keep the equipment functional and address downtimes, this model will ensure those spare parts are available in the fastest possible time. The downtimes are the lowest in this model. With full control over production, the customer and the OEM can ensure good quality.

The lead times in this model are low. Due to the customer having the printers at his own location, the lead time is lower compared to model 1a. The limited technology availability may increase the lead time. Just like model 1a, the certification process for specific, high-quality parts may take time, thereby increasing the lead time.

Similar to model 1a, the technology flexibility offered is low. The OEMs would invest only in certain technology and machines to save on costs. Economically, it might not make sense for OEMs to invest in a range of technologies. The customers can procure the materials they need for printing the parts.

Approaches used in Model 1b - Customer with OEM printers

In the previous model 1a, the local print center could expect orders from more than one customer for different spare parts, indicating that a combination of MTO and MTS would be suited considering the demand. But in this model, the customer has the printer at their own facility which can be used for themselves to print spare parts when needed. The customer would be able to see when their equipment goes down due to the spare parts not being available, and can print accordingly. The MTO approach would be suitable for this model where customer could reap the benefits of AM that is low setup costs, on-demand production in low volumes, better control over production and fast lead times. The customer demand favours the pull system. The CODP is located upstream, meaning that the printing activities could be postponed till spare parts are needed. The customer can request for the spare parts design from the OEM which would have the same BOM and product specifications. The raw materials (powders, metal, filament) will be procured by the customer to use for the machine anticipating demand for spare part that may arise. Customer can perform post - processing operations on the part to meet the strength requirements and obtain better surface finish. The pull - based ETO approach could also be used here provided the OEM is willing to custom design the part as per customer requirements. But due to limited technology flexibility, this might not always be possible. With the ETO approach, the postponement begins at the design stage itself (figure 6.2). The CODP is completely upstream. The customer might want to use the MTS approach so that the printer is utilized to the fullest extent possible and their investment (material, personnel, energy) is justified. MTS would be suitable only when the customer can expect a large quantity of spare parts (predictable demand) to be printed, which mostly is not the case in this scenario. In this case, the customer is printing for themselves. Therefore, MTS would not be suitable.

7.4. OEM with certified external printing service providers – Model 2

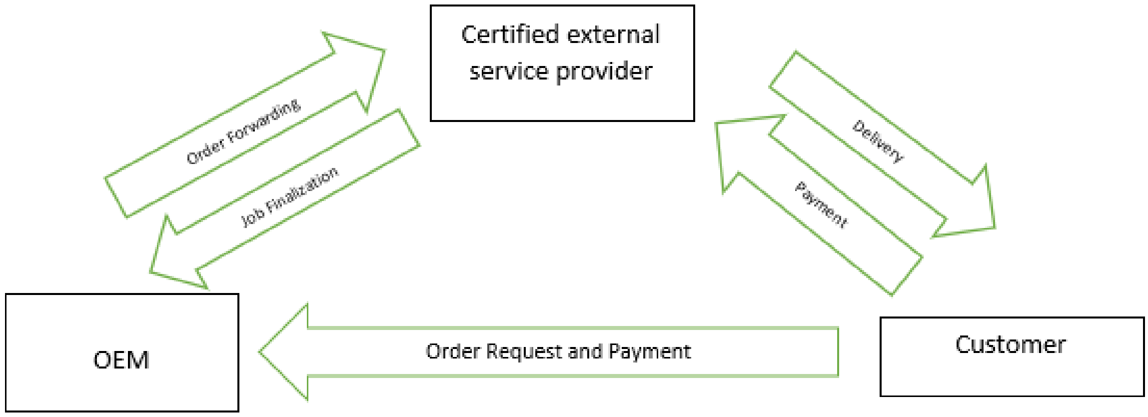


Figure 7.5: OEM with certified external printing service providers (own illustration)

The figure 7.5 describes the activities followed. Here, the customer first places an order request to the OEM for spare parts. Upon receiving the order request from the customer, the OEM checks its part library for the design files and approves the customer order. With the additive manufacturing software platform, The OEM performs a check on the service providers available for the customer order (specifications) received. Then, the OEM assigns the service provider accordingly and forwards them the design files. The certifying process for the external service providers and IP protection for design files, physical parts is carried out by the OEM. The OEM establishes the quality and compliance requirements of the printed parts, and the external provider has to ensure the requirements are met. The service provider receives the order from the OEM and allocates machines for printing the parts as per the instructions received in the order. Once the parts are printed, the service provider delivers them to the customer. The customer receives two separate invoices, one by the OEM for the design file and the other by the service provider for part printing & delivery. The OEM is paid for the design file and the service provider is paid for the physical parts.

The OEMs need not have to procure machines and invest in its maintenance. There is no need for the OEMs to keep an inventory and safety stock of raw materials (powders, metal, filament). All these factors would be taken care of by the external service provider. The OEM will only have to handover the design files to the external service provider. This model will be less capital intensive for the OEM, indicating the costs incurred for OEMs here is much lower than models 1a and 1b.

Regarding the criticality and downtime, this model addresses it well by ensuring the on - demand availability of parts will be ensured to a good extent. But logistics risk could exist as there's no guarantee that the service provider will be located near every customer location. This model can help ensure minimal downtimes. When spare parts are urgently required to keep the equipment functional and address downtimes, models 1b and 3 would be able to address the issue better as the printers are at the customer location itself.

The lead times are low in this model. Due to the extensive availability of certified service providers who can provide different technology and material options in close proximity to the customer, the parts can be produced and delivered in quick time. The lead times in this model could be lower than model 1a, but higher than models 1b and 3.

The technology flexibility offered in this model is high due to the availability of many service providers who could offer technology and material options.

Approaches used in Model 2 - OEM with certified external printing service providers

The certified providers in this model could be partners with many OEMs. They could expect orders for similar or different parts from a single OEM, or different OEMs. The demand for the spare parts could vary highly. Here, the pull - based MTO approach would be the best suited, being driven by customer demand. The certified providers are in possession of the printers and raw materials. The design is provided by the OEM. Anticipating orders to arrive anytime from OEMs, the certified providers would procure raw materials (powders, metal, filament) along with safety stock in advance to cater to the demand. The printing activities can be postponed till the orders arrive from the OEM. The CODP is located upstream in this model, meaning that inventory of raw materials can be held early on, and the finished parts inventory will be ready only for final delivery to the customer. The certified provider can take advantage of the benefits of AM that is on-demand production, low inventory costs and low setup times. The providers could be near the customer location, but this is not the case always. Therefore, fast delivery lead times need to be ensured by partnering with 3PL companies. This MTO approach would help save raw material inventory. With the MTO approach, the bill of materials (BOM) and specifications provided by the OEM remain the same. As per customer requirements, post - processing operations can be carried out on the parts to meet the strength requirements and obtain better surface finish. Furthermore, the ETO approach could also work in this model. The certified provider can re-engineer the part design received from the OEM and customize it for the customer. With high technology flexibility available in this model, it is possible for the certified provider to re - engineer the part design. However, this would need approval from the OEM regarding the strength and safety standards. This pull – based ETO approach would require working directly with the customer and this would mean the CODP is located completely upstream. The push – based MTS approach may not be advisable in this model. Due to partnerships with many OEMs, the certified provider would definitely be able to recover the machine costs by utilizing it for many parts, unlike models 1a and 1b. Therefore, the certified provider need not worry about machine utilization. The essence of this service provider model is to help print parts on - demand when demand arises and OEMs are not able to fulfil it themselves.

7.5. Customers with their own printers (not supplied by the OEM) – Model 3

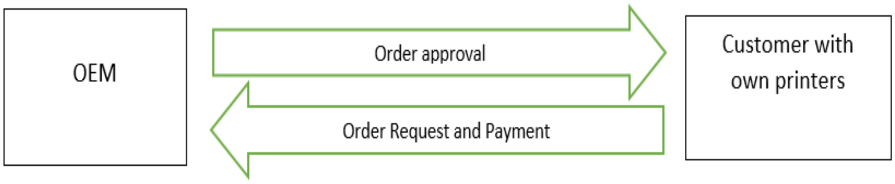


Figure 7.6: Customers with their own printers (own illustration)

First, the customer places an order request to the OEM for spare parts. Upon receiving the order request from the customer, the OEM checks its part library for the design files and approves the customer order. The OEM forwards the design files to the customer and sends an invoice along with the design files. The OEM protects its design IP. The OEM establishes the quality and compliance requirements of the printed parts, and the customer has to ensure the requirements are met. The customer pays the OEM for the design file and receives the file. The OEM provides instructions on the materials and technology to be used. The customer needs to procure materials and the machines to print parts.

The OEMs need not have to procure machines and invest in its maintenance. There is no need for the OEMs to keep an inventory and safety stock of raw materials (powders, metal and filament). All these factors would be taken care of by the customer. The OEM will only have to handover the design files to the customer. This model will be very cost effective for an OEM, indicating the costs incurred for OEMs here is low (similar to model 2). However, for the customer this model would be very capital intensive.

The criticality and downtime factors are addressed well here as the machines are with the customer. Customer has full control over production and can produce on-demand in the lowest possible time. The on - demand availability of parts with good quality will be ensured to a good extent in this model. When spare parts are urgently required to keep the equipment functional and address downtimes, this model would be addressing the issue as good as model 1b as the printers are at the customer location itself. The lead times in this model could be lower compared to models 1a and 2 and similar to model 1b, as the printer is with the customer and technology options are available with the customer. This further indicates that the model offers high technology flexibility.

Approaches used in Model 3 – Customers with their own printers (not supplied by the OEM)

In this model, the customer has the printer at their own facility which can be used by themselves to print spare parts when needed. The customer would know when their equipment, component or assembly goes down due to dysfunctional spare parts, and can print accordingly. The raw materials (powders, metal, filament) will be procured by the customer to use for the machine anticipating demand for spare part that may arise. The

MTO approach would be suitable for this model where customer could gain the benefits of AM that is low setup costs, on-demand production in low volumes, better control over production and fast lead times. The customer demand favours the pull system. The CODP is located upstream, meaning that the printing activities could be postponed till spare parts are needed. The customer can request for the spare parts design from the OEM which would have the same BOM and product specifications. Customer can perform post - processing operations on the parts to meet the strength requirements and obtain better surface finish. The pull - based ETO approach could also be used here. With high technology flexibility, the customer can re-engineer the part design for his requirements. With the pull – based ETO approach, the postponement begins at the design stage itself (figure 6.2). The CODP is completely upstream. If the ETO approach is adopted, the customer can start reengineering the part design first and then procure the materials to print the spare part. This would however need approval from the OEM regarding the strength and safety standards. The MTS approach would not be suitable here because the customer is printing spare parts for themselves and they cannot expect the machine to be utilized to a large extent.

7.6. Chapter 7 Sub – Conclusion

Table 27: Business Models Description

Models	Criteria					Approaches suitable
	Cost	Criticality	Downtime	Lead times	Technology flexibility	
1a) OEM with local print center (customer without OEM printers)	Highly capital intensive for the OEM.	Addressed well but logistics risks could exist.	Low	Low, but can increase due to the print center's off-site presence	Low	Combination of MTS and MTO
1b) Customer with OEM printers	Capital intensive for the OEM.	Since the printers are with the customers at their own location, no logistics risks exist. Parts can be produced on demand in the lowest possible time	Lower than models 1a) and 2) due to printers located at the customer location	Lower than models 1a) and 2) due to printers located at the customer location	Low	MTO
2) OEM with certified external printing providers	Cost-effective for the OEMs.	Addressed well but logistics risks could exist.	Low	Low compared to model 1a) but higher compared to models 1b) and 3)	High	Combination of MTO and ETO
3) Customers with their own printers (not supplied by the OEM)	Cost-effective for the OEMs.	Since the printers are with the customers at their own location, no logistics risks exist. Parts can be produced on demand in the lowest possible time	Lower than models 1a) and 2) due to printers located at the customer location.	Lower than models 1a) and 2) due to printers located at the customer location.	High	Combination of MTO and ETO

In this chapter, the four business models were studied with reference to certain criteria like costs, downtime, lead time, criticality and technology flexibility (explained in table 27). Each business model has benefits and trade-offs as discussed in sections 7.2 - 7.5. Models 1a and 1b would be capital intensive (costly) for the OEMs. In model 1a, the OEMs need to bear the costs of machine procurement, maintenance within the premises (includes labour), material feed (powders, metal, filament), operation (software), rent and electricity. In model 1b, the OEM needs to bear the machine procurement and maintenance costs (outside the OEM premises) and the other costs would be covered by the customer. Therefore, model 1a is highly capital intensive for the OEM and model 1b is less capital intensive compared to 1a for the OEM. Models 2 and 3 would be cost effective for the OEMs. Models 1b and 3 would be better suited to address lead time, criticality and downtime as the printer is at the customer location, minimizing logistics risks. Models 2 and 3 are more technologically flexible than models 1a and 1b. When the business model topic was discussed with the interviewees, they briefly mentioned models 1a and 1b would be helpful in quickly reacting to demand and is economically useful when used frequently. The respondents felt that model 2 which consists of certified providers would be cost – effective for OEMs and in future this model would be helpful to carry forward the adoption of AM in spare part production. Adding on, the respondents commented that model 3 at the moment would be difficult to implement as it is not easy to convince customers to procure their own AM machines. Furthermore, the approaches such as MTO, MTS and ETO have been studied in relation to each of the business models. For model 1a, it was found that the combination of the MTS and MTO approaches would be ideal, considering the spare parts demand and the high capital investment costs for AM technology. For model 1b, the MTO approach would be ideal as the customer is printing for themselves. For models 2 and 3, a combination of MTO and ETO approaches could be used.

8. Use Cases

This chapter explains the use cases carried out to validate the MCDM tools that is AHP and PROMETHEE. The validation has been carried out only for two parts of the support process that is the criteria description and the decision - making among the criteria for selecting spare parts for AM. The steps followed in the MCDM tools are same as described in chapter 6. Two companies, one in the automotive sector & the other in the sectors of automotive and industrial equipment have been consulted for validating the MCDM tools. Each use case contains a brief description of the company consulted (shown in sub-sections 8.1 and 8.2). The company representatives requested anonymity. Therefore, their names, designations and companies they represent are not described here. These details are known to the researcher and the thesis supervisors.

8.1. Use Case 1

The first use case was conducted with an automotive OEM. The globally acclaimed company produces cars of all segments - sedans, hatchbacks and SUVs (sports utility vehicles). The company is active in producing petrol, diesel and hybrid electric cars. It is one of the leading automakers in the world. As of 2021, the company produced over 3 million units globally and accounted for sales revenues exceeding $4.1 million. The quantities of spare parts they manage is approximately 250,000 which continues to increase every year due to newer product versions being introduced at a fast rate, and an already existing installed base of previous versions.

A discussion was held with a senior manager in the customer service division, which deals with the aftermarket spare parts business. They deal with an extremely diverse spare parts assortment which differs based on the seven storage techniques and Just-in-time principles. To serve customers with spare parts, the company uses mostly the make-to-stock strategy. They also make use of the make-to-order strategy. The decision regarding strategy is dependent on the market demand. The challenges they are facing in managing spare parts are briefly supplier inventory and external situations such as the covid-19 pandemic that has forcefully induced lockdowns and made transportation cumbersome. The respondent expressed that certain plastic and rubber components for spare parts of old vehicles is difficult to produce and manage with conventional manufacturing. The tool procurement and setup consume a lot of time. The respondent felt 3D printing could be helpful in these scenarios. Currently, the company is using 3D printing for prototype parts and exploring future opportunities for spare parts. To carry forward the AM adoption in the company, the importance of external service providers who could offer AM support when needed on - demand was highlighted. This was mentioned keeping in mind the high production costs which they would incur by having 3D printers on – site.

The capabilities of AM to improve responsiveness, minimize costs and others were discussed with them. The company respondent found the objective of reducing costs to be the most important for their business. The criteria listed by the company for reducing costs are 3D printing software licensing & design cost, inventory cost and tooling & tool maintenance cost. The 3D printing software licensing & design cost was chosen as the non –

beneficial criteria by the respondent, and the inventory costs along with tooling & tool maintenance costs were considered beneficial criteria. The AHP and PROMETHEE tools were explained to the company. The company felt both the tools are helpful. For the PROMETHEE tool, the respondent was asked to list spare parts that they would technically consider for AM production. The tables below explain the AHP and PROMETHEE for this second use case. The costs are stated in Indian Rupees. The tables 28 – 35 represent use case 1.

Table 28: AHP Criteria (own illustration)

Reducing costs	Inventory cost	Tooling and tool maintenance costs	3D Printing software licensing and design costs
Inventory cost	1	3	7
Tooling and tool maintenance costs	0.33	1	5
3D Printing software licensing and design costs	0.1428	0.2	1
SUM	1.47	4.20	13.00

Inventory cost with respect to tooling & tool maintenance costs = 3, indicating that tooling & tool maintenance costs with respect to Inventory cost = 1/3 = 0.33

Inventory cost with respect to 3D Printing software licensing & design costs = 7, indicating that 3D Printing software licensing & design costs with respect to Inventory cost = 1/7 = 0.1428

Tooling & tool maintenance costs with respect to 3D Printing software licensing & design costs = 5, indicating that 3D Printing software licensing & design costs with respect to Tooling & tool maintenance costs = 1/5 = 0.2. The sum is calculated column wise. For example, 1.47 = 1 + 0.33 + 0.1428.

Table 29: Criteria Weights (own illustration)

Reducing costs	Inventory cost	Tooling and tool maintenance costs	3D Printing software licensing and design costs	Criteria weight
Inventory cost	0.68	0.71	0.54	0.64
Tooling and tool maintenance costs	0.22	0.24	0.38	0.28
3D Printing software licensing and design costs	0.10	0.05	0.08	0.07

Here, the value of each cell is obtained by dividing the value listed in the previous table by the sum of the columns. For example, 1/1.47 = 0.68, 3/4.2 = 0.71 and 7/13 = 0.64. The criteria weight is calculated by the row-wise average that is (0.68+0.71+0.64)/3 = 0.64.

Table 30: PROMETHEE (own illustration)

Reducing costs	3D Printing software licensing and design costs	Inventory cost	Tooling and tool maintenance costs
Weights	0.07	0.64	0.28
Ornament sub-assembly	1650	55000	2200
Moulding front bumper	156	5190	208
Moulding radiator	1800	60000	2400
Cover Front bumper hole	6000	2,00,000	8000
Max	6,000.00	2,00,000.00	8000
Min	156.00	5,190.00	208

Table 31: Normalizing the matrix (own illustration)

Ornament sub-assembly (P1)	0.744	0.26	0.255
Moulding front bumper (P2)	1	0	0
Moulding radiator (P3)	0.718	0.281	0.282
Cover Front bumper hole (P4)	0	1	1

Here the step 3 of PROMETHEE is used:

For beneficial criteria: Rij = [Xij - min (Xij)] / [max (Xij) – min (Xij)]
For non - beneficial criteria: Rij = [max (Xij) - Xij] / [max (Xij) – min (Xij)]
Where i (number of alternatives) = 1, 2..., n and j (number of criteria) = 1, 2..., m

Here, the 3D printing software licensing & design cost was chosen as the non – beneficial criteria by the respondent, and the inventory costs along with tooling & tool maintenance costs were considered beneficial criteria.

For example:
Ornament sub – assembly (column 1, row 1): [6000 – 1650] / [6000 – 156] = 0.744. This is for the non-beneficial criteria that is ‘3D printing software licensing & design cost’. The formula used here is Rij = [max (Xij) - Xij] / [max (Xij) – min (Xij)].

Table 32: Determining the deviation by pairwise comparison (own illustration)

D(P1-P2)	- 0.255	0.26	0.2556
D(P1-P3)	0.0256	-0.03	-0.0256
D(P1-P4)	0.744	-0.74	-0.744
D(P2-P1)	0.255	-0.26	-0.255
D(P2-P3)	0.281	-0.281	-0.281
D(P2-P4)	1	-1	-1
D(P3-P1)	-0.0256	0.03	0.0256
D(P3-P2)	-0.281	0.281	0.281
D(P3-P4)	0.718	-0.718	-0.718
D(P4-P1)	- 0.744	0.74	0.74
D(P4-P2)	-1	1	1
D(P4-P3)	- 0.718	0.718	0.718

Here, step 4 of PROMETHEE is used:
Dj (a, b) = Gj(a) – Gj(b)
Dj (a, b) = difference between the evaluations of alternative ‘a’ and alternative ‘b’ on each criterion.
D(P1-P2) = 0.744 – 1 = -0.255, D(P1-P3) = 0.744 – 0.718 = 0.0256

Table 33: Preference function and the multi-criteria preference index (own illustration)

D(P1-P2)	0	0.26	0.2556	0.239
D(P1-P3)	0.0256	0	0	0.0018
D(P1-P4)	0.7443	0	0.282	0.13
D(P2-P1)	0.2556	0	0	0.02
D(P2-P3)	0.281	0	0	0.02
D(P2-P4)	1	0	0	0.07

D(P3-P1)	0	0.03	0.0256	0.02
D(P3-P2)	0	0.281	0.28	0.26
D(P3-P4)	0.718	0	0	0.05
D(P4-P1)	0	0.74	0.74	0.69
D(P4-P2)	0	1	1	0.93
D(P4-P3)	0	0.718	0.718	0.67

Here steps 5 & 6 are used. The preference function Pj (a, b) = Fj [dj (a,b)]. Pj (a, b) = difference between the evaluations of one alternative with another alternative on each criterion. These values range from 0 to 1. The negative values obtained are equated to zero and the positive values are taken as it is.
Preference index = Σ Wj * Pj (a, b). The last column on the right side shows the preference index values.

For example, D(P1-P2) = (0.07*0) + (0.64*0.26) + (0.28*0.255) = 0.239. The weights 0.07, 0.64 and 0.28 have been found using AHP in table 29.

Table 34: Calculation of the leaving flow and entering flow (own illustration)

	P1	P2	P3	P4	Leaving flow
P1 (Ornament sub-assembly)	-	0.24	0.00	0.13	0.09
P2 (Moulding front bumper)	0.02	-	0.02	0.07	0.03
P3 (Moulding radiator)	0.02	0.26	-	0.05	0.08
P4 (Cover front bumper hole)	0.69	0.93	0.67	-	0.76
Entering Flow	0.18	0.36	0.17	0.09	

For example:
Leaving flow for ornament sub – assembly = (0.24 + 0.00 + 0.13) / 4 = 0.09

From table 33, the preference index values obtained have been used to calculate the leaving flow and the entering flow in table 34. For example, D(P1-P2) = 0.24 has been used in table 34 and similarly all other values have been used. The leaving flow is calculated by taking the average of the rows and the entering flow is calculated by taking the average of the columns. As shown in table 34, 0.09 = (0+ 0.24 + 0 + 0.13) / 4 and 0.18 = (0 + 0.02+ 0.02 + 0.69) / 4 = 0.18

Table 35: Full ranking (own illustration)

	Leaving flow	Entering flow	Difference	Rank
P1 (Ornament sub-assembly)	0.09	0.18	-0.0876	2
P2 (Moulding front bumper)	0.03	0.36	-0.33	4
P3 (Moulding radiator)	0.08	0.17	-0.09	3
P4 (Cover front bumper hole)	0.76	0.09	0.67	1

The full ranking shown in table 35 is obtained by calculating the difference between the leaving flow and the entering flow for each spare part. The spare part with the highest value in the difference column is ranked first and subsequently the other spare parts are ranked.

8.2. Use Case 2

A second use was conducted with an Indian company well established in the automotive and the non-automotive sectors. In the automotive segment, the company produces single and multi -cylinder diesel engines with power ranging from 8 HP - 135 HP and CNG (Compressed Natural Gas) engines with 9 HP - 15 HP. These engines deliver high fuel efficiency, offer good performance, cost-effective and strictly meet the regulatory norms in India. The engines are made mainly for passenger and commercial vehicles (4 wheelers, 3 wheelers and 2 wheelers). In the non-automotive segment, the company produces industrial generator sets with power ranging from 1000 kVA - 2500 kVA; pump sets, power tillers for agriculture applications; industrial engines for construction and marine applications. Moreover, they also produce electric 2 wheelers and 3 wheelers. Being an equipment producer that caters to different customer segments, the company manages a massive spare parts aftermarket business consisting of over 6000 retail stores for spare parts.

A discussion was held with a person heading the automotive aftermarket business. According to the respondent, the company manages over 5000 quantities of spare parts. Some of the spare parts that they manage are rubber gaskets, rubber shocks, gear shafts, clutch springs etc. The company uses a combination of make-to-stock and make-to-order strategy to deliver spare parts to customers. The challenge that the firm is facing currently is the ability to service old vehicles (faced out of the market) with spare parts, implying product obsolescence is an issue. This is where they felt 3D printing would be helpful. The 3D printing awareness of the organization is low. The respondent highlighted that the firm is currently performing research on 3D printing technologies and using it for testing prototypes. In future, they are planning to use 3D printing not only for spare parts but also assemblies. They expect issues like product obsolescence, low volumes and customization to be tackled with 3D printing. Furthermore, the respondent mentioned the importance of external service providers for 3D printing spare parts as they would be cost-effective and best suited to produce parts in low volumes for the company.

The objectives of improving responsiveness and reducing costs were explained to the respondent. As obtained in the interviews conducted previously for the study, the criteria for improving responsiveness were on - demand availability, lead time and downtime (shown in section 6.1). But, in this use case responsiveness was explained by the respondent using the criteria of emergency response, vehicle downtime and scale of parts (demand range). The AHP and PROMETHEE tools were shown. The company respondent felt that the AHP tool is currently helpful. The tables 36 – 37 represent use case 2.

Table 36: AHP Criteria chosen by the use case 2 respondent (own illustration)

Improving Responsiveness	Emergency response	Vehicle downtime	Demand Range
Emergency response	1	7	9
Vehicle downtime	0.1428	1	9
Demand Range	0.11	0.11	1
SUM	1.254	8.1	19

Emergency response with respect to vehicle downtime = 7, indicating that vehicle downtime with respect to emergency response = 1/7 = 0.1428

Emergency response with respect to demand range = 9, indicating that demand range with respect to emergency response = 1/9 = 0.111

Vehicle downtime with respect to demand range = 9, indicating that demand range with respect to vehicle downtime = 1/9 = 0.111

Table 37: Weights using AHP (own illustration)

Improving Responsiveness	Emergency response	Vehicle downtime	Demand Range		Criteria weight
Emergency response	0.797	0.863	0.473		0.711
Vehicle downtime	0.114	0.123	0.473		0.236
Demand Range	0.088	0.013	0.0526		0.051

Here, the value of each cell is obtained by dividing the value listed in the previous table by the sum of the columns. For example, 1/1.253 = 0.797, 7/8.11 = 0.863 and 9/19 = 0.473. The criteria weight is calculated by the row-wise average that is (0.797 + 0.863 + 0.473)/3 = 0.711.

8.3. Chapter 8 Sub - Conclusion

Two use cases have been conducted to validate the MCDM tools described in the study. In the first use case, both AHP and PROMETHEE tools were found to be helpful. Using the PROMETHEE tool, the cover front bumper hole was ranked 1st, ornament sub-assembly was ranked 2nd, moulding radiator was ranked 3rd and the moulding front bumper was ranked 4th. This is shown in table 35. When the respondent was asked to rate the preference of the parts for 3D printing without the PROMETHEE tool, the 1st priority was assigned for ornament sub-assembly, and 2nd priority for the cover front bumper hole. The other two parts were the same. The difference is due to the fact ornament sub - assembly is lower in demand and slow - moving compared to the cover front bumper hole. The respondent expressed that expensive tooling and maintenance costs can be saved on the ornament sub - assembly. Even though the costs associated with the cover front bumper hole are much higher, the respondent felt that the economies of scale are being met with conventional production and the costs are justified. Therefore, 3D printing would be helpful for the ornament sub – assembly by printing on demand. The respondent further stated that inventory of ornament sub – assembly is in excess and its costs are on the rise. Moreover, this part is of small size and would be easier to print compared to the other parts.

In the 2nd use, only the AHP tool was found to be helpful. The respondent felt the PROMETHEE tool which helps in prioritizing spare parts for AM needs more discussion. The respondent expressed that this is due to the fact that objectives and criteria for each company to manage spare parts vary. Moreover, when the respondent was asked to quantify emergency response, vehicle downtime and market demand, it was difficult to provide accurate information as they would be different for every spare part. Also, the spare parts would be different across product lines. An average of values for emergency response, vehicle downtime and market demand were suggested. The average values however don’t help in prioritizing spare parts for AM. All values would end up being equal and the prioritization for AM production cannot be done. The respondent suggested that the decision - making tool should have many more criteria and inputs need to be taken from different stakeholders. Adding on, the respondent felt that the tool is industry specific. The AHP tool was useful for both the companies and it helped prioritize the objectives and decide on the relevant criteria for AM production of spare parts.

9. Conclusion, Recommendations and Discussions

The purpose of this chapter is to answer the research questions and derive important conclusions (shown in sub-section 9.1). Furthermore, this chapter describes study limitations and the recommendations for further research (shown in sub-sections 9.2 - 9.3). The chapter discusses the research contributions and implications of the study (shown in sub-section 9.4). Also, the chapter describes the personal reflection and the feedback to the Management of Technology masters' program (shown in sub-sections 9.5 – 9.6).

9.1. Conclusion

To achieve the thesis objective, a market study has been conducted and a support process has been developed using the study on perceived usefulness, spare part selection tools and business models for spare part production. A market study has been made regarding the AM Technologies, materials, factors affecting AM product quality and cost drivers for AM adoption, benefits of AM and challenges to AM adoption in spare parts and end products. This has been done to explore the future potential of AM in spare parts. It was found that Powder Bed Fusion (PBF) is the most preferred technique for industrial AM adoption, for both metal and polymer applications. PBF supports the usage of many materials, indicating that it is very versatile. The cost drivers driving AM adoption in spare parts were found to be machine, materials, post processing, labour and energy. The challenges to AM adoption (section 5.4) were found to be Technology awareness, costs and ROI, strength and other physical properties.

The design objective of the thesis was to develop a support process for machine users and machine producers to make the right selection of spare parts for AM and decide on the appropriate business models to produce the spare parts by AM. It is shown in the figure below:

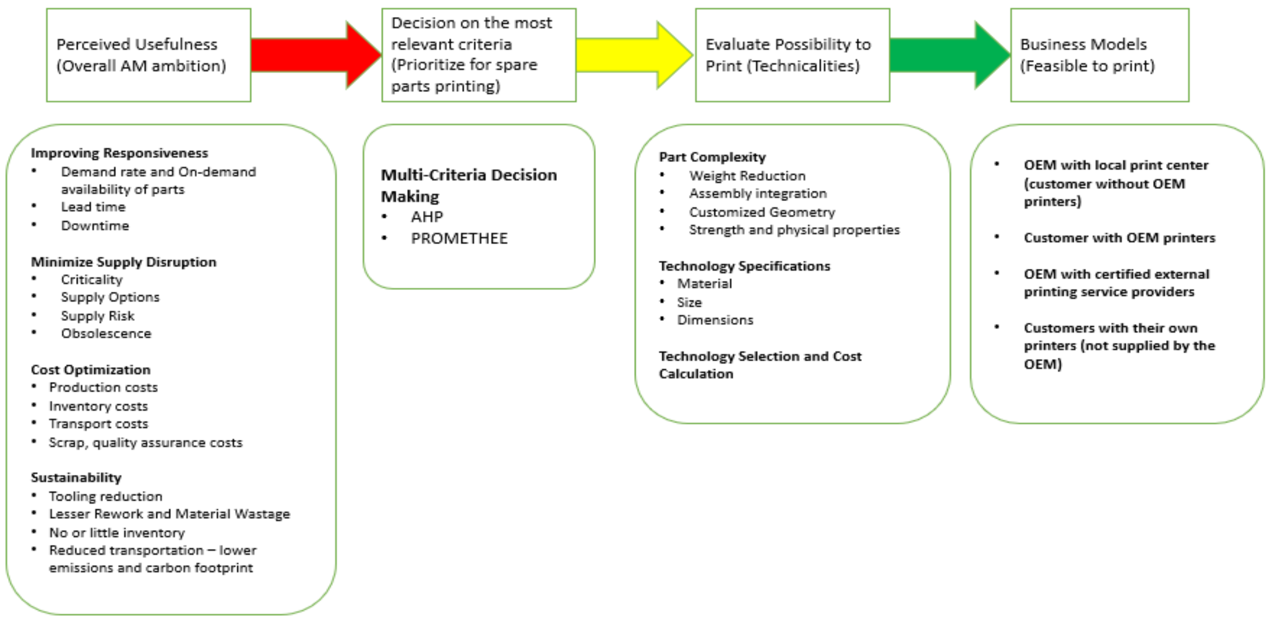


Figure 9.1: Support Process

For achieving the design objective, three research questions had been formulated in Chapter 2. All these questions have been answered with a combination of interviews and literature study.

- The first research question is – "What could be the criteria to describe the perceived usefulness of AM for those producing spare parts?"

This research describes perceived usefulness using performance parameters such as Increased Responsiveness, Minimized Supply Disruption, Cost Optimization, Part Complexity and Sustainability. These have been further explained in detail using economic and technical criteria in the paragraphs below.

The concept of Increased Responsiveness has been explained by Demand Rate and Availability of parts on - demand, Lead times and Downtime as these were the options chosen by the interviewees. AM enables production on demand, reducing the need to stock up spare parts as inventory. For parts with low and volatile demand rates and slow-moving parts with intermittent and lumpy patterns, AM could definitely be a possible solution. Firms could minimize the inventory of these kinds of parts and also save on costs associated with them by printing on - demand. With constantly changing product lifecycles, these issues occur and could be tackled by using AM. By having digital design files, parts can be printed near the location of the customer and delivered, leading to a reduction in lead times (production, delivery and replenishment). With AM, machine downtimes could be addressed, by making parts available as quickly as possible to keep the equipment running.

Minimized supply disruption takes into account Criticality, Supply Options, Supply Risk and Obsolescence. As discussed previously the study by Molenaars et al. (2012) classified spare parts into the categories of vital, essential and desirable. For each of these categories, the usage of AM can be justified to address the issues of limited supply options and part failures in short durations of time. When it comes to spare parts classified according to levels of criticality as low, medium and high where unavailability of a part becomes an issue and risks in supply cannot be tolerated, AM could be helpful. In the traditional manufacturing scenario, the supply risks and obsolescence are major issues. With the ability to store design files and economically print in small lot sizes, the issues of supply risk and obsolescence can be tackled.

Cost optimization considers costs associated with production, quality assurance and scrap, inventory and transportation. At the moment, the production costs of AM compared to conventional manufacturing is high, although it helps save on tooling and injection moulds. AM however helps on reducing transportation costs by printing on-location (minimizing distances) and saves on inventory costs by storing inventory digitally. AM enables reduction of costs associated to scrap, therefore testing prototypes is cheaper with AM.

Part complexity is explained by the ability of AM to create parts that are difficult to create using traditional manufacturing, provide customized geometry, minimize weight, integrate assemblies and use different materials to obtain desired physical properties. This has been described with industry use cases (attached in appendix).

Sustainability is described with the help of tooling reduction, lesser material wastage and rework, reduced transportation and inventory. In conventional manufacturing, tools and injection moulds have to be setup and tools will need to be replaced once they get worn out. For low volume spare parts, this will not be economical indicating AM could be helpful to produce in low quantity and minimize the tools needed in the process. AM processes being less resource dependant, curbs the problem of material wastage and the rework is not costly. Prototypes can be designed and tested multiple times with AM, which would be very costly otherwise. Due to production on location and minimization of long transport distances, AM would make the entire process greener and reduce carbon emissions.

- Moving on, the second research question is - "Based on the criteria, how could spare parts be selected to be produced by AM?"

This question deals with how objectives of organizations with respect to spare parts management can be decided and choosing the criteria to achieve those objectives. Also, this question deals with the prioritization of spare parts for AM. MCDM tools namely AHP and PROMETHEE have been used because of their ability to be user - friendly, handle as many objectives and alternatives as possible and their success in decision making problems. The steps used in both the tools have been described in chapter 6.

The use of the AHP and PROMETHEE tools have been displayed in the use cases shown in chapter 8. In the 1st use case, both AHP and PROMETHEE tools were useful to help select spare parts for AM. The respondent picked the objective of reducing costs in the 1st use case and listed the criteria of 3D printing software licensing & design cost, inventory cost and tooling & tool maintenance cost. Using the PROMETHEE tool, a ranking of spare parts for AM production was obtained. This was compared with the respondent's preferences without the PROMETHEE tool and found that minor differences in preference exists. In the 2nd use case, only the AHP was found to be useful. The respondent picked the objective of improving responsiveness and listed the criteria for it (emergency response, vehicle downtime and demand range), but was unable to provide numbers for it.

- The third research question is – "What could be the possible business models to produce the spare parts, given the spare part criteria?"

Totally four business models have been studied which are – 1a) OEM with local print center (customers without OEM printers), 1b) customer with OEM printers, 2) OEM with certified external service providers and 3) Customers with their own printers. Each of these models have been described according to criteria such as costs, lead time, downtime, criticality and flexibility.

From the study conducted in chapter 7, it was found that models 1a and 1b would be capital intensive for the OEMs, whereas models 2 and 3 would be cost effective for the OEMs. Models 1b and 3 would be better suited to address lead time, criticality and downtime as the printer is at the customer location, minimizing logistics risks. Models 2 and 3 are more technologically flexible than models 1a and 1b. Furthermore, it was found that models 1a and 1b would be helpful in quickly reacting to demand and is economically useful when used frequently. From the interviews, it has been found that the business models that could see increasing adoption in future are the first three (models 1a, 1b and 2) as described above. The respondents expressed it would be difficult to implement Model 3 because at the moment, it is not easy to convince customers to invest in 3D printing. Moreover, for models 2 and 3 the issues of design IP were put forth by the respondents, indicating that OEMs would not offer consent easily to external providers or outside customers as it is risky.

Adding on, the MTO, MTS and ETO approaches have been studied in relation to each of the business models. For model 1a, it was found that the combination of the MTS and MTO approaches would be ideal, considering the spare parts demand and the high capital investment costs for AM technology. For model 1b, the MTO approach would be ideal as the customer is printing for themselves. For models 2 and 3, a combination of MTO and ETO approaches could be used.

From the market study and the perceived usefulness parameters obtained in Chapter 5, it can be inferred that currently 3D printing the entire quantity of spare parts of different varieties across firms will not be possible. The parts which are generally difficult to design, produce and manage in the conventional scenario should be preferred for AM production. It is shown previously in research and the interviews conducted that the slow - moving spare parts for phased - out products are difficult to manage, whereas the high-demand spare parts for latest products with a high installed base is easy to manage. Firms utilize a combination of make-to-stock (MTS) and make-to-order (MTO) approaches as discussed previously. Therefore, AM would be ideally suited to complement the ongoing MTS approach with MTO and ETO approaches for producing the slow - moving spare parts. Moreover, the study shows that criteria desired for parts to be AM produced are commonly small lot sizes, fluctuating demand rates, long lead times and downtime, high inventory costs, high supply risks and obsolescence.

9.2. Limitations of the Study

Like any other research project, this project too has limitations. First and foremost, five interviews have been conducted for this project. It was possible to obtain sufficient quantity of information with good quality, but the quality can definitely improve with a higher sample size. Moreover, only one OEM was available to participate in the research study. The firms contacted for this research study were interested in the spare parts business and found this to be a good application area for AM but were not managing spare parts directly. Only one firm (the OEM) was managing spare parts directly.

With the MCDM tools, AHP was found to be well applicable given that it can handle many objectives and criteria put forth by decision makers. However, the PROMETHEE tool needs to be tested in the industry specifically to prioritize spare parts for AM production.

Moreover, given the time constraints and the availability of interviewees, the business models could not be tested and validated. From the interviewees, it was only possible to obtain the opinions regarding the benefits and drawbacks of each business model, and how they would foresee the future adoption of each business model.

9.3. Recommendations for further research

Due to certain limitations listed above, there exists potential for further research and discussions.

It would be advisable to involve more OEMs when studying AM for spare parts as they would be managing spare parts directly. The information obtained in this study is qualitative. Quantitative studies featuring numbers and other statistics would definitely be extra helpful in strategizing for AM adoption.

When using MCDM tools such as PROMETHEE, it is recommended to carry out a field study in the industry and address specifically their objectives. As explained in the second use case, spare parts in a company vary across product lines with respect to criteria such as vehicle downtime, market demand and emergency response. As stated in Chapter 8, it was difficult to obtain values for the criteria and prioritize spare parts for AM. This is for a single automotive company. Across industries, the variation can be much more. For companies in other sectors such as aircrafts, rail and ships, the objectives they seek to achieve will vary. In aircrafts, mostly weight reduction is desired because this would help in achieving fuel savings. With this in mind, the aircraft sector would adopt AM as shown in certain industry use cases (attached in appendix). Also, it is recommended to have a data - driven tool that relies on industry specific statistics.

The discussion on business models to produce spare parts by AM is fairly new. As of this moment, only four business models have been discussed in the study. Certain criteria have been explained for the business models. These business models however need to be tested in the industry to gain in-depth knowledge of the involved costs, downtimes, lead times, technology flexibility and other criteria. Issues such as Intellectual Property (IP) and Quality with AM technologies need to be dealt with in greater detail in future studies. To validate the support process with use cases, this study has considered the criteria selection and the decision - making part, leaving out the business models. Therefore, the business models' part of the support process needs to be validated.

9.4. Discussions (Research Contribution and Practical Implications)

This section discusses the contribution of the study to research, and the practical implications of the study.

The research conducted previously on the use of AM technology in spare parts is limited. The thesis project contributes to academic research on additive manufacturing in spare parts by developing a theory of perceived usefulness. The perceived usefulness of AM in spare parts has been investigated in this study with economic and technical criteria, which had not been done previously. The perceived usefulness theory and the MCDM tools could be helpful for technology managers and aftermarket business experts to describe their objectives for spare parts management, decide on the relevant criteria and prioritize spare parts for AM. The project also contributes to research by expanding on the MCDM tools and the feasible business models to 3D print spare parts. Previously, only AHP was used as an MCDM tool, but now this study has incorporated both AHP and PROMETHEE to help select spare parts for AM. The market study could be useful for industry practitioners (managers or entrepreneurs) to know the current AM market trends with respect to technology, materials, factors driving AM adoption, benefits and challenges of AM in spare parts. With the market study, the appropriate technology can be chosen (given the costs and other limitations) to print spare parts on demand. The business models described in this research and not been done before is relevant for industry and academia. For established firms who have adopted AM on a small scale, plan to adopt AM in future, or for start - ups, the business models presented could help them decide whether to perform the AM activities in-house or outsource to external providers. From an academic perspective, the business models could be studied further on the basis of criteria such as criticality, lead times, downtime, technology flexibility etc. used in the study. This project could drive further research on the perceived usefulness of AM in spare parts, testing of the business models and application of MCDM tools in different sectors. The study moreover contributes to research by incorporating a business perspective which is needed to increase the adoption of AM. Normally otherwise the topic would be studied from a technical point of view. Overall, the project reflects on the importance of the spare parts business for firms and how AM could help in achieving competitive advantage. It is important for firms to strategically adopt AM in combination with Traditional Manufacturing to reduce complexities in spare parts management. The support process as shown in Figure 9.1 can be used by firms to strategize for AM production.

9.5. Reflection

Overall, working on the master thesis project was an exhilarating experience. I enjoyed learning the topic of additive manufacturing. I generally like reading about Industry 4.0 technologies and additive manufacturing is one among them, hence I picked this topic to work on for my master thesis. I learned that it is definitely a challenge to implement this technology in organisations due to the costs involved and the skills required, but provides many long - term business opportunities in the spare parts business. AM is being adopted by industries nowadays on an increasing scale as its benefits are being realised.

The literature study at the start of the thesis provided a lot of valuable information which was of immense value. This process of literature study demanded good academic knowledge and critiquing ability, which I could develop over the course of time. This allowed me to independently think and go beyond my limits to look for research gaps and fill them accordingly. The interviews with subject and business experts gave me a chance to gain insights which I wouldn't have obtained otherwise. I was able to ask different kinds of questions and come to conclusions, which is important for a researcher.

The process of combining interview observations with literature study was indeed time - consuming and rewarding. By conducting more interviews, I gained confidence in my capabilities and was able to make better interpretations of the information gained. I spent long hours on this project learning new concepts and improving my writing skills. Throughout the course of the thesis project, I learned that it is extremely necessary to have a study focus that would lead to answering the research questions and filling the research gaps.

When I look back, I realize the importance of the feedback given by my supervisors which helped in improving the quality of the research project. Through this experience, I learned to not only improve my work quality, but also improve myself as a person. I look forward to the journey ahead.

9.6. Feedback to the MOT Program

The Masters journey of two years (2019 - 2021) in Management of Technology (MOT) at TU Delft taught me a lot of new things. Through lectures, assignments and exams, the course provided me the opportunity to learn and apply different techniques to solve problems that could arise in research and business. By interacting with professors and classmates, I got a chance to expand my horizons, be sensitive to different cultures and gain more knowledge. I would definitely recommend more assignments (both group and individual) to be organized across courses where students will be able to apply the theoretical concepts in a practical setting. Moreover, for the incoming students (from 2021 onwards), I feel it would be good to include mandatory internships in the MOT curriculum as this would provide a great opportunity for practical application of theoretical concepts. Also, it would be good if course assignments could be organised as case studies within the industry, where students would be exposed to applying the knowledge gained from all MOT subjects to solve real – life problems.

References

3D Hubs. (2020). 3D printing trends 2020 industry highlights and market trends. https://www.3dhubs.com

3D printing at DB | Deutsche Bahn AG. (2016). Deutsche Bahn. https://www.deutschebahn.com/en/Digitalization/technology/New-Technology/3d_printing-3520386

3D Printing on Demand - Establishing a Sustainable Spare Parts Management System. (2019). EOS GmbH. https://www.eos.info/en/3d-printing-examples-applications/all-3d-printing-applications/daimler-3d-printing-on-demand

Albastroiu, I. (2012). Supply Chain Strategies. Valahian Journal of Economic Studies, 45---52.

Abdulhameed, O., Al-Ahmari, A., Ameen, W., & Mian, S. H. (2019). Additive manufacturing: Challenges, trends, and applications. Advances in Mechanical Engineering, 11(2), 1–27. https://doi.org/10.1177/1687814018822880

Abdullah, L., Chan, W., & Afshari, A. (2019). Application of PROMETHEE method for green supplier selection: a comparative result based on preference functions. Journal of Industrial Engineering International, 15(2), 271–285. https://doi.org/10.1007/s40092-018-0289-z

Alghamdi, S. S., John, S., Choudhury, N. R., & Dutta, N. K. (2021). Additive manufacturing of polymer materials: Progress, promise and challenges. Polymers, 13(5), 1–39. https://doi.org/10.3390/polym13050753

Arts, J. J. (2014). Spare parts planning and control for maintenance operations. In Civil-Comp Proceedings (Vol. 104, Issue 2013). https://doi.org/10.4203/ccp.104.301

ASTM International. (2013) Standard Terminology for Additive Manufacturing Technologies (Standard No. F2792 − 12a).

Bacchetti, A. (2010). Challenges in managing spare parts for durable goods : an empirical study. Service Management, June 2010, 1–26. https://doi.org/10.13140/2.1.1067.8726

Bacchetti, A., & Saccani, N. (2012). Spare parts classification and demand forecasting for stock control: Investigating the gap between research and practice. Omega, 40(6), 722–737. https://doi.org/10.1016/j.omega.2011.06.008

Bacchetti, Plebani, Saccani, & Syntetos. (2010). Spare Parts Classification and Inventory Management: a Case Study. Salford Business School Working Papers Series, 408, 1–32. https://doi.org/10.13140/2.1.2968.4161

BASF FORWARD AM. (2021, July 13). BASF 3D Printing Company | BASF FORWARD AM. BASF 3D Printing Materials and Services. https://forward-am.com/

Berman, B. (2012). 3-D printing: The new industrial revolution. Business Horizons, 55(2), 155–162. https://doi.org/10.1016/j.bushor.2011.11.003

Binder Jetting | Additive Manufacturing Research Group | Loughborough University. (2014). Loughborough. https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/binderjetting/

Binkhuysen, A., Hermsen, N., & Schipper, M. (2020). Additive Manufacturing for spare parts: Reducing Risks and Costs — Increasing Service and Functionality.

https://www2.deloitte.com/nl/nl/pages/energy-resources-industrials/articles/industry40-additive-manufacturing-for-spare-parts.html

Boissonneault, T. (2019, February 13). Ultimaker to supply 3D printing tech to Airbus' EU facilities. 3D Printing Media Network - The Pulse of the AM Industry. https://www.3dprintingmedia.network/ultimaker-3d-printing-airbus-eu

Boissonneault, T. (2019b, June 21). Safran introduces Add+ engine demonstrator with 30% 3D printed parts. 3D Printing Media Network - The Pulse of the AM Industry. https://www.3dprintingmedia.network/safran-add-engine-demonstrator-3d-printed/

Boissonneault, T. (2019c, August 28). thyssenkrupp TechCenter granted first DNV GL certification for 3D printed maritime parts. 3D Printing Media Network - The Pulse of the AM Industry. https://www.3dprintingmedia.network/thyssenkrupp-techcenter-gnv-gl-certification-maritime/

Boissonneault, T. (2019d, November 21). Stratasys focuses on 3D printing in transport with Rail Industry Solution. 3D Printing Media Network - The Pulse of the AM Industry. https://www.3dprintingmedia.network/stratasys-focuses-on-3d-printing-in-transport-with-rail-industry-solution/

Boissonneault, T. (2021). Automotive AM: Additive Manufacturing finds its role in the ever evolving automotive sector (Issue January). 3dpbm. https://www.3dprintingmedia.network/3dpbm-publishes-automotive-am-focus-2020-ebook/

Boylan, J. E., & Syntetos, A. A. (2010). Spare parts management: A review of forecasting research and extensions. IMA Journal of Management Mathematics, 21(3), 227–237. https://doi.org/10.1093/imaman/dpp016

Brax, S. (2005). A manufacturer becoming service provider - Challenges and a paradox. Managing Service Quality, 15(2), 142–155. https://doi.org/10.1108/09604520510585334

Campbell, T. W. (2012). Technologies, Potential, and Implications of Additive Manufacturing. Cbpp.Uaa.Alaska.Edu. http://www.cbpp.uaa.alaska.edu/afef/Additive MFG .pdf

Cardeal, G., Höse, K., Ribeiro, I., & Götze, U. (2020). Sustainable business models–canvas for sustainability, evaluation method, and their application to additive manufacturing in aircraft maintenance. Sustainability (Switzerland), 12(21), 1–22. https://doi.org/10.3390/su12219130

Carlota, V. (2020, June 19). All you need to know about ABS for 3D printing. 3Dnatives. https://www.3dnatives.com/en/abs-3d-printing-060620194/

Carlota, V. (2019, August 16). All you need to know about PLA for 3D printing. 3Dnatives. https://www.3dnatives.com/en/pla-3d-printing-guide-190820194/

Çelebi, D., Bayraktar, D., & Aykaç, D. S. Ö. (2008). Multi criteria classification for spare parts inventory. 38th International Conference on Computers and Industrial Engineering 2008, 2(October), 1780–1787. https://doi.org/10.2139/ssrn.1362575

Chatzoglou, P., Vraimaki, E., Diamantidis, A., & Sarigiannidis, L. (2010). Computer acceptance in Greek SMEs. Journal of Small Business and Enterprise Development, Vol. 17, No. 1, pp. 78-101.

Chen, L., He, Y., Yang, Y., Niu, S., & Ren, H. (2017). The research status and development trend of additive manufacturing technology. International Journal of Advanced Manufacturing Technology, 89(9–12), 3651–3660. https://doi.org/10.1007/s00170-016-9335-4

Chiririwa, H. (2021). An overview of recent trends in additive manufacturing with polymer powders, production, applications and developments. Asian Journal of Chemistry, 33(4), 701–711. https://doi.org/10.14233/ajchem.2021.23075

Chua, C. K., & Leong, K. F. (2015). 3D Printing and Additive Manufacturing: Principles and Applications (4th ed.). World Scientific Publishing Company.

Cohen, M. A., & Agrawal, N. (2006). Aftermarket. Harvard Business Review, May. https://doi.org/10.1007/0-387-26336-5_55

Cooper, T., Reagan, I., Chad, P., & Chris, P. (2019). Global fleet & MRO market forecast commentary 2019-2029. In Oliver Wyman.

Cotteleer, M., & Joyce, J. (2014). 3D Opportunity Additive Manufacturing Paths to Performance. Deloitte Development LLC, 3–19. https://www2.deloitte.com/insights/us/en/deloitte-review/issue-14/dr14-3d-opportunity.html

Criales, L. E., Arısoy, Y. M., Lane, B., Moylan, S., Donmez, A., & ÖZel, T. (2017). Laser powder bed fusion of nickel alloy 625: Experimental investigations of effects of process parameters on melt pool size and shape with spatter analysis. International Journal of Machine Tools and Manufacture, 121, 22–36. https://doi.org/10.1016/j.ijmachtools.2017.03.004

Cummins, N. (2020, August). Post Covid-19: Why the Aviation MRO and Aircraft Parts Market Is Going To Grow. Eways Aviation. https://eways-aviation.com/article/post-covid-19-why-the-aviation-mro-and-aircraft-parts-market-is-going-to-grow/

Dantin, M. J., Furr, W. M., & Priddy, M. W. (2018). TOWARDS AN OPEN-SOURCE, PREPROCESSING FRAMEWORK FOR SIMULATING MATERIAL DEPOSITION FOR A DIRECTED ENERGY DEPOSITION PROCESS. Solid Freeform Fabrication 2018: Proceedings of the 29th Annual International Solid Freeform Fabrication Symposium. https://www.researchgate.net/publication/339851144_TOWARDS_AN_OPEN-SOURCE_PREPROCESSING_FRAMEWORK_FOR_SIMULATING_MATERIAL_DEPOSITION_FOR_A_DIRECTED_ENERGY_DEPOSITION_PROCESS

Davies, S. (2020, June 16). Marine supplier Wärtsilä 3D prints CE-certified lifting tool with Markforged. TCT Magazine. https://www.tctmagazine.com/additive-manufacturing-3d-printing-news/marine-w%C3%A4rtsil%C3%A4-3d-prints-ce-certified-lifting-tool/

Davis, F. (1989). Perceived Usefulness, Perceived Ease of Use, and User Acceptance of Information Technology. MIS Quarterly, Vol. 13, No. 3, pp. 319-340. 53 Davis, F. (1993). User acceptance of information technology: System characteristics, user perceptions and behaviour impacts. International Journal of Man-Machine Studies, Vol. 38, pp. 475-487.

Davis, F., & Venkatesh, V. (1996). A critical assessment of potential measurement biases in the technology acceptance model: Three experiments. International Journal of Human-Computer Studies, Vol 45, pp. 19-45.

Dicken, P. (2011) Global shift: Mapping the changing contours of the world economy. 6th edition. New York: The Guilford Press.

Digital Alloys. (2019, July 11). Metal Binder Jetting.https://www.digitalalloys.com/blog/binder-jetting/

Directed Energy Deposition | Additive Manufacturing Research Group | Loughborough University. (2014). Loughborough. https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/directedenergydeposition/

Donaldson, B. (2019, May 20). Mission Critical: GE Additive. https://www.additivemanufacturing.media/mission-critical/

Dongdong, G., & Xingwu, Y. (2018). The Lean Management of Spare Parts in Automotive Manufacturing. International Conference on Information Processing and Control Engineering, 214. https://doi.org/10.1051/matecconf/201821404005

Durão, L. F. C. S., Christ, A., Anderl, R., Schützer, K., & Zancul, E. (2016). Distributed Manufacturing of Spare Parts Based on Additive Manufacturing: Use Cases and Technical Aspects. Procedia CIRP, 57, 704–709. https://doi.org/10.1016/j.procir.2016.11.122

Eaves, A. H. C., & Kingsman, B. G. (2004). Forecasting for the ordering and stock-holding of spare parts. Journal of the Operational Research Society, 55(4), 431–437.

https://doi.org/10.1057/palgrave.jors.2601697

EOS. (2021a). EOS Metal 3D Printing Materials. EOS GmbH. https://www.eos.info/en/additive-manufacturing/3d-printing-metal/dmls-metal-materials

EOS. (2021b). EOS Polymers for Additive Manufacturing. EOS GmbH. https://www.eos.info/en/additive-manufacturing/3d-printing-plastic/sls-polymer-materials/polyamide-pa-12-alumide

FIGIEFA. (2020). COVID-19 Survey - Impact on independent spare parts distributors (Issue 1). https://doi.org/10.12681/bioeth.22615

Frandsen, C. S., Nielsen, M. M., Chaudhuri, A., Jayaram, J., & Govindan, K. (2020). In search for classification and selection of spare parts suitable for additive manufacturing: a literature review. International Journal of Production Research, 58(4), 970–996. https://doi.org/10.1080/00207543.2019.1605226

Frowein, B., Lang, N., Schmieg, F., & Sticher, G. (2014). Returning to Growth A Look at the European Automotive Aftermarket.

Automotive Aftermarket Industry Worth $529.25 Billion By 2028. (2021). Grand View Research. https://www.grandviewresearch.com/press-release/global-automotive-aftermarket-industry

Geissbauer, Dr. Reinhard Wunderlin, J., & Lehr, D. J. (2017). The future of spare parts is 3D: A look at the challenges and opportunities of 3D printing. In Pricewaterhouse Coopers (Issue 1). https://www.strategyand.pwc.com/gx/en/insights/2017/the-future-spare-parts-3d/the-future-of-spare-parts-is-3d.pdf

Genevois, M. E., Gure, U., & Ocakoglu, K. (2014). Supply Chain Flexibility Metrics Evaluation. In Interdisciplinary Topics in Applied Mathematics, Modeling and Computational Science (117th ed.). Springer.

Gill, P., Stewart, K., Treasure, E., & Chadwick, B. (2008). Methods of data collection in qualitative research: Interviews and focus groups. British Dental Journal, 204(6), 291–295. https://doi.org/10.1038/bdj.2008.192

Godina, R., Ribeiro, I., Matos, F., Ferreira, B. T., Carvalho, H., & Peças, P. (2020). Impact assessment of additive manufacturing on sustainable business models in industry 4.0 context. Sustainability (Switzerland), 12(17), 1–21. https://doi.org/10.3390/su12177066

González-Varona, J. M., Poza, D., Acebes, F., Villafáñez, F., Pajares, J., & López-Paredes, A. (2020). New business models for sustainable spare parts logistics: A case study. Sustainability (Switzerland), 12(8), 3071. https://doi.org/10.3390/SU12083071

Goulding, C. (2020, July 23). 3D Printing: A Lifeline for Automakers Adapting to a Changing Industry. Fabbaloo. https://www.fabbaloo.com/blog/2019/6/28/3d-printing-a-lifeline-for-automakers-adapting-to-a-changing-industry

Gunasekaran, A.T., & Cheng, E. (2008). Special Issue on Logistics: New Perspectives and Challenges. Omega, 36 (4), 505---508.

Haria, R. (2018, February 13). Porsche green-lights 3D printed spare parts for classic cars. 3D Printing Industry. https://3dprintingindustry.com/news/porsche-green-lights-3d-printed-spare-parts-classic-cars-128792/

Heutger, M., & Kückelhaus, M. (2016). 3D Printing and the Future of Supply Chains.

Holmström, J., Partanen, J., Tuomi, J., & Walter, M. (2010). Rapid manufacturing in the spare parts supply chain: Alternative approaches to capacity deployment. Journal of Manufacturing Technology Management, 21(6), 687–697. https://doi.org/10.1108/17410381011063996

Holzmann, P., Breitenecker, R. J., & Schwarz, E. J. (2019). Business model patterns for 3D printer manufacturers. Journal of Manufacturing Technology Management, 31(6), 1281–1300. https://doi.org/10.1108/JMTM-09-2018-0313

Hopkins, N., & Dickens, P. (2003). Analysis of rapid manufacturing - using layer manufacturing processes for production. Journal of Mechanical Engineering Science, 31-39.

HP Multi Jet Fusion 3D Printing Technology - Powder 3D Printer | HP® Official Site. (2021). Hewlett Packard. https://www.hp.com/us-en/printers/3d-printers/products/multi-jet-technology.html

Hsu, C.-L., & Lin, J. (2008). Acceptance of blog usage: The roles of technology acceptance, social influence and knowledge sharing motivation. Information and Management, Vol. 45, No. 1, pp. 65-74.

IATA. (2009). Guidance Material and Best Practices for Fuel and Environmental Management (Issue October).

Iftikhar, U. (2018, December 10). Stratasys to 3D print spare parts on demand for Angel Trains. 3D Printing Industry. https://3dprintingindustry.com/news/stratasys-to-3d-print-spare-parts-on-demand-for-angel-trains-145194/

Jackson, B. (2018, December 12). Volkswagen opens advanced 3D printing center, looks to additive manufacturing in production. 3D Printing Industry. https://3dprintingindustry.com/news/volkswagen-opens-advanced-3d-printing-center-looks-to-additive-manufacturing-in-production-145362/

Jouni, P., Huiskonen, J., & Pirttilä, T. (2011). Improving global spare parts distribution chain performance through part categorization: A case study. International Journal of Production Economics, 133(1), 164–171. https://doi.org/10.1016/j.ijpe.2010.12.025

Kempf, S., Michor, L., Schmidt, M., Comet, A., & Breitschwerdt, D. (2017). The Changing Aftermarket Game - and how autmotive suppliers can benefit from arising opportunities. In Advanced Industries (Issue June). https://www.mckinsey.com/~/media/McKinsey/Industries/Automotive and

Assembly/Our Insights/The changing aftermarket game and how automotive suppliers can benefit from arising opportunities/The-changing-aftermarket-game.ashx

Khajavi, S. H., Partanen, J., & Holmström, J. (2014). Additive manufacturing in the spare parts supply chain. Computers in Industry, 65(1), 50–63. https://doi.org/10.1016/j.compind.2013.07.008

Kim, D.-Y. (2009). The moderating effect of individual and organizational factors on information technology acceptance: the case of U.S. CVBs' internet marketing. Journal of Travel & Tourism Marketing, Vol. 26, No. 3, pp. 329-343.

Knofius, N., Van Der Heijden, M. C., & Zijm, W. H. M. (2016). Selecting parts for additive manufacturing in service logistics. Journal of Manufacturing Technology Management, 27(7), 915–931. https://doi.org/10.1108/JMTM-02-2016-0025

Knulst, R. (2016). 3D printing of marine spares A case study on the acceptance in the maritime industry. Open University Netherlands, 159.

Kok, Y.; Tan, X.P.; Wang, P.; Nai, M.; Loh, N.H.; Liu, E.; Tor, S.B (2018). Anisotropy and heterogeneity of microstructure and mechanical properties in metal additive manufacturing: A critical review. Mater. 139, 565–586.

Kumar, H.A.; Kumaraguru, S. Distortion in Metal Additive Manufactured Parts (2019). In 3D Printing and Additive Manufacturing Technologies; Springer: Berlin/Heidelberg, Germany; pp. 281–295.

Lambert, D.M., & Cooper, M.C. (2000). Issues in Supply Chain Management. Industrial Marketing Management, 65-83.

Lee, J. M., Sing, S. L., Zhou, M., & Yeong, W. Y. (2018). 3D bioprinting processes: A perspective on classification and terminology. International Journal of Bioprinting, 4(2). https://doi.org/10.18063/ijb.v4i2.151

Li, Y., Jia, G., Cheng, Y., & Hu, Y. (2017). Additive manufacturing technology in spare parts supply chain: a comparative study. International Journal of Production Research, 55(5), 1498–1515. https://doi.org/10.1080/00207543.2016.1231433

Mandina, S., & Karisambudzi, J. (2016). Customer retention strategies: A panacea to reducing attrition in the Zimbabwean airline industry. Journal of Marketing Development and Competitiveness, 10(2), 91.

Material Extrusion | Additive Manufacturing Research Group | Loughborough University. (2014b). Loughborough. https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialextrusion/

Material Jetting | Additive Manufacturing Research Group | Loughborough University. (2014). Loughborough. https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/materialjetting/

Miladinov, S. (2018). Adoption of 3D printing technology and its impact on the business. https://lutpub.lut.fi/bitstream/handle/10024/156717/Master_thesis_Miladinov_Stanisha.pdf?sequence=4&isAllowed=y

Molenaers, A., Baets, H., Pintelon, L., & Waeyenbergh, G. (2012). Criticality classification of spare parts: A case study. International Journal of Production Economics, 140(2), 570–578. https://doi.org/10.1016/j.ijpe.2011.08.013

Mordor Intelligence. (2020). COMMERCIAL AIRCRAFT AFTERMARKET PARTS MARKET - GROWTH, TRENDS, COVID-19 IMPACT, AND FORECASTS (2021 - 2026). https://www.mordorintelligence.com/industry-reports/commercial-aircraft-aftermarket

Murat S, Kazan H, Coskun SS (2015) An application for measuring performance quality of schools by using the PROMETHEE multi criteria decision making method. 195(1):729–738

Nath, S. D., & Nilufar, S. (2020). An overview of additive manufacturing of polymers and associated composites. Polymers, 12(11), 1–33. https://doi.org/10.3390/polym12112719

Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T. Q., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. Composites Part B: Engineering, 143(February), 172–196. https://doi.org/10.1016/j.compositesb.2018.02.012

Niaki, M. K., Torabi, S. A., & Nonino, F. (2019). Why manufacturers adopt additive manufacturing technologies: The role of sustainability. Journal of Cleaner Production, 222, 381–392. https://doi.org/10.1016/j.jclepro.2019.03.019

Öberg, C., Shams, T., & Asnafi, N. (2018). Additive Manufacturing and Business Models: Current Knowledge and Missing Perspectives. Technology Innovation Management Review, 8(6), 15–33. https://doi.org/10.22215/timreview/1162

Olhager, J. (2010). The role of the customer order decoupling point in production and supply chain management. Computers in Industry, 61(9), 863–868. https://doi.org/10.1016/j.compind.2010.07.011

Oosthuizen, G. A., Hagedorn-Hansen, D., & Gerhold, T. (2013). Evaluation of Rapid Product Development Technologies for Production of Prosthesis in Developing Communities. SAIIE25 Proceedings, July, 590.1-590.14. http://conferences.sun.ac.za/index.php/saiie25/SAIIE25/paper/viewFile/590/217

Pannett, L. (2019). Supercharg3d: How 3D Printing Will Drive Your Supply Chain (1st ed.). Wiley.

Peeters, K., & van Ooijen, H. (2020). Hybrid make-to-stock and make-to-order systems: a taxonomic review. International Journal of Production Research, 58(15), 4659–4688. https://doi.org/10.1080/00207543.2020.1778204

Pei, E.; Loh, G.H. Future challenges in functionally graded additive manufacturing (2019). In Additive Manufacturing—Developments in Training and Education; Springer: Berlin/Heidelberg, Germany; pp. 219–228.

Perumal, H. (2006). Improving Supply chain in your business. International Institute of Management.

Petrovic, V., Vicente Haro Gonzalez, J., Jordá Ferrando, O., Delgado Gordillo, J., Ramon Blasco Puchades, J., & Portoles Grinan, L. (2011). Additive layered manufacturing: Sectors of industrial application shown through case studies. International Journal of Production Research, 49(4), 1061–1079. https://doi.org/10.1080/00207540903479786

Powder Bed Fusion | Additive Manufacturing Research Group | Loughborough University. (2014). Loughborough. https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/powderbedfusion/

Ramanathan, R. (2006). ABC inventory classification with multiple-criteria using weighted linear optimization. Computers and Operations Research, 33(3), 695–700. https://doi.org/10.1016/j.cor.2004.07.014

Rayna, T., & Striukova, L. (2016). From rapid prototyping to home fabrication: How 3D printing is changing business model innovation. Technological Forecasting and Social Change, 102, 214–224. https://doi.org/10.1016/j.techfore.2015.07.023

Reeves, P., & Mendis, D. (2015). The Current Status and Impact of 3D Printing Within the Industrial Sector: An Analysis of Six Case Studies The Current Status and Impact of 3D Printing Within the Industrial Sector: An Analysis of Six Case Studies Published by The Intellectual Property Of (Issue February). www.econolyst.co.uk

Reeves, P., Tuck, C., & Hague, R. (2010). Mass Customization Engineering and Managing Global Operations. In Mass Customization Engineering and Managing Global Operations.

Renishaw: Additive manufacturing case studies. (2021). Renishaw. https://www.renishaw.com/en/additive-manufacturing-case-studies--44452

Ribeiro, H. (2019, November 8). Volkswagen on its way to mass production with HP Metal Jet. Metal Additive Manufacturing. https://www.metal-am.com/volkswagen-on-its-way-to-mass-production-with-hp-metal-jet/

Ribeiro, H. (2019a, February 15). Liebherr begins serial metal Additive Manufacturing of aerospace components. Metal Additive Manufacturing. https://www.metal-am.com/liebherr-begins-serial-metal-additive-manufacturing-of-aerospace-components/

Ryan, M. J., Eyers, D. R., Potter, A. T., Purvis, L., & Gosling, J. (2017). 3D printing the future: scenarios for supply chains reviewed. International Journal of Physical Distribution & Logistics Management, 47(10), 992–1014. https://doi.org/10.1108/ijpdlm-12-2016-0359

Rylands, B., Böhme, T., Gorkin, R., Fan, J., & Birtchnell, T. (2016). The adoption process and impact of additive manufacturing on manufacturing systems. Journal of Manufacturing Technology Management, 27(7), 969–989. https://doi.org/10.1108/JMTM-12-2015-0117

Saaty, R. W. (1987). The analytic hierarchy process-what it is and how it is used. Mathematical Modelling, 9(3–5), 161–176. https://doi.org/10.1016/0270-0255(87)90473-8

Sasson, A., & Johnson, J. C. (2016). The 3D printing order: variability, supercenters and supply chain reconfigurations. International Journal of Physical Distribution and Logistics Management, 46(1), 82–94. https://doi.org/10.1108/IJPDLM-10-2015-0257

Sekaran, U., & Bougie, R. (2016). Research Methods for Business (7th Editio). John Wiley & Sons Ltd.

Seifi, M.; Gorelik, M.; Waller, J.; Hrabe, N.; Shamsaei, N.; Daniewicz, S.; Lewandowski, J.J (2017). Progress towards metal additive manufacturing standardization to support qualification and certification. JOM 2017, 69, 439–455.

Shah, J., Snider, B., Clarke, T., Kozutsky, S., Lacki, M., & Hosseini, A. (2019). Large-scale 3D printers for additive manufacturing: design considerations and challenges. The International Journal of Advanced Manufacturing Technology, 104(9–12), 3679–3693. https://doi.org/10.1007/s00170-019-04074-6

Sheet Lamination | Additive Manufacturing Research Group | Loughborough University. (2014). Loughborough. https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/sheetlamination/

Shiu, C. P., Hua, P., & Feng, L. (2013). Driving Aftermarket Value : Upgrade Spare Parts Supply Chain.

Simpson, T.W.; Williams, C.B.; Hripko, M (2017). Preparing industry for additive manufacturing and its applications: Summary & recommendations from a National Science Foundation workshop. Addit. Manuf. **2017**, 13, 166–178.

Singamneni, S., LV, Y., Hewitt, A., Chalk, R., Thomas, W., & Jordison, D. (2019). Additive Manufacturing for the Aircraft Industry: A Review. Journal of Aeronautics & Aerospace Engineering, 08(01). https://doi.org/10.35248/2168-9792.19.8.215

Staff, W. (2021). What are the differences between PA12 and PA11? Weerg. https://www.weerg.com/en/global/blog/what-are-the-differences-between-pa12-and-pa11

Stevenson, K. (2020, July 23). 3D Printing in Automotive: Has The Time Come? Fabbaloo. https://www.fabbaloo.com/blog/2019/5/6/3d-printing-in-automotive-has-the-time-come?utm_source=Fabbaloo+Weekly+Newsletter&utm_campaign=c5bf26df14-RSS_EMAIL_CAMPAIGN&utm_medium=email&utm_term=0_8e413a483a-c5bf26df14-116561513

Stevenson, K. (2020b, August 21). BMW's New Additive Manufacturing Plant Won't Be The Last. Fabbaloo. https://www.fabbaloo.com/blog/2020/8/21/bmw-additive-manufacturing-plant-wont-be-the-last?utm_source=newsletter&utm_medium=email&utm_campaign=fabbaloo_weekly_3d_printing_news&utm_term=2020-08-24

Syntetos, A. A., & Boylan, J. E. (2001). On the bias of intermittent demand estimates. International Journal of Production Economics, 71(1–3), 457–466. https://doi.org/10.1016/S0925-5273(00)00143-2

Tavana M, Behzadian M, Pirdashti M, Pirdashti H (2013) A PROMETHEE-GDSS for oil and gas pipeline planning in the Caspian Sea basin. J Energy Econ 36(1):716–728

Thewihsen, F., Karevska, S., Czok, A., Jones-Pateman, C., & Krauss, D. (2016). If 3D printing has changed the industries of tomorrow , how can your organization get ready today ? In Ernst and Young 3D Printing Report 2016. www.ey.com/3Dprinting%0Ahttp://www.ey.com/Publication/vwLUAssets/Accelerate_your_3D_technology_journey_in_oil_and_gas/$FILE/ey-3dprinting-journey-oil-and-gas.pdf

Thomas, D. S., & Gilbert, S. W. (2015). Costs and cost effectiveness of additive manufacturing: A literature review and discussion. Additive Manufacturing: Costs, Cost Effectiveness and Industry Economics, 1–96.

Topan, E., & Bayindir, Z. (2012). Multi - item two echelon spare parts inventory control problem with batch ordering in the central warehouse under compound Poisson demand. The Journal of the Operational Research Society, 1143---1152.

Vafadar, A., Guzzomi, F., Rassau, A., & Hayward, K. (2021). Advances in metal additive manufacturing: A review of common processes, industrial applications, and current challenges. Applied Sciences (Switzerland), 11(3), 1–33. https://doi.org/10.3390/app11031213

Van der Auweraer, S., Boute, R. N., & Syntetos, A. (2018). Forecasting Spare Part Demand with Installed Base Information: A Review. SSRN Electronic Journal, April 2019. https://doi.org/10.2139/ssrn.3104452

VAT Photopolymerisation | Additive Manufacturing Research Group | Loughborough University. (2014). Loughborough. https://www.lboro.ac.uk/research/amrg/about/the7categoriesofadditivemanufacturing/vatphotopolymerisation/

Velasquez, M., & Hester, P. (2013). An analysis of multi-criteria decision making methods. International Journal of Operations Research, 10(2), 56–66.

Wagner, S. M., Jönke, R., & Eisingerich, A. B. (2012). A strategic framework for spare parts logistics. California Management Review, 54(4), 69–92. https://doi.org/10.1525/cmr.2012.54.4.69

Wahba, E. M., Galal, N. M., & El-kilany, K. S. (2012). Framework for Spare Inventory Management. World Academy of Science, Engineering and Technology, 68(8), 1849–1856.

Waters, C. (2019). Advancing the role of additive manufacturing in rail. Globalrailwayreview. https://www.globalrailwayreview.com/article/93150/interview-stefanie-brickwede-3d-printing/

Widmer, M., & Rajan, V. (2016). 3D opportunity for intellectual property risk. Deloitte University Press.

Wing, I., Gorham, R., & Sniderman, B. (2017). 3D opportunity for quality assurance and parts qualification. Deloitte University Press, 1–37. https://www2.deloitte.com/content/dam/insights/us/articles/3d-printing-quality-assurance-in-manufacturing/DUP_1410-3D-opportunity-QA_MASTER1.pdf

Yarbrough, A., & Smith, T. (2007). Technology Acceptance among Physicians: A New Take on TAM. Medical Care Research and Review, Vol. 64, No. 6, pp. 650-672.

Yusuf, S. M., Cutler, S., & Gao, N. (2019). Review: The impact of metal additive manufacturing on the aerospace industry. Metals, 9(12). https://doi.org/10.3390/met9121286

Zayer, E., & Hoffmann, M. (2020). Covid-19 Will Hurt the Auto Parts Market in 2020 and Beyond. https://www.bain.com/insights/covid-19-will-hurt-the-auto-parts-market-in-2020-and-beyond-infographic/

APPENDICES

APPENDIX 1 - Interview Notes

1.1. Firm 1 (OEM)

Value added in engineering with AM:

1. **Could you give us a description of the parts your company produces (Simple, Complex)?**

   Yes, we produce both simple and complex parts.

2. **Which production technology are you currently using to produce the complex parts?**

   We use CNC technology with 5 axes (or more) machines, laser cutting, sheet metal cutting machines. With respect to AM, we use FDM, SLA and Poly-jet technology for polymer parts and DMLS for metal parts. The materials use for polymer applications are PA 11, PA 12 and ABS, and for metal applications we use Aluminium, Titanium and Stainless Steel.

3. **Could AM be an alternative way of manufacturing parts and products and why?**

   Yes, it could be an alternative in cases where complex parts can be produced only through AM and is economical to do so. AM does have certain rules to be followed, this could sometimes restrict the use of AM.

4. **Do you have an AM strategy and if yes, what are the major elements of it?**

   Yes, we have an AM strategy. We implement AM not only in R&D but also in production. We aim to use AM to best support our Traditional Manufacturing (TM) processes. We are in the process of exploring new materials for AM purposes that could exhibit physical and mechanical properties like those used in TM.

5. **Do you employ AM in your company already? In which areas is it employed: prototyping, new parts manufacturing or spare parts manufacturing?**

   Yes, AM is used at maximum for prototyping (80%), followed by new parts production (15%) and spare parts manufacturing (5%).

6. **Does your design for new products include 3D printed parts or will it in the future? If yes, what types of parts are in scope?**

   Our designs already include 3D printed parts. We will design more of those simple and complex parts with AM in the future. Some parts that I could think of are gears, shaft, cochlea and engine protection cover.

7. **If AM has been incorporated, what are the differences being observed (production and delivery lead time, design complexity, weight reduction, cost reduction, material wastage etc.)?**

   Cost reduction, design complexity and lead time reduction have been observed.

Value added in manufacturing with AM:

1. **Are you able to incorporate modifications in your parts based on design changes made by R&D in product development?**

   Yes, we are able to modify prototypes on a regular basis. For end products, it is not very easy. It is quite challenging.

2. **Which major KPIs drive your production efficiency? E.g.: Production lead time, number of production steps, lot size etc.**

   For our firm, it would mostly be lot sizes, overall costs of the production process and production lead time.

3. **How would you see AM influence these KPIs?**

   As AM technologies are growing, I expect AM to make it more affordable to produce parts as there will be minimal costs upfront with respect to tooling and moulds. The problem now is that the machine and material costs for AM is very high. I foresee that in the future these costs would reduce, thereby fostering the use of AM and improving upon the KPIs.

4. **Could you foresee a production of parts or components of your product directly on customer premises e.g., a wind turbine blade at the location where the wind turbine is assembled? How would this affect shipping and warehouse costs?**

   Yes, this is our objective for the future. We expect shipping and warehousing costs to reduce, making it more sustainable. The pollution caused due to long distance transportation will be minimized.

5. **How could AM support the trend of increasing customization of products and would that be relevant for your business?**

   Yes, AM would be relevant in the long-run for our business. We do produce a certain set of parts only for specific customer segments. These are for highly specific requirements and at the moment we do have dedicated machines to produce those parts. This is where we feel AM could help us.

6. **In the long run, how would you assess your position in the market (competitive advantage due to customization)?**

   Customization is one of our core strengths. This is a good area for us. We do have good reputation in the market for this. With AM, we do expect more advantages in the next 5-10 years.

7. **In what way would customization affect customer service and loyalty?**

   Currently, customer service is not a problem at all. With increasing customization through AM, we expect that our current business will be supported better.

8. **For low demand, small quantity parts, are you able to fulfil orders?**

Yes, most of the orders are fulfilled. Approximately 90,000 new part drawings are made every year and 4 parts per drawing are produced.

Value added in customer service with AM:

1. **How are you addressing the spare parts market demand? Do you feel that you can manage customer demand with your existing business model?**

   Yes, we can manage with our existing model. Once we receive the order, we ship the parts if they are available in stock with us. If they are not available, we produce it through a combination of AM and TM. At the moment, we print in-house. In the future, we would like to print in the customer location, sell digital parts and not physical parts.

2. **What is your approximate delivery lead time from the receipt of the order of spare parts and delivery of spare parts to the customer? Would you like to optimize your delivery lead time?**

   The delivery lead time for parts in stock is usually 24 hours. For customer specific parts, the delivery lead time could be maximum 9 weeks. To these customers, we deliver an AM produced part with post processing and surface finish. We also use TM for these parts. These are done mostly on a priority basis.
   Yes, we would like to optimize our delivery lead time.

3. **What is the revenue share of your spare parts business compared to your overall revenue in %?**
   It is 10% approximately.

4. **What is the number of spare parts in your company portfolio? What is the share of self-produced spare parts compared to procured spare parts?**

   The number of single parts could be on average 20,000. For each item or product, there are many parts involved. We cannot disclose the share of self-produced spare parts.

5. **What percentage of spare parts stock is obsolete or don't contribute to margins?**

   This is a very small percentage. It is less than 5%.

6. **Which approach do you follow: Make-to-stock or Make-to-order?**

   We follow a make-to-stock approach for most of the standard parts that are in constant demand. For customized parts, we follow the make-to-order approach.

7. **What is approximately the service life of the products you produce? Do you keep the spare parts in inventory throughout the entire service life?**

   The service life of all our machines is approximately 20 years. We keep spare parts in inventory for the entire service life and beyond the service life.

8. **Have you thought about changing your spare parts business model to a hybrid one involving AM for "complex" and "old" parts?**

   Currently, some of these parts are in high stock due to the demand being high. This would however lead to increase in inventory stock and costs associated with it in the long-run and that is when we would incorporate AM.

9. **Do you sense a customer demand for on-premise and on-demand spare parts manufacturing?**

   Yes, customers would be interested to the potential savings on costs and time.

10. **What are your company objectives (more than 1) for spare parts management?**

    Our objectives are Improving Responsiveness and Reducing costs.

11. **Based on the company objectives and the challenges faced, what would be the attributes/criteria (technical and economical) to qualify spare parts for AM? Which criteria, when improved could lead to achieving the objective better? Please do indicate on the scale of relative importance (At least 3 criteria). Please do list more than one objective and the criteria for it.**

    Explanation of scale of relative importance:
    1- Equal importance, 3 – Moderate importance, 5 – Strong importance, 7 – Very strong importance, 9 – Extremely strong importance.
    2,4,6,8 – intermediate values

    Objective 1: Reducing costs – Inventory costs, Production costs, transport costs.

    Inventory costs with respect to production costs: 7
    Inventory costs with respect to transport costs: 5
    Production costs with respect to transport costs: 3

    Objective 2: Improve Responsiveness – Downtime, Availability of parts, Replenishment lead time

    Downtime with respect to availability of parts: 7
    Downtime with respect to Replenishment lead time: 5
    Availability of parts with respect to Replenishment lead time:3

12. **What would the technical criteria be to qualify parts for AM (both production parts and spare parts)? For example: Material, weight, dimensions and tolerances. Could you please provide approximate values for the criteria? (Any other technical criteria would also be helpful)**

    We would pay attention to design complexity. Our focus at the moment is on creating parts that would be difficult to create using conventional manufacturing. So, all the criteria listed are important.

13. **In case AM could be adopted for your spare parts business, which business model would you pursue?**
    1. Implementing own 3D printers on the premises of your service partners and/or customers?
    2. Using certified 3D printing service providers in proximity of your customers for spare parts production?
    3. Urge the customers to invest into own printing capacities for spare parts production?
    4. Combinations of the above?

As of now, we are following model 1 where we have an internal department in our factory which does research and development on 3D printing. We have 3D printers installed for polymer as well as metal parts. Discussions are going on to partner with external service providers who offer a range of technologies that can be used, ultimately that can help our customers.

<u>**Perceived Usefulness of AM Technologies**</u>

1. **Which among the spare part criteria would you chose to quantify Increased Responsiveness? (Can be more than one option)**

If you decide to choose the option 'other', could you please mention what it is?

a. Safety stock and inventory
b. Availability of parts (on demand)
c. Downtime
d. Demand rate
e. Production and delivery lead time
f. Replenishment lead time
g. Other

Answer: Production and delivery lead time, Availability of parts on demand.

2. **Which among the spare part criteria would you chose to quantify Minimized Supply Disruption? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a. Criticality
b. Supply options
c. Supply risk
d. Obsolescence
e. Other

Answer: Criticality and Obsolescence

3. **Which among the spare part criteria would you chose to quantify Cost optimization? (Can be more than one option)**
   If you decide to choose the option 'other', could you please mention what it is?

   a. Post-Production Cost
   b. Quality assurance related costs
   c. Cost for scrap
   d. Inventory costs
   e. Safety stock costs
   f. Transportation costs
   g. Other

   Answer: Post production, inventory and safety stock costs

4. **Which among the spare part criteria would you chose to quantify Part Complexity? (Can be more than one option)**
   If you decide to choose the option 'other', could you please mention what it is?

   a. Creation of functional parts that are normally difficult to create otherwise
   b. Part or assembly integration
   c. Weight reduction
   d. Customized geometry
   e. Strength and other mechanical properties
   f. Use of different materials
   g. Other

   Answer: Creation of functional parts that are normally difficult to create otherwise, Part or assembly integration, Customized geometry.

5. **Which among the spare part criteria would you chose to quantify Sustainability? (Can be more than one option)**
   If you decide to choose the option 'other', could you please mention what it is?

   a. Reduction in tooling (jigs, fixtures and moulds)
   b. Lesser Material wastage
   c. Less Rework
   d. Reduced or no transportation
   e. No or little inventory
   f. Other

   Answer: Reduced or no transportation, No or little inventory

1.2. Firm 2 (Printer producer)

AM Technology

1. **What are the additive manufacturing technologies and materials that you focus on?**

   We focus on SLS for plastics and metals. To be more specific, we use DMLS technology for metals. The materials we use for plastic are PA 11 and PA 12. For metals, we are focused on Aluminum, Titanium and Stainless Steel.

2. **Why have you decided to focus on a particular 3D printing technology?**

   We focus on SLS because we feel it is the most industry ready technology which helps offer good processing speed and good product quality.

3. **How, in your opinion, the market for 3D printing technology for man ufacturing companies will develop? Which technologies will gain importance?**

   I feel SLS is the main driver for industrial AM. We are able to use this laser technology to a good extent. Now, with the LaserProFusion technology we have an array of lasers that help in melting the material to obtain the required product. I would say this can help improve productivity and help achieve good product quality in the long run. Along with the above, I believe electron beam technologies will develop due to ongoing innovation and R&D.

AM Benefits

1. **Apart from the common benefits of AM (e.g., no limitations on geometric designs and almost no set up times) which specific benefits do you see in the future related to the development of printer technology and materials?**

As mentioned previously, better processing speed is something I would expect in the future. The possibility to create lightweight parts is very interesting for industries. Moreover, AM technology is sustainable due to the possibility to recycle and reuse powder materials and save on disposal costs.

2. **What benefits do you see especially regarding AM for spare parts?**

For spare parts, AM helps in maintaining inventory online and producing near the customer location when customers need it. This helps overcome the high costs associated with stocking inventory in the warehouse. AM enables distributed production through its own printer facilities/partner providers near customer locations. AM helps counter the issue of spare parts going out of stock with the ability to print anytime, anywhere with the design files.

AM Limitations

- Materials:

1. How would you describe the market for AM materials today?

For metals, there are many companies offering a diverse range of materials. For plastics, the market is dominated by a few big players namely BASF and Evonik.

2. Which materials are the commonly used materials for AM production?

The materials for plastic are PA 11 and PA 12. For metals, focus is on Aluminum, Titanium and Stainless Steel. We have our own materials for metal applications - Stainless Steel, Nickel alloys, Copper, Titanium etc.

3. How do you see the market for AM materials evolving? Among the future prospects, which specific materials would be the most suitable for AM and for which product?

The AM materials market is very big. The aerospace industry demands lightweight components which creates interesting use cases for the application of Aluminium and Titanium. Medical applications demand mostly Titanium.

4. With the listed materials, what are the possibilities to produce a product (prototype, final product)?

With plastics, it is possible to produce plenty of prototypes and also final products. With metals, it depends on exactly what is needed i.e., complex designs that cannot be achieved conventionally.

- Quality:

1. **How does the material chosen affect the quality of the product produced?**

Materials play a very important role in product quality. Materials need to be used for the right purposes to achieve good strength and mechanical properties.

2. How would you describe the quality of materials for AM today and in what direction will the material quality develop in the future?

At the moment, the quality of materials is very good, and in the future, I expect it to improve. The manufacturing processes to get good quality materials need to be more fine-tuned.

3. What could be the other factors affecting the quality of an AM product? What will contribute to more AM product quality in the future, printer technology and or quality monitoring (solutions)?

I would say the production process or technology is very important along with stability offered by the machines. The software monitoring solutions need to be able to monitor the process and part quality. The energy used needs to be controlled through the software.

4. **Where do you see challenges to better product quality?**

   Challenges are machine stability throughout the process and most importantly the knowledge of the worker to interpret the process monitoring data and make the necessary changes.

- Cost:

1. **What are the major cost drivers in additive manufacturing for a manufacturing company?**

   The post processing cost is a major driver. For plastic parts, costs are incurred with coloring the parts. For metals, the extra grinding and the hipping process to strengthen the parts incur high costs.

2. **What is the total cost of ownership for an AM machine (machine, maintenance, delivery etc.) today and how will it evolve?**

   It could range from 5000 euros per month – 30000 euros per month.

3. **What is the share of material costs, labour and energy costs in the overall cost for an AM manufactured part or product and how will it develop?**

   The material, labour and energy cost each account for 10%, totally 40%. The rest of the costs should be for post-processing, machine acquisition and maintenance.

4. **In general, with respect to quality, costs, materials and speed, how does AM compare with traditional manufacturing? How do you expect it to develop?**

   I do not have exact numbers for this. It still doesn't make sense today to produce parts that are specifically optimized for TM through AM. TM is still preferred due to better product quality and processing speed. AM is good when there are specific goals to be achieved – weight reduction, part complexity etc. I expect AM to become economical over time.

5. **How would you describe the unit costs of a product made by AM in comparison with traditional manufacturing?**

   I have no exact numbers.

6. **With reference to the spare parts sector, where could AM possibly be applied?**

   AM could be applied to produce parts that are needed urgently, failing which the machine cannot operate. AM can help react to sudden demand through on-demand, decentralized production. The risk of obsolescence can be mitigated with AM, that can help make the parts even when machines or products are faced out of the market.

7. **What needs to be done in order to increase the adoption of AM by the spare parts sector?**

   The OEMs, design owners need to readily agree to offer their designs to customers for printing. This could lead to issues of IP infringement. I feel most companies would rely on external service providers and not invest on printers themselves. Therefore, the proliferation of service providers is needed for AM adoption in the spare parts sector.

- Spare Parts:

1. **Do you sense a customer demand for on-premise and on-demand spare parts manufacturing?**

   Yes, but however it is not that huge at the moment. I sense the market would grow and there is a rising potential for this.

2. **What according to you could be the objectives for an OEM or a supplier for spare parts management? E.g., Reduce downtime, reduce costs, minimize inventory, secure supply (Could be anything else as well)**

   I feel the objectives would be improving responsiveness and reducing costs.

3. **Based on the objectives and the challenges faced, what would be the attributes/criteria (technical and economical) to qualify spare parts for AM? Which criteria, when improved could lead to achieving the objective better? Please do list more than one objective and the criteria for it.**

   Explanation of scale of relative importance: 1- Equal importance, 3 – Moderate importance, 5 – Strong importance, 7 – Very strong importance, 9 – Extremely strong importance.

   2,4,6,8 – intermediate values

   Objective 1: Reducing costs – Inventory costs, Production costs, transport costs.

   Inventory costs with respect to production costs: 7
   Inventory costs with respect to transport costs: 7
   Production costs with respect to transport costs: 5

   Objective 2: Improve Responsiveness – Downtime, Availability of parts, Replenishment lead time

   Downtime with respect to availability of parts: 7
   Downtime with respect to Replenishment lead time: 5
   Availability of parts with respect to Replenishment lead time: 3

4. **What would the technical criteria be to qualify parts for AM (both production parts and spare parts)? For example: Material, weight, dimensions and tolerances. Could you please provide approximate values for the criteria? (Any other technical criteria would also be helpful)**

   I consider all these criteria as important.

5. **Based on your experience, could you name the spare parts that generally cause challenges to businesses? Which among them would you choose to be produced by AM according to both technical and economic criteria (at least 4 parts)? Also, can you provide the approximate response time, lead time and the costs (production, transport) for each part please?**

   I would pick the armrest for Daimler Evobus and certain aircraft turbine parts that are subject to wear and tear.

6. **In case AM could be adopted for spare parts business, which business model would you pursue?**
   1. Implementing own 3D printers on the premises of your service partners and/or customers?
   2. Using certified 3D printing service providers in proximity of your customers for spare parts production?
   3. Urge the customers to invest into own printing capacities for spare parts production?
   4. Combinations of the above?

   I feel Model 2 would be the most suitable as investments in high amounts are not needed. Model 2 would allow experimentation with different technologies, but however the quality of products produced could be an issue due to limited control over production.

<u>**Perceived Usefulness of AM Technologies**</u>

1. **Which among the spare part criteria would you chose to quantify Increased Responsiveness? (Can be more than one option)**

If you decide to choose the option 'other', could you please mention what it is?

a. Safety stock and inventory
b. Availability of parts (on demand)
c. Downtime
d. Demand rate
e. Production and delivery lead time
f. Replenishment lead time
g. Other

Answer: Availability of parts (on demand), Downtime, Production and delivery lead time

2. **Which among the spare part criteria would you chose to quantify Minimized Supply Disruption? (Can be more than one option)**
   If you decide to choose the option 'other', could you please mention what it is?

   a. Criticality
   b. Supply options
   c. Supply risk
   d. Obsolescence
   e. Other

Answer: Criticality and Supply risk

3. **Which among the spare part criteria would you chose to quantify Cost optimization? (Can be more than one option)**
   If you decide to choose the option 'other', could you please mention what it is?

   a. Post-Production Cost
   b. Quality assurance related costs
   c. Cost for scrap
   d. Inventory costs
   e. Safety stock costs
   f. Transportation costs
   g. Other

Answer: Post-Production Cost, Cost for scrap and Inventory costs

4. **Which among the spare part criteria would you chose to quantify Part Complexity? (Can be more than one option)**
   If you decide to choose the option 'other', could you please mention what it is?

   a. Creation of functional parts that are normally difficult to create otherwise
   b. Part or assembly integration
   c. Weight reduction
   d. Customized geometry
   e. Strength and other mechanical properties
   f. Use of different materials
   g. Other

Answer: Creation of functional parts that are normally difficult to create otherwise, Weight reduction and Use of different materials.

5. **Which among the spare part criteria would you chose to quantify Sustainability? (Can be more than one option)**
   If you decide to choose the option 'other', could you please mention what it is?

   a. Reduction in tooling (jigs, fixtures and moulds)
   b. Lesser Material wastage
   c. Less Rework
   d. Reduced or no transportation
   e. No or little inventory
   f. Other

Answer: Lesser Material wastage and no or little inventory

1.3. Firm 3 (Material producer)

<u>AM Technology</u>

1. **What are the additive manufacturing technologies and materials that you focus on?**

   For polymer applications, we utilize PA11, PA12, PLA and ABS and focus on SLS, SLA and FFF technologies. For metals, we make use of metal filament (mainly stainless steel) composites and apply FFF and SLS technologies.

2. **Why have you decided to focus on a particular 3D printing technology?**

   The technologies mentioned above are very useful from an industry point of view. Using these technologies, we are able to print at a good speed and obtain desired product quality.

3. **How, in your opinion, the market for 3D printing technology for manufacturing companies will develop? Which technologies will gain importance?**

   I feel Powder Bed Fusion techniques like SLS and Vat Polymerisation techniques like SLA will drive indutrial growth. Along with these two, the HP Multi-jet fusion technique is growing in popularity. So SLS, SLA and multi-jet fusion would enable printing more good quality parts and achieve design complexity. For further development, the printing technologies should become more reliable, faster and affordable to produce parts.

AM Benefits

4. **Apart from the common benefits of AM (e.g., no limitations on geometric designs and almost no set up times) which specific benefits do you see in the future related to the development of printer technology and materials?**

   I expect the possibility of producing small lot sizes and achieving customization with AM adoption. Materials can be used in different ways to achieve the desired behaviour in the final product. There are AM technologies that enable the use of multiple materials in different forms. Another important benefit is AM processes are more sustainable, meaning certain raw materials like powders can be reused and need not be disposed.

5. **What benefits do you see especially regarding AM for spare parts?**

   I find the use cases for spare parts to be interesting as AM makes it possible to store inventory online, indicating that in the long run inventory need not be stored in warehouses and possibly warehouses could be eliminated. Also, the transportation activities from factory to customer can be reduced and the costs associated with it can be minimized.

AM Limitations

- Materials:

6. **How would you describe the market for AM materials today?**

   The market for AM materials is quite complex. There are niche players who offer materials for specific applications. Certain machine makers sell materials along with the machine.
   At the moment, the materials market is limited and focused. I would expect it to grow in future as I witness research going on with AM materials in polymer and metal applications.

7. **Which materials are the commonly used materials for AM production?**

   The materials are specific to the technology used. Overall, we use the following materials namely PA11 and PA12, PLA, ABS and metal filament (stainless steel) composites. For PBF techniques, I expect increasing usage of PA11 and PA12. For other techniques like Vat Polymerization, I expect PLA, ABS and metal filaments to be utilized on an increasing scale.

8. **How do you see the market for AM materials evolving? Among the future prospects, which specific materials would be the most suitable for AM and for which product?**

   The AM materials market is very big with opportunities for growth. I do see increasing potential for more players to enter the market and compete with the existing players.

9. **With the listed materials, what are the possibilities to produce a product (prototype, final product)?**

   With respect to prototypes, production is currently done on a large scale due to the absence of quality requirements. For end products, it is very important that the production complies to the quality standards put forth by the customer. Therefore, for end products, AM is currently done on a small scale.

- Quality:

10. **How does the material chosen affect the quality of the product produced?**

    Materials play a very important role in product quality. Materials need to be used for the right purposes to achieve good strength and mechanical properties. When material is complex, it gets difficult to produce and this might impact quality.

11. **How would you describe the quality of materials for AM today and in what direction will the material quality develop in the future?**

    At the moment, the quality of materials is very good, and in the future, I expect it to improve. We ourselves as a company are very competitive. We expect that customers would be able to track the product quality in future.

12. **What could be the other factors affecting the quality of an AM product? What will contribute to more AM product quality in the future, printer technology and or quality monitoring (solutions)?**

    I feel the printer is the most important, meaning that it should be stable and reliable. The software used would definitely help in ensuring quality. The process of checking for quality with the software would be crucial.

13. **Where do you see challenges to better product quality?**

    The main challenges as mentioned previously is the machine stability. Adjustments should be made available to react in real-time, as quickly as possible.

- Cost:

14. **What are the major cost drivers in additive manufacturing for a manufacturing company?**

    According to me, machine and material costs are the main drivers. I feel these two together would account for 70% of the total costs. The labor and energy costs will account for the rest.

15. **What is the total cost of ownership for an AM machine (machine, maintenance, delivery etc.) today and how will it evolve?**

    I do not have exact numbers to provide for this.

16. **What is the share of material costs, labour and energy costs in the overall cost for an AM manufactured part or product and how will it develop?**

    The target is to obtain cheaper materials. When the material costs decrease and printing processes run at faster speeds, the costs per part would decrease.

17. **In general, with respect to quality, costs, materials and speed, how does AM compare with traditional manufacturing? How do you expect it to develop?**

    Even today, in most cases it makes sense economically to use traditional manufacturing. Only when lot sizes are small and variety is desired, that is when AM would be helpful.

18. **How would you describe the unit costs of a product made by AM in comparison with traditional manufacturing?**

    I have no exact numbers.

19. **With reference to the spare parts sector, where could AM possibly be applied?**

    AM can be applied to react to sudden demand changes through on-demand, decentralized production. For faster availability of parts to achieve lower lead times and improved downtimes, AM would be advisable.

20. **What needs to be done in order to increase the adoption of AM by the spare parts sector?**

    AM produced parts should prove its capability to show strength and physical properties like the conventionally manufactured parts. It is important that processes of the customer comply with the AM production quality standards.

- Spare Parts:

21. **Do you sense a customer demand for on-premise and on-demand spare parts manufacturing?**

    Yes, there is expectations for this in the future. For example, there are interesting use cases of Daimler Evobus and Deutsche Bahn. When a train or a bus is grounded due to certain spare parts not being available on time, that’s when AM would be of good use.

22. **What according to you could be the objectives for an OEM or a supplier for spare parts management? E.g., Reduce downtime, reduce costs, minimize inventory, secure supply (Could be anything else as well)**

    I feel reducing costs is the main objective.

23. **Based on the objectives and the challenges faced, what would be the attributes/criteria (technical and economical) to qualify spare parts for AM? Which criteria, when improved could lead to achieving the objective better?**
    Please do list more than one objective and the criteria for it.

    Explanation of scale of relative importance:

    1- Equal importance, 3 – Moderate importance, 5 – Strong importance, 7 – Very strong importance, 9 – Extremely strong importance.

    2,4,6,8 – intermediate values

    I consider inventory and transport costs to be important. As I do not belong to an OEM, I cannot comment much on which criteria would be more important.

24. **What would the technical criteria be to qualify parts for AM (both production parts and spare parts)? For example: Material, weight, dimensions and tolerances. Could you please provide approximate values for the criteria? (Any other technical criteria would also be helpful)**

    These criteria vary from customer to customer. Usually, all these criteria are important. The dimensions and tolerances could be few micrometres or millimetres.

25. **Based on your experience, could you name the spare parts that generally cause challenges to businesses? Which among them would you choose to be produced by AM according to both technical and economic criteria (at least 4 parts)? Also, can you provide the approximate response time, lead time and the costs (production, transport) for each part please?**

    I feel for this it could be large sized parts that are complex that need to be AM produced.

26. **In case AM could be adopted for spare parts business, which business model would you pursue?**

    1) Implementing own 3D printers on the premises of your service partners and/or customers?
    2) Using certified 3D printing service providers in proximity of your customers for spare parts production?
    3) Urge the customers to invest into own printing capacities for spare parts production?
    4) Combinations of the above?

    Model 1 helps react very fast to demand. This model is cost efficient when it is used a lot. Compared to model 1, model 2 is more cost efficient.

    Model 3 would depend on who the customer is. If it an automobile customer, it is difficult to monitor how he would be printing. In case of buses or rail, it would probably make sense if there are maintenance shops at the customer location to offer service.

Perceived Usefulness of AM Technologies

1. **Which among the spare part criteria would you chose to quantify Increased Responsiveness? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a) Safety stock and inventory
b) Availability of parts (on demand)
c) Downtime
d) Demand rate
e) Production and delivery lead time
f) Replenishment lead time
g) Other

Answer: Availability of parts (on demand), Downtime, Demand rate

2. **Which among the spare part criteria would you chose to quantify Minimized Supply Disruption? (Can be more than one option)**

If you decide to choose the option 'other', could you please mention what it is?

a) Criticality
b) Supply options
c) Supply risk
d) Obsolescence
e) Other

Answer: Criticality and Obsolescence

3. **Which among the spare part criteria would you chose to quantify Cost optimization? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a) Post-Production Cost
b) Quality assurance related costs
c) Cost for scrap
d) Inventory costs
e) Safety stock costs
f) Transportation costs
g) Other

Answer: Inventory costs and Quality assurance costs

4. **Which among the spare part criteria would you chose to quantify Part Complexity? (Can be more than one option)**
   If you decide to choose the option 'other', could you please mention what it is?

   a) Creation of functional parts that are normally difficult to create otherwise
   b) Part or assembly integration
   c) Weight reduction
   d) Customized geometry
   e) Strength and other mechanical properties
   f) Use of different materials
   g) Other

   Answer: Weight reduction.

5. **Which among the spare part criteria would you chose to quantify Sustainability? (Can be more than one option)**
   If you decide to choose the option 'other', could you please mention what it is?

   a) Reduction in tooling (jigs, fixtures and moulds)
   b) Lesser Material wastage
   c) Less Rework
   d) Reduced or no transportation
   e) No or little inventory
   f) Other

   Answer: Lesser Material wastage and reduced or no transportation

1.4. Firm 4 (Solutions provider)

AM Technology and Benefits

1) **How, in your opinion, the market for 3D printing technology for manufacturing companies will develop? Which technologies will gain more importance?**

   The market is growing. I would expect rapid growth in the next 5-10 years. Every year new firms are being set up, indicating a growth in the number of start-ups working on various 3D printing technologies. Research is being carried out on AM technologies. Along with new firms, new technologies are also being introduced to the market. These technologies would be used more and more as firms evolve from developing prototypes to developing finished products. With respect to metal-based AM technologies, Powder Bed Fusion (SLS) is the most common and this would gain more importance in future. Pertaining to polymer-based AM, Selective Laser Sintering (a PBF technique) and SLA are widely used, and this will grow in future.

2) **Apart from the common benefits of AM (e.g., no limitations on geometric designs and almost no setup times) which specific benefits do you see in the future related to the development of printer technology and materials?**

I believe irrespective of what the AM technology is, the benefit of AM as a whole is that it enables the production of parts when and where you need it. It gives rise to the concept of distributed manufacturing that helps minimize inventory and logistics cost and reduce the risk of obsolescence. Coming to the materials side, the market is very competitive and I could expect stronger and light weight components.

3) **What benefits do you see especially regarding AM for spare parts?**

The use cases of spare parts are very fascinating and lifecycle of certain products is still not known and cannot be predicted very well. This might lead to firms maintaining excess quantity of spare parts which may not be needed or used in the long run. For example, with the current scenario in the rail industry, suppliers would require manufacturers to sign a contract for a specified quantity of spare parts. Only then will the suppliers produce and deliver the spare parts to the manufacturer. Thereby, the manufacturer will end up procuring a huge quantity of spare parts and incur high warehousing costs. This is where AM could be helpful.

AM Limitations

- Materials:

1) **How would you describe the market for AM materials today?**

The market is growing. A lot of new materials are coming to the market. However, I cannot comment much as we are not involved in the materials side of the industry.

2) **Which materials are the commonly used materials for AM production?**

Polymers are the highest in terms of usage, followed by metals next and then resins.

3) **How do you see the market for AM materials evolving? Among the future prospects, which specific materials would be the most suitable for AM and for which product?**

Plenty of research and innovation is taking place with AM materials, particularly for metal-based AM technologies. The use cases for metal-based AM need to develop and this can be done with better, more improved materials. With respect to polymer-based AM, there are many use cases already.

4) **With the listed materials, what are the possibilities to produce a product (prototype, final product)?**

The possibility of both prototypes and end products is possible. The aircraft, automotive and defence industries have displayed the capability to produce both prototypes and end products. However, there are challenges. At the moment it is difficult to achieve the physical and mechanical properties in components that are AM produced, compared to the ones produced through casting and moulding processes.

- Quality:

1. **How does the material chosen affect the quality of the product produced?**

The chosen materials matter very much across the entire product lifecycle. It's important to have the right material. More importantly, these materials need to be tested and certified for use. The testing and certification standards still haven't developed internationally, meaning that there are no worldwide accepted standards for AM materials.

2. **How would you describe the quality of materials for AM today and in what direction will the material quality develop in the future?**

At the moment, developments are going to improve material quality. Be it polymers, metals or resins, quality is evolving. Looking at the scale of R&D along with significant investments into the materials side of AM, I would expect the quality overall to grow and improve.

3. **What could be the other factors affecting the quality of an AM product? What will contribute to more AM product quality in the future, printer technology and or quality monitoring (solutions)?**

Materials is indeed very important. Along with materials, the technology and the machines used matter a lot. The software used throughout the lifecycle offering different functionalities and security too have an impact on quality. Significant human skill is required to use the software and operate AM machines. Investments have to be made in training employees to use this technology.

4. **Where do you see challenges to better product quality?**

   Some of the challenges to generate quality components are the physical properties of the AM materials, stability and repeatability of the AM processes, knowledge acquisition regarding AM technology and the processes involved.

- Cost:

1. **What are the major cost drivers in additive manufacturing for a manufacturing company?**

   Equal investments need to be made in materials, machine, software, labour and processes.

2. **With reference to the spare parts sector, where could AM possibly be applied?**

   In situations where a spare part is immediately needed for the functioning of an equipment or a component, AM would be helpful. Moreover, when the demand for specific parts is uneven or unpredictable, parts are out-of-stock or needed in small quantities, AM can help find a solution.

3. **What needs to be done in order to increase the adoption of AM by the spare parts sector?**

Investments need to be made in hardware, software and materials. The processes should be repeatable in the long run. Employees need to be trained to use the software and run the machines. As the awareness about the impact of AM in spare parts among firms is low, AM knowledge should be disseminated to all employees across organisations. More use cases need to be developed to justify investments for AM in spare parts. Moreover, firms need to be confident enough that the new technology doesn't destroy the existing business.

Value added in engineering with AM:

1. **Could AM be an alternative way of manufacturing parts and products and why?**

   Yes, it can be an alternative. For certain complex products that would be difficult to produce using traditional manufacturing, AM would be helpful. AM would also ensure costs are not high for these kinds of products. Even simple parts can be AM produced. It mostly depends on the application being considered.

2. **Do you have an AM strategy and if yes, what are the major elements of it?**

   No. This does not apply to us.

Value added in manufacturing with AM:

3. **How could AM support the trend of increasing customization of products and would that be relevant for your business?**

   Yes, this would be relevant for our business as the trend of customization is on the rise. More importantly, customers are looking forward to this in the future in order to ensure their unmet needs are satisfied.

4. **In the long run, how would you assess your position in the market (competitive advantage due to customization)? In what way would customization affect customer service and loyalty?**

   This does not apply to us.

5. **Could you foresee a production of parts or components of your product directly on customer premises e.g., a wind turbine blade at the location where the wind turbine is assembled? How would this affect shipping and warehouse costs?**

   Yes, instead of shipping the parts that would incur high transport costs, it would make sense to ship the machine so that the required parts can be produced at the location of the customer. Both, shipping and warehousing costs would reduce as there won't be a need to maintain inventory.

Value added in customer service with AM:

6. **Do you sense a customer demand for on-premise and on-demand spare parts manufacturing?**

   Yes, I do sense expectations for this. I would say in the next 3-5 years probably it's going to increase a lot, and become mainstream later on.

7. **What according to you could be the objectives for an OEM or a supplier for spare parts management? E.g., Reduce downtime, reduce costs, minimize inventory, secure supply (Could be anything else as well)**

   I expect the main objective would be to reduce costs. To be specific, they would intend to reduce logistics and inventory working capital costs. Generating a new stream of revenue would be the overall aim.

8. **Based on the objectives and the challenges faced, what would be the attributes/criteria (technical and economical) to qualify spare parts for AM? Which criteria, when improved could lead to achieving the objective better?**

   Explanation of scale of relative importance:

   1- Equal importance, 3 – Moderate importance, 5 – Strong importance, 7 – Very strong importance, 9 – Extremely strong importance.

   2,4,6,8 – intermediate values

   I would rate it the following way: Production costs > Assembly + rework costs > Transport costs > Supply options. Adding on to this, I would say the diversity of supply is important as it enhances competition which would allow the firm to choose the right supplier to fulfil their overall objectives. The quality of the part along with the ability to service the part after acquisition is to be considered. Moreover, its key to ensure responsiveness that will ultimately lead to customer satisfaction.

9. **Based on your experience, could you name the spare parts that generally cause challenges to businesses? Which among them would you choose to be produced by AM?**

   With respect to parts, it could range from simple parts like polymer knobs to very complex parts. For example, in shipping industry, emphasis would be places on how critical the part is for the functioning of the component.

10. **In case AM could be adopted for spare parts business, which business model would you pursue?**
    1) Implementing own 3D printers on the premises of your service partners and/or customers?
    2) Using certified 3D printing service providers in proximity of your customers for spare parts production?
    3) Urge the customers to invest into own printing capacities for spare parts production?

4) Combinations of the above?

I feel it will mostly be a combination of 1 and 2 in the future as customers cannot be pressurized to build 3D printing capabilities. Model 1 would ensure good quality products are produced but restricts the use of different technologies as investment would be made only on a particular technology. Model 2 would allow experimentation with different technologies, but however the quality of products could get compromised and also IP protection issues could arise.

Perceived Usefulness of AM Technologies

1. **Which among the spare part criteria would you chose to quantify Increased Responsiveness? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a. Safety stock and inventory
b. Availability of parts (on demand)
c. Downtime
d. Demand rate
e. Production and delivery lead time
f. Replenishment lead time
g. Other

I would pick the following - Availability of parts (on demand), Production and delivery lead time, Replenishment lead time.

2. **Which among the spare part criteria would you chose to quantify Minimized Supply Disruption? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a. Criticality
b. Supply options
c. Supply risk
d. Obsolescence
e. Other

I would pick the following - Supply options and Supply risk

3. **Which among the spare part criteria would you chose to quantify Cost optimization? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a. Post-Production Cost
b. Quality assurance related costs
c. Cost for scrap
d. Inventory costs

e. Safety stock costs
f. Transportation costs
g. Other

All of the above.

4. **Which among the spare part criteria would you chose to quantify Part Complexity? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a. Creation of functional parts that are normally difficult to create otherwise
b. Part or assembly integration
c. Weight reduction
d. Customized geometry
e. Strength and other mechanical properties
f. Use of different materials
g. Other

Creation of functional parts that are normally difficult to create otherwise, Part or assembly integration, Customized geometry, Strength and other mechanical properties.

5. **Which among the spare part criteria would you chose to quantify Sustainability? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a. Reduction in tooling (jigs, fixtures and molds)
b. Lesser Material wastage
c. Less Rework
d. Reduced or no transportation
e. No or little inventory
f. Other

Lesser Material wastage, Less Rework, Reduced or no transportation

1.5. Firm 5 (Solutions provider)

<u>AM Technology and Benefits</u>

1) **How, in your opinion, the market for 3D printing technology for manufacturing companies will develop? Which technologies will gain more importance?**

The market is growing. I do see an increasing trend in the number of companies adopting. Approximately, in the next 5-10 years there would be a minimum growth of 10% every year. I see significant investments being made for innovation and R&D on 3D printing technologies. With respect to technology, Powder Bed Fusion techniques like SLS has grown significantly and become very important in a short period of time for both metal and polymer applications. Recently, the HP multi-jet fusion technology (Binder jetting technique) has become important due to the high precision it offers. Also, I do see work being done on photopolymerization techniques like SLA.

2) **Apart from the common benefits of AM (e.g., no limitations on geometric designs and almost no setup times) which specific benefits do you see in the future related to the development of printer technology and materials?**

The benefits which I could possibly foresee are the possibility of producing parts as and when customers need it at their respective locations and ability to produce in small quantities economically. The increasing need for customization drives the growth of AM technologies. Each AM technology has its own set of benefits. Some technologies are suited for producing small sized parts, and the others are suited for large sized parts.

3) **What benefits do you see especially regarding AM for spare parts?**

The possibility to produce near the customer would help save logistics costs. For customers, it would be economical due to the possibility of producing a part even if the machine is very old. In the Traditional Manufacturing scenario, as machines grow old and become obsolete, spare parts will mostly not be available in stock and customers will have to buy a new machine to replace the old one. With AM, customers can buy spare parts to keep the machine functional, thereby extending the machine life. There is no need to buy a new machine in this scenario. Also, tooling and moulding costs can be minimized.

<u>AM Limitations</u>

- Materials:

4) **How would you describe the market for AM materials today?**

A lot of R&D and innovation is going on in the AM materials market. At the moment there are limited players in the market. The market is controlled by a few companies, indicating the market for AM materials is niche compared to Traditional Manufacturing. For example, BASF has grown to be a dominant player offering materials for niche applications.

5) **Which materials are the commonly used materials for AM production?**

For filaments, I think it would be ABS and PLA. For powders, Polyamide 12. Among the metals, I would pick Aluminium, Titanium and Stainless Steel. For Resins, Polyurethane.

6) **How do you see the market for AM materials evolving? Among the future prospects, which specific materials would be the most suitable for AM and for which product?**

There are more specialized materials for advanced applications coming into the market.

7) **With the listed materials, what are the possibilities to produce a product (proto type, final product)?**

For metal-based applications, the possibility to produce high precision parts that cannot be achieved through Traditional Manufacturing (TM) makes AM a good candidate. Moreover, AM is preferred in the Automotive and aircraft industries where high strength, less weight and high quality is desired. With regard to polymers, it is mostly possible to produce all the products. With photopolymers, sometimes the products end up being weak (low strength).

- Quality:

8) **How does the material chosen affect the quality of the product produced?**

   The chosen materials matter very much across the entire product lifecycle. It's important to have the right material.

9) **How would you describe the quality of materials for AM today and in what direction will the material quality develop in the future?**

   At the moment, developments are going on to improve material quality. Be it polymers, metals or resins, quality is evolving. Right now, the strength and mechanical properties offered by TM is better and more preferred than AM. Most manufacturers are still in favour of TM. However, I would expect the quality of AM materials to grow and improve.

10) **What could be the other factors affecting the quality of an AM product? What will contribute to more AM product quality in the future, printer technology and or quality monitoring (solutions)?**

    Along with materials, the manufacturing process and the machines used matter a lot. The software used throughout the lifecycle has an impact on quality. The software could be sensitive sometimes and managing the entire process workflow is challenging. Workers need to be trained to use the software and operate the machines.

11) **Where do you see challenges to better product quality?**

    The general image is that products made with AM are not very good looking compared to the ones produced by TM. AM products do need post processing to be carried out for good surface finish. To achieve certain mechanical properties, innovations in chemistry are required. For example, certain car parts need to be flame retardant. It is difficult to achieve this with AM materials.

- Cost:

12) **What are the major cost drivers in additive manufacturing for a manufacturing company?**

    Significant investments need to be made in materials, machine and labour. In TM, the upfront costs for tooling and moulds are high, therefore AM helps minimize those costs. The number of parts to be printed does not matter in AM unlike in TM where it is economical only when higher quantities are produced.

13) **With reference to the spare parts sector, where could AM possibly be applied?**

    In situations where a spare part is immediately needed for the functioning of an equipment or a component, AM would be helpful. Moreover, AM could be beneficial when machines or components become obsolete and spare parts are not available. Digital inventory and printers would help solve the problem.

14) **What needs to be done in order to increase the adoption of AM by the spare parts sector?**

Before making the products, producers need to think about managing spare parts for it in order to keep them functional over the service life. Keeping in mind the product obsolescence, firms can use AM to produce and deliver the spare parts. Along with this, OEMs should be willing to share their digital files with customers or external partners.

Value added in engineering with AM:

15) **Could AM be an alternative way of manufacturing parts and products and why?**

Yes, it can be an alternative. It depends on how simple or complex the parts to be produced are and the range of materials available to produce them.

16) **Do you have an AM strategy and if yes, what are the major elements of it?**

Yes. We intend to make AM more widespread and affordable to customers. We look to provide highly competitive products and target specific niche applications.

Value added in manufacturing with AM:

17) **How could AM support the trend of increasing customization of products and would that be relevant for your business?**

Yes, AM is for customization. I observe that this trend is slowly growing. I see that more interest being shown by customers for products with specific requirements. More awareness is present about cost savings that can be achieved through minimization of tooling and moulds.

18) **In the long run, how would you assess your position in the market (competitive advantage due to customization)? In what way would customization affect customer service and loyalty?**

I feel anybody adopting this technology is benefited. It is common that when value-added products are delivered, customers are content and loyal irrespective of the technology used to produce them.

19) **Could you foresee a production of parts or components of your product directly on customer premises e.g., a wind turbine blade at the location where the wind turbine is assembled? How would this affect shipping and warehouse costs?**

It will definitely impact shipping and warehouse costs. Localized production would be possible. It is difficult to comment on how much of an impact would be made.

Value added in customer service with AM:

20) **Do you sense a customer demand for on-premise and on-demand spare parts manufacturing?**

    Yes, I do sense expectations for this. In the current scenario where there are challenges with respect to logistics (shipping of parts from factory to customer being very costly) and obsolete products (maintaining inventory throughout the service life requires more storage space and incurs high costs), AM could indeed help overcome them.

21) **What according to you could be the objectives for an OEM or a supplier for spare parts management? E.g., Reduce downtime, reduce costs, minimize inventory, secure supply (Could be anything else as well)**

    I do not have a specific answer for this. I would expect all the mentioned examples to be the objectives. It depends on the industry and the situation faced by them with respect to spare parts management.

22) **Based on the objectives and the challenges faced, what would be the attributes/criteria (technical and economical) to qualify spare parts for AM? Which criteria, when improved could lead to achieving the objective better?**

    Explanation of scale of relative importance:

    1- Equal importance, 3 – Moderate importance, 5 – Strong importance, 7 – Very strong importance, 9 – Extremely strong importance.

    2,4,6,8 – intermediate values

    I do not have a specific answer for this. I would expect all the mentioned examples to be the objectives. It depends on the industry and the situation faced by them with respect to spare parts management.

    Regarding the technical criteria, I feel the materials, sizes and weight to be important. Going by the current observations, big sizes are less relevant for AM. Coming to the tolerance part, if we consider a Swiss watch as an example, it may not be possible to produce small and tiny parts through AM. However, dimension-wise it may be acceptable for AM production.

23) **Based on your experience, could you name the spare parts that generally cause challenges to businesses? Which among them would you choose to be produced by AM?**

    I do not have any specific parts in mind. With respect to cars or any machinery, it could be certain technical parts that have an impact on overall performance. Adding on, certain replacement parts or obsolete parts could be candidates for AM production.

24) **In case AM could be adopted for spare parts business, which business model would you pursue?**
    1) Implementing own 3D printers on the premises of your service partners and/or customers?

2) Using certified 3D printing service providers in proximity of your customers for spare parts production?
3) Urge the customers to invest into own printing capacities for spare parts production?
4) Combinations of the above?

It could be combinations of the above depending on the situation. For Model 1, the benefits could be the higher control over production, ability to immediately address the market demand (quick turnaround time). The trade-offs are investments that need to made, knowledge that needs to be acquired and the machine usage not being very high.

For Model 2, the advantage is that investments in high amounts are not needed. The drawback is that control over production is not possible.

For Model 3, convincing a customer to invest in 3D printing capabilities is quite a challenge as it should be economically justifiable for the customer. Also, OEMs should consent on the IP rights of the design files before they hand them over to customers.

Perceived Usefulness of AM Technologies

1. **Which among the spare part criteria would you chose to quantify Increased Responsiveness? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a. Safety stock and inventory
b. Availability of parts (on demand)
c. Downtime
d. Demand rate
e. Production and delivery lead time
f. Replenishment lead time
g. Other

b) Availability of parts (on demand), c) Downtime, e) Production and delivery lead time, f) Replenishment lead time

2. **Which among the spare part criteria would you chose to quantify Minimized Supply Disruption? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a. Criticality
b. Supply options
c. Supply risk
d. Obsolescence
e. Other

d) Obsolescence

3. **Which among the spare part criteria would you chose to quantify Cost optimization? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a. Post-Production Cost
b. Quality assurance related costs
c. Cost for scrap
d. Inventory costs
e. Safety stock costs
f. Transportation costs
g. Other

d) Inventory costs, e) Safety stock costs

4. **Which among the spare part criteria would you chose to quantify Part Complexity? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a. Creation of functional parts that are normally difficult to create otherwise
b. Part or assembly integration
c. Weight reduction
d. Customized geometry
e. Strength and other mechanical properties
f. Use of different materials
g. Other

a) Creation of functional parts that are normally difficult to create otherwise, b) Part or assembly integration.

5. **Which among the spare part criteria would you chose to quantify Sustainability? (Can be more than one option)**
If you decide to choose the option 'other', could you please mention what it is?

a) Reduction in tooling (jigs, fixtures and molds)
b) Lesser Material wastage
c) Less Rework
d) Reduced or no transportation
e) No or little inventory
f) Other

Lesser Material wastage, Less Rework, Reduced or no transportation

Other – Avoiding disposal of products that are old or obsolete.

APPENDIX 2 – Use Cases Discussion Questions

Use Case 1:

1) **What are the quantities of spare parts your firm manages approximately?**

   We keep track mainly on number of lines [approximately 50,000 stocked Lines] and quantity per line is on average 5. Therefore, we manage 250,000 spare parts and this is expected to increase every year.

2) **How diverse is your spare part assortment? How do the parts differ?**

   The spare part assortment of our organisation differs mainly on the Just-in-Time principles and seven storage techniques.

3) **Could you describe the approach your company uses to serve customers with spare parts (make-to-stock, make-to-order, engineer-to-order etc)?**

   We mostly use a combination of the make-to-stock and the make-to-order strategies.

4) **What are the challenges you are currently facing with spare parts management? What causes those challenges?**

   The challenges we are facing deal mainly with managing supplier inventory management and most recently the COVID-19 pandemic that has forcefully enforced lockdowns.

5) **Could you briefly name the spare parts causing those challenges? What kind of spare parts cause those challenges?**

   The challenges are caused by a few plastic and rubber components for spare parts of older generation vehicle models. It is increasingly difficult to produce these with conventional manufacturing. This is where AM could be helpful.

6) **How do you classify spare parts at the moment?**

   We classify spare parts according to demand that is fast, medium & slow - moving parts.

7) **How familiar is your organization with Additive Manufacturing? Has it been used as a method for production? What has it been used for? (E.g: Prototypes, end products, spare parts)**

   At the moment, we are using 3D printing for prototypes. Research is going on for the application of 3D printing of spare parts as we aim to utilize this technology in future.

Use Case 2:

1) **What are the quantities of spare parts your firm manages approximately?**

   We manage over 5000 stock keeping units of spare parts.

2) **How diverse is your spare part assortment? How do the parts differ?**

   The spare part assortments differ based on application and market segmentation.

3) **Could you describe the approach your company uses to serve customers with spare parts (make-to-stock, make-to-order, engineer-to-order etc)?**

   We use a combination of make-to-stock and make-to-order strategies depending on market/customer requirements.

4) **What are the challenges you are currently facing with spare parts management? What causes those challenges?**

   We are facing challenges with the serviceability of old vehicles. Product obsolescence is an issue for this at the moment. I feel AM could be helpful in tackling these scenarios.

5) **Could you briefly name the spare parts causing those challenges? What kind of spare parts cause those challenges?**

   Unfortunately, this cannot be disclosed as it is confidential information.

6) **How do you classify spare parts at the moment?**

   We classify spare parts based on vehicle applications mainly, along with customer & market segmentation.

7) **How familiar is your organization with Additive Manufacturing? Has it been used as a method for production? What has it been used for? (E.g: Prototypes, end products, spare parts)**

   The overall awareness of AM in our company is low. We are carrying out research on AM technologies and using it for testing prototype parts. In future (maybe within 10 years), I would expect AM to be applied for spare part production and also for certain end products.

APPENDIX 3 – AM Technologies and Materials

3.1. AM Technologies in Detail

Material Extrusion is the most used technique to produce low volume parts (Material Extrusion | Additive Manufacturing Research Group | Loughborough University, 2014b). The machine consists of a nozzle where the material is heated, dispensed and deposited layer by layer. The platform of the machine moves up and down as layers are deposited and the nozzle moves horizontally. The material added through the nozzle should be done under constant pressure and speed, both these parameters should be maintained to achieve good build quality. Fused deposition modelling is a popular material extrusion technology.

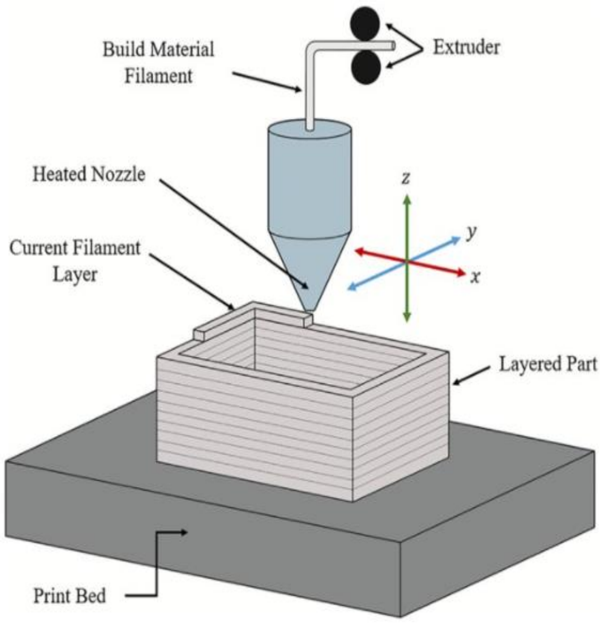


Figure: Material extrusion (Shah, Snider, Clarke, 2019)

The Binder Jetting process utilizes two materials namely the binder and the build material in powder form (Binder Jetting | Additive Manufacturing Research Group | Loughborough University, 2014). The binder which is in liquid form acts as an adhesive to bind the two powder layers. The binder jetting machine consists of a print head that moves horizontally along the X and Y axes to deposit the binder and the build material alternatively. After the completion of each layer, the platform of the machine is lowered. The 3D printing technology falls under the segment of Binder Jetting. The strength of the build material achieved is not very high and this process is not suitable for structural parts. However, for prototyping and tooling this process is very good.

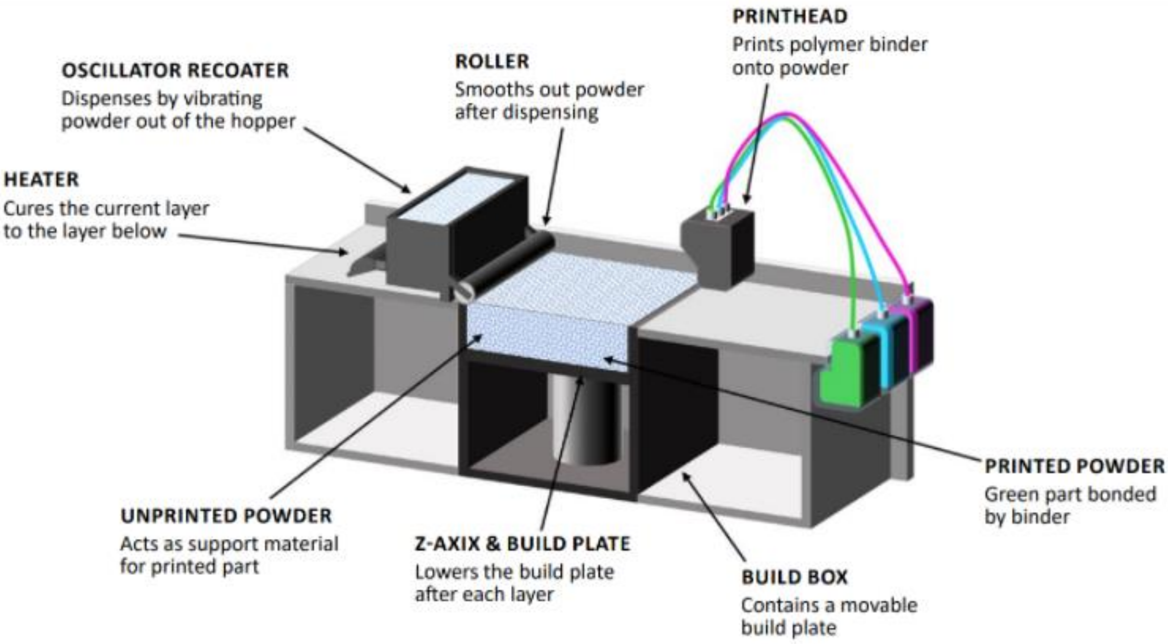


Figure: Binder Jetting (Digital Alloys, 2019)

The Vat Polymerization process uses a vat filled with liquid resin (Vat Polymerization| Additive Manufacturing Research Group | Loughborough University, 2014). An ultraviolet light source is used to harden the resin. The liquid resin is solidified in places only where the light source makes contacts the liquid surface. The machine platform moves down after each layer has been added, so that new layers can be added on top. The parts produced have a smooth surface. The common technology here is Stereolithography (SLA).

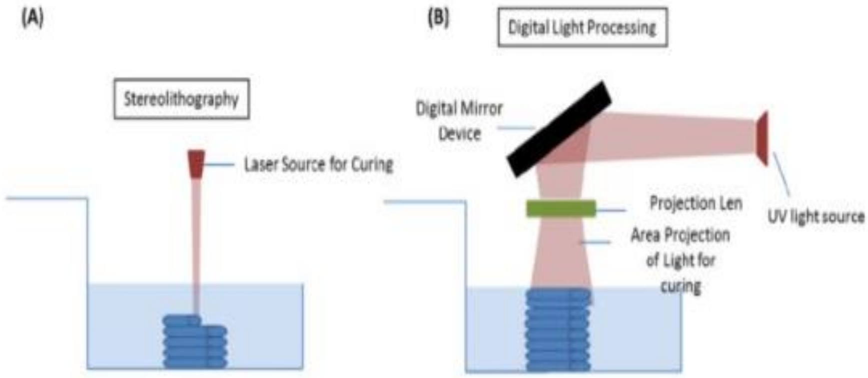


Figure: Vat Polymerization (Lee, Sing, Zhou, 2018)

In the Powder Bed Fusion process, the build platform is filled with powder. This process makes use of either a laser beam or electron beam to fuse material powder together (Powder Bed Fusion | Additive Manufacturing Research Group | Loughborough University, 2014). Upon where the beam (energy source) is directed, the powder fusion happens. This helps to obtain the desired shape. The process can be used for metal and plastic parts. Highly strong parts or structures of good quality can be produced with this process. Technologies such as

Selective Laser Sintering (SLS), Selective Laser Melting (SLM) and Electron Beam Welding are examples of Powder Bed Fusion being carried out.

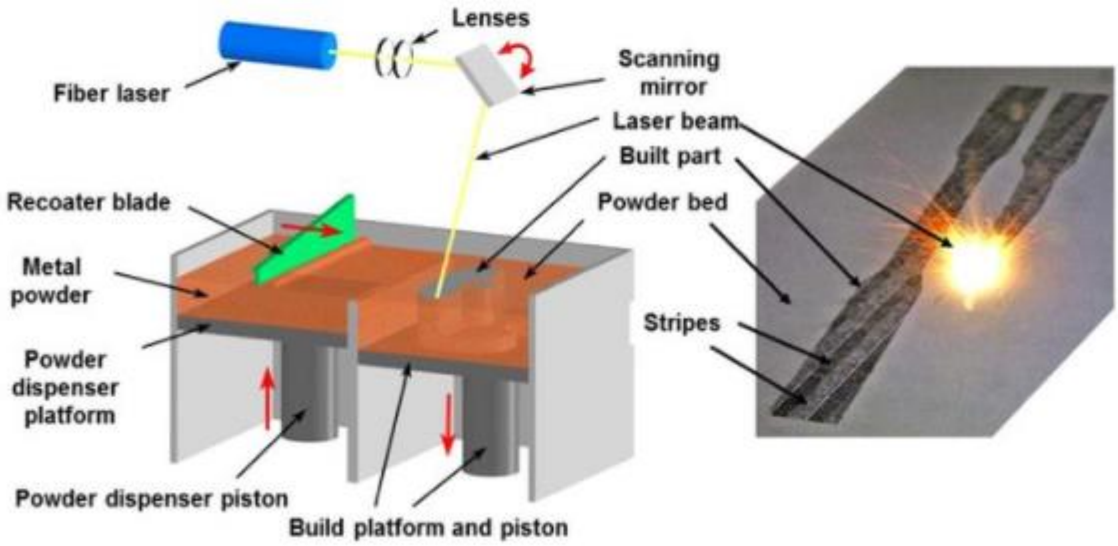


Figure: Powder Bed fusion (Criales, Arisoy, Lane, Ozel, 2017)

The Directed Energy Deposition (DED) Process is like the Material Extrusion Process with the exception that the nozzle moves in multiple directions and is not fixed to one particular axis (Directed Energy Deposition | Additive Manufacturing Research Group | Loughborough University, 2014). The DED machine consists of a multi-axis arm (normally 4, 5 axes) on which the nozzle is mounted. The multi axis arm moves over the surface of a fixed object. The nozzle deposits the material onto the surface in either powder or wire form. The material is melted on with the help of an electron beam, laser. Further material is added layer by layer upon solidification.

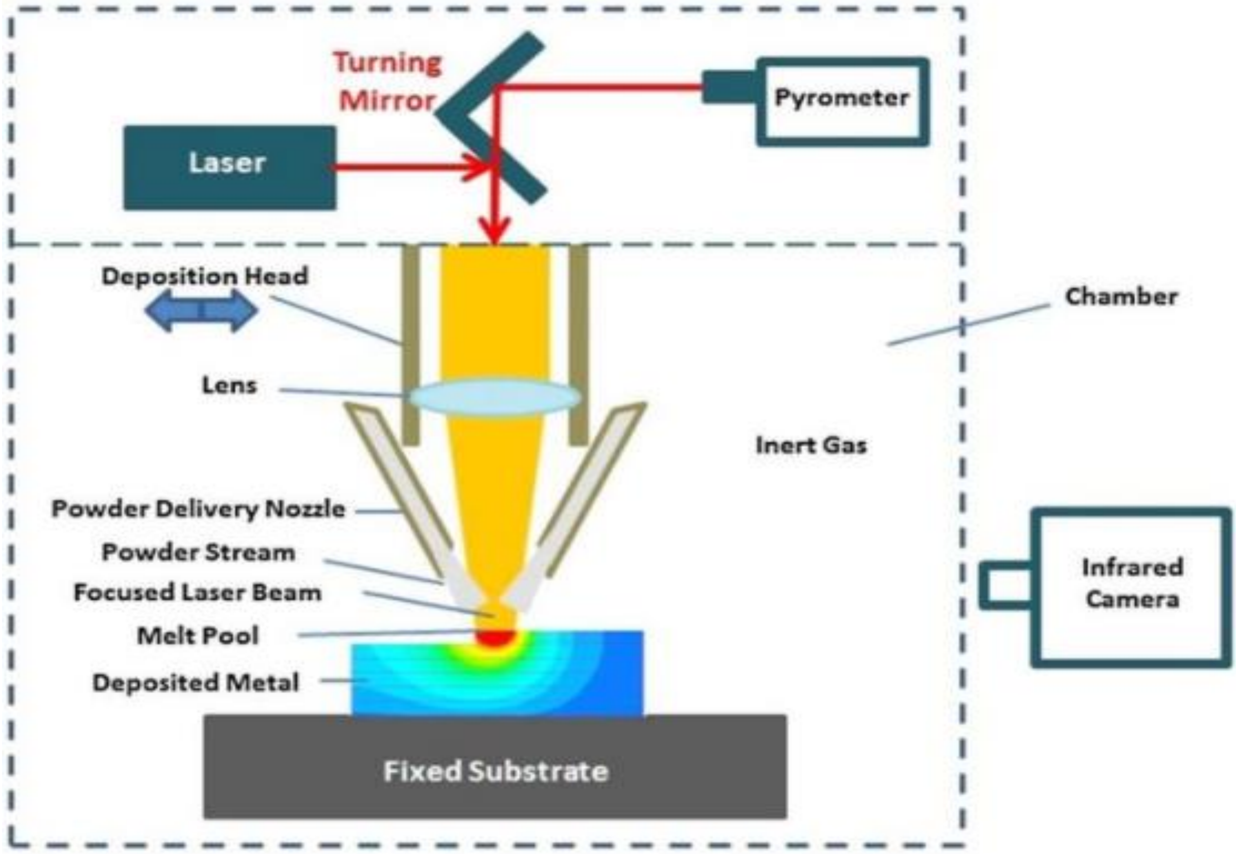


Figure: Directed Energy Deposition (Dantin, Furr, Priddy, 2018)

Sheet Lamination is an AM technique which includes processes such as ultrasonic additive manufacturing (UAM) and laminated object manufacturing (LOM). The UAM process uses ultrasonic welding to weld metal sheets and hold them together (Sheet Lamination | Additive Manufacturing Research Group | Loughborough University, 2014). This process requires removal of the unbound metal for which it uses CNC machining as well. The UAM process uses metals like copper, aluminium and stainless steel. The Laminated object manufacturing (LOM) processes is like the UAM process, except that it uses paper as adhesive to hold the layers together instead of welding. The strength of objects produced by LOM isn't very high, so it is not suited for structural purposes but only for aesthetic purposes.

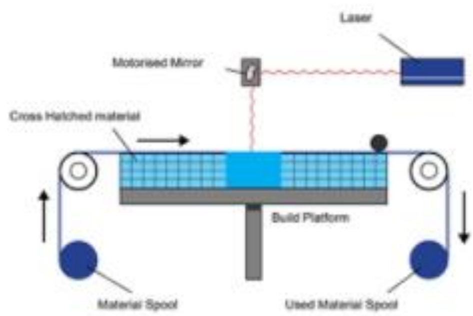


Figure: Sheet Lamination (Sheet Lamination | Additive Manufacturing Research Group | Loughborough University, 2014)

The Material Jetting process is like the 2D inkjet printer. The printer head is held in position above the build platform (Material Jetting | Additive Manufacturing Research Group | Loughborough University, 2014). Material is deposited on to the surface from the printer head using a drop-on-demand approach. The material is solidified to form a layer using the ultraviolet light. More material is added and solidified to form new layers. The materials suitable are polymers and wax.

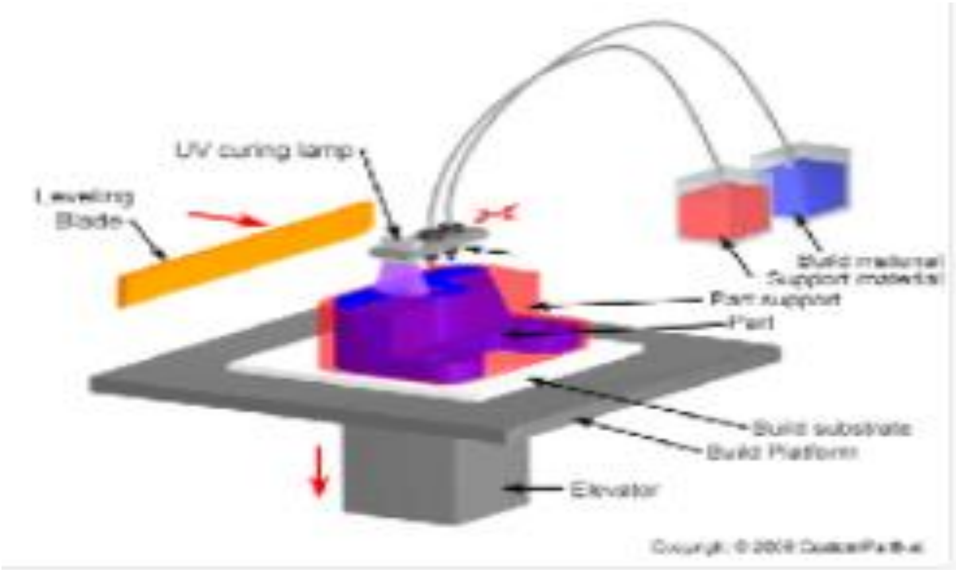


Figure: Material Jetting (Material Jetting | Additive Manufacturing Research Group | Loughborough University, 2014)

3.2. AM Materials in Detail

ABS

ABS is among the most used AM plastics. ABS consists of 20% Acrylonitrile, 25% Butadiene and 55% Styrene (Carlota, 2020). Butadiene polymer provides more shock resistance and the ability to withstand low temperatures. Styrene helps enhance the rigidity. When applied in PBF processes like Selective Laser Sintering, it is used in powder form. In Stereolithography, it is used in liquid form. ABS is used in AM processes demanding a temperature range of 230 – 260 Celsius. Its melting temperature is close to 200C. ABS has the capability to withstand low temperatures like -10 Celsius. ABS can be reused again and again, but however like most plastics it is not biodegradable. ABS does not require a lot of post processing. ABS must not be exposed to moisture and it should be kept dry.

PLA

The advantage with PLA is that it is biodegradable. PLA is from renewable products such as corn starch, sugarcane etc (Carlota, 2019). PLA can be used to print at a lower temperature range like 190 C to 230 C. The consistency that can be achieved with PLA is high. It has a range of colours and is friendly to use. PLA is not as resistant and flexible as ABS, but it has very good heat resistance. Not much post processing is required with PLA. PLA can be further treated with acetone solution.

Nylon

Nylon used for 3D printing is normally in the form of Polyamides that is PA11 or PA12. PA11 is a polyamide powder made from renewable sources like vegetable oil and castor oil. PA11 is heat-resistant both chemically and mechanically, and highly shock resistant (Staff, 2021). It has a tensile modulus of 1600 MPa, tensile strength of 48 MPa, melting temperature of 201 C and density of 990 kg/m3. PA12 is a synthetic powder made from non-renewable sources like petroleum. Parts made out of PA12 are chemically resistant extremely strong, rigid and flexible (EOS, 2021). PA12 Has a tensile modulus of 1650 MPa, tensile strength of 48 MPa, melting temperature of 176 C and density of 930 kg/m3. Both PA-11 and PA-12 are mostly used in car parts, aircraft parts and nowadays in the medical industry.

Aluminium

The commonly used Aluminium alloys are AlSi10Mg for prototypes and in automotive, aerospace and mechanical engineering industries. This possesses yield strength in the range of 230-270 MPa and tensile strength of 450-460 MPa, in the manufactured state. The AlF357 alloy is very good for high strength structural components as it has a high load bearing capacity, low weight and good corrosion resistance. Its yield strength is 260 MPa and tensile strength is 330MPa (EOS, 2021a).

Titanium

Titanium alloys such as Ti64, Ti64ELI, Ti64 grade 5 and Ti64 Grade 23 are used in aerospace medical and automobile industries. They normally possess a yield strength of 945 MPa and ultimate tensile strength of 1080 MPa (EOS, 2021a). They are known for their low specific weight, biocompatibility, high corrosion resistance and ductility.

Stainless Steel

Stainless steel alloys for 3D printing are 316L, 17-4PH, 254, PH1. They normally possess a yield strength ranges from 400 - 1800 MPa and ultimate tensile strength ranges from 500 2000 MPa. They are known for their hardness, ductility, high corrosion resistance and high fatigue resistance.

APPENDIX 4 - AM and Supply Chain

AM could make the supply chain processes simpler (Berman, 2012). AM does not require thousands of assemblies and subparts as the entire product can be produced in a single setting on a machine. This implies that the assembly lines would get eliminated in the long run and there is reduction in the number of stock-keeping units (Campbell et al., 2011). The raw material required for AM can be procured from a few select suppliers locally unlike Traditional Manufacturing where the materials and subcomponents would come from suppliers distributed all over the globe (Berman, 2012). With the adoption of AM, offshoring of production to countries like China, Vietnam etc., will reduce and would return to the consumer economies. So as a result, the massive distances in the supply chain would reduce. The occurrence of errors like overproduction, excess safety stock and obsolescence will be minimized. As goods are produced closer to the consumer, responsiveness is higher with AM. Along with responsiveness, AM can ensure quick reaction to changes in market demand. AM could impact various stakeholders in the supply chain from the supplier all the way to the way to the customer.

'Make' element of the supply chain - AM could help achieve the flexibility that is nowadays required in manufacturing. Traditional manufacturing would need several production lines for each product variant that needs to be adjusted to demand accordingly. An AM machine removes the need for a production line by offering variety and complexity on the same machine. Also, the machines have a lot of capability in terms of materials, speed, accuracy and precision. Many versions of the product can be produced on the same machine without extra tooling and costs. AM reduces the human resources needed to make, assemble and deliver the finished goods and other inventory. AM is highly adaptable, meaning to say that it can be deployed quickly and production using AM can be ramped or down according to the demand (Pannett, 2019).

'Delivery' element - AM enables the creation of a digital warehouse to store the CAD data of the parts (Heutger & Kückelhaus, 2016). Rather than holding thousands of slow-moving parts, WIP inventory and finished goods, AM provides the opportunity to hold limited stock and replenish as and when needed. This is attractive especially in the aircraft industry which is characterized by MRO. As the need to move and hold stock is reduced, the fulfilment costs are reduced. As the manufacturer is close to the consumer location, order fulfilment cycle time gets reduced, thereby customer satisfaction improved (Pannett, 2019).

'Return' element – As designs can be modified quickly and spare parts could be produced according to demand, the need to hold parts reduces. Therefore, the risk of obsolescence and its associated costs decreases (Pannett, 2019).

'Source' element - AM indicates a shift from procuring physical items to procuring data. The issues of how suppliers will be evaluated, licensing, intellectual property and security come into the picture here. AM simplifies the product portfolio as the whole assembly can be printed at once, without having the need to produce each part and then assemble everything. As everything moves digital with AM, it's easier to store, update and change CAD data. If the process parameters and dimensions are not adhered to, changes can be made easily before final production. Therefore, there is no need to rework each part which could be very costly (Pannett, 2019).

APPENDIX 5 - Industry Use Cases

Along with the journal papers, many AM news databases and company websites were visited to gather secondary data that provides important facts and figures to begin the process of data collection and analysis. The OEM, AM machine producers and material manufacturers' websites have been considered for AM technology and its respective applications.

OEMs

Automotive

The adoption of AM by the automobile industry is quite evident with stalwarts such as Volkswagen and its group of companies like Porsche and Bugatti. This has been done with an intention to reduce product lead times and improve manufacturing capabilities throughout the product life cycle. Volkswagen's 3D printed spare parts initiative launched in May 2017 signalled the beginning of the use of AM to print spare parts as well as complex parts (Jackson, 2018). Starting from the design of the corrado adapter, Volkswagen has gone on to produce high performance parts with structural requirements like gearshift knobs and mirror mounts. Volkswagen in partnership with HP Inc. and GKN Powder Metallurgy developed an electric powered 3D printed Golf GTI in just 9 months, showing massive improvements production time (Ribeiro, 2019). The FDM Machines helped them save $160,000 in tooling costs in 2016, which is expected to increase every year. With Volkswagen, other adopters of FDM technology are General Motors and Lamborghini. Along with FDM, Volkswagen is exploring the HP Multi-jet fusion technology. Porsche started producing 3D printed engine pistons for its 911 supercar using Laser Metal fusion. Porsche is working together with Mahle and Trumpf to 3D print engine pistons (Haria, 2018). With APWorks, Bugatti has produced a few components using PBF technology (Selective laser melting) and achieved weight reduction, better performance. Some of those components produced by Bugatti include the titanium brake calliper, spoiler bracket, motor bracket and the exhaust tailpipe. Also, Audi has incorporated the PBF Technology for metal applications such as the water connecting pipes for its W12 engine.

In 2019, Daimler launched a completely automated metal AM system called the NextGenAM for producing metal parts that are difficult to produce conventionally and are more expensive. Daimler aims to achieve approximately 50% cost savings on production. This system has jointly been released with EOS and Premium Aerotec. Daimler visualizes the concept of 'Digital Inventory', where spare parts are stored digitally and not in huge quantities in the warehouse (Stevenson, 2020). Their intention is to reduce the quantity of spare parts in stock and the costs associated with it. Moreover, Mercedes Benz has adopted the polymer based PBF technology for printing the spark plug holder and sunroof rollers for its cars. Fiat Chrysler, Renault and Nissan have used 3D printing for prototyping as well as producing end products (Goulding, 2020). The technology used by Fiat Chrysler, Ford and General Motors is mainly SLA. Together, they have achieved better testing capability, enhanced fluid dynamics, engine weight reduction and improved aerodynamics. Toyota

Motorsports and 3D Systems collaborated in the same year to produce lightweight, high-quality parts for the Toyota motorsport cars.

BMW recently opened an AM plant in July 2020 with an aim to produce approximately 50,000 parts every year along with 10,000 spare parts (Stevenson, 2020b). The BMW i8 roadster is among the first few cars being produced by AM. Rolls Royce (owned by the BMW group) has begun to use AM (Polymer based HP Multi-jet fusion) for certain specific parts in the car interiors. The metal parts for the exterior are made using the EOS SLS technology (both BMW and Rolls Royce). Continental AG which manufactures auto parts along with tyres, has partnered with Stratasys (FDM Technology) to produce functional parts with AM. Continental aims to complement its traditional manufacturing processes by 3D printing jigs and fixtures, prototypes for its respective production lines. General Motors' Chevrolet has started to integrate 3D printed parts into its motorsport cars and off-road trucks. The Chevrolet Indy V6 race car recently contained 3D printed parts in its exhaust system. The Camaro ZL1's body was fitted with more than 500 3D printed parts. The Silverado off-road truck was fitted an AM produced carbon fibre plastic rear dumper shield. Chevrolet claims massive improvements in design freedom, cost & weight reduction and aerodynamic performance.

Aircraft

When it comes to AM adoption to produce complex parts, the aircraft industry is no different. In 2012, Titomic Ltd. signed an agreement with Airbus to use the Titomic Kinetic Fusion (TKF) AM technology for the manufacturing of high-performance aircraft metal parts. A titanium bracket was produced in 2014 using the TKF technology. Airbus announced its partnership with Ultimaker in 2019 to take advantage of metal AM technologies and polymer capabilities to produce high strength complex parts. Ultimaker was selected due to its ability to meet the extremely stringent aerospace requirements for non-flying parts. Airbus seeks to leverage this partnership to produce jigs, fixtures, tools on-site near the customer with support from Ultimaker for spare parts, software services and raw materials (Boissonneault, 2019). An R&D project called Metallic Advanced Materials for Aeronautics (MAMA) had been started by Sciaky Inc. in 2019 in collaboration with Airbus, Aubert & Duval, for the purpose of enquiry into the use of Electron Beam AM technology for producing titanium aircraft parts. Liebherr Aerospace started additively manufacturing components for Airbus, after having received the approval from Airbus for the use of the nose landing gear brackets for the Airbus A350 (Ribeiro, 2019a). The AM produced nose landing gear (EOS SLS Technology) helped Airbus achieve a weight reduction of 29% and stiffness of over 100%. Previously, Liebherr produced a 3D printed valve block for Airbus that is 35% lighter, has fewer parts and offers the same performance as the traditionally produced one. This could be achieved due to Liebherr taking advantage of the AM solutions offered by EOS solutions (SLS technology). Satair, an Airbus subsidiary additively produced wingtip fence parts after realizing the difficulties in producing it conventionally. AM helped in reducing the cost per piece, the processing time per piece and the overall lead time. Most importantly, these parts were certified by the EASA.

During the Paris Air show in 2019, Safran released the Add+ engine technological demonstrator, consisting of approximately 30% 3D printed components (Boissonneault, 2019b). The PBF technology that Safran used is Selective Laser Melting (SLM) to produce engine parts. Safran desired to utilize the advantage of AM to reduce the number of assembly parts. For example, the gearbox that originally consisted of 12 parts had been consolidated to 2 parts. In early 2019, GE Additive procured highly advanced AM machines for the production of additively manufactured turbine blades for the GE9X engine to be used on the Boeing 777X and more aircraft engine parts (Donaldson, 2019). The machines used here are Arcam A2X machines that can produce 6 blades per batch in 3 days, giving rise to expectations of higher production in the future. Most importantly, the titanium produced blades help achieve a weight reduction of nearly 200 kg and 10% reduction in fuel consumption over the nickel-alloy turbine blades. The GE9X engine consists of 304 AM parts. Titanium parts are gaining an increased focus in the aircraft industry. To produce the fuel nozzle, GE Additive made use of advanced laser AM machines. Premium Aerotec achieved a process qualification for production and supply of AM produced titanium parts, signalling the increasing use of titanium and mostly the adoption of AM to produce those critical parts. Adding on to this, Premium Aerotec partnered with Lockheed Martin to identify parts that have the potential to be AM produced. The idea was to minimize the costs of producing storing those respective parts and improve process efficiency.

In 2020, Pratt & Whitney brought a 3D printed aircraft engine component into production, signalling its entry into Maintenance, Repair and Overhaul (MRO) operations. The entry into MRO operations happened with contributions from ST Engineering and Component Aerospace Singapore. The whole essence of this MRO project is to realize the capability of on-demand printing, reduce dependency on external suppliers and conduct faster repairs. Marshall Aerospace has adopted 3D printing to produce air conditioner ducts, knife holders and switches (FDM technology). Marshall has 3D printed a ducting adapter with Nylon 12 material and achieved a significant cost and weight reduction of close to 65%. The capabilities of AM have been further enhanced to produce wing flaps, by Stelia Aerospace and Bombardier. Most recently, Honeywell developed a bearing housing which is a critical engine component using 3D printing. Honeywell has been able to produce the part without compromising on quality, time and costs. The bearing housing has been certified by the FAA.

To highlight the AM advancements taking place in the aerospace sector, the announcement by GKN Aerospace on two new research programs in 2019 counts as a significant contribution. The programs called ‘AIRLIFT’ and ‘DAM’ seek to explore the Laser Metal Deposition technology and utilize the industry 4.0 concepts to design tools and products using AM. Furthermore, the collaboration between BAE systems and Stratasys to explore AM technologies such as FDM and materials adds to the advancements taking place.

Rail

One of the earliest adopters of AM in the rail industry was Deutsche Bahn (DB). Upon facing difficulties in sourcing spare parts which normally have high waiting times, DB started using AM (Waters, 2019). Starting from a coat hanger to a buffer box and then a spring locker assembly, DB now prints many spare parts. The buffer box replacement would usually take 9 months, meaning the trains must be kept out of service for 9 months. With AM, massive improvements in lead time have been observed. Also, storage and warehousing costs were being incurred in millions previously. Now, DB has saved a lot of those costs.

Siemens Mobility opened its first digital maintenance centre in 2018, focused on eliminating the inventory of certain spare parts. Siemens uses the Stratasys Fortus 450mc 3D printer, which enables it to produce spare parts at much lesser costs and time. Siemens claims that production time for each part has been reduced by 95%.

Naval

Governmental organisations have started to adopt 3D printing on a small scale. In 2018, the Singapore Maritime and Port Authority agreed to bring an AM production facility to the Pasir Panjang terminal. The key focus is to move to digital inventory, signalling a shift from storing spare part inventory at warehouses. This is expected to make the sourcing of obsolete marine spare parts easier. Other examples include the Indian Navy where 3D printed centrifugal pump impellors have been produced, and the Australian Navy using AM for maintaining patrol vessels.

In 2019, ThyssenKrupp received certification and approval from DNV GL to produce 3D printed parts for the naval sector (Boissonneault, 2019c). In 2020, Wilhelmsen produced and delivered 3D printed scupper plugs to BergeMafadi. Scupper plugs are important spare parts which prevent oil spills aboard the ship. If the scupper plugs are broken, they cannot be repaired, and fresh pieces are needed. This is where 3D printing is very helpful. Moreover, the emphasis on lead time and cost reduction along with reduced inventory has propelled the naval industry to adopt 3D printing. Wartsila, a cargo ship producer recently produced a lifting tool with 3D printing and achieved massive cost savings of 100,000 euros (Davies, 2020). According to Davies (2020), Wartsila saves 1000 euros per produced tool. Also, the newly AM produced lifting tool was much lighter and stronger than the original one.

Machine Makers and Material producers

Founded in 1989, EOS Solutions has grown to be a massive 3D printing technology provider, whose offerings range from machines and materials to training and consulting. Due to the enablement of design freedom, reduced production and delivery times, recycling of leftover material and lightweight designs, EOS has become the go-to 3D printing solutions provider for many manufacturers. By using the EOS Formiga P110 machine which works on SLS technology, Deutsche Bahn (DB) was able to reduce the manufacturing cycle time for fixtures from 4 weeks to 1 week and save 80% of costs due to elimination of injection moulding. Also, the fixtures produced were reliable and met the safety standards. Bus manufacturer Daimler EvoBus maintains an inventory of more than 320,000 spare parts, with the promise of satisfying customers throughout the product life cycle (more than 15 years). This incurs heavy inventory and warehousing costs, along with high lead times. EvoBus consulted EOS Additive Minds for a solution for which EOS helped to identify 2600 parts for AM and select the appropriate materials (3D Printing on Demand - Establishing a

Sustainable Spare Parts Management System, 2019). Through this, EvoBus achieved faster lead times, reduced inventory costs and tooling costs (quantitative information not disclosed by EvoBus). EvoBus utilized the EOS SLS Technology to print the spare parts. In the aircraft industry, MTU Aero engines and Liebherr benefited from the EOS technology by achieving high design freedom, cost efficiency, faster lead times, quality assurance, assembly integration and weight reduction.

Stratasys, an Israeli 3D printing company was founded in 1989, provides strong competition to EOS solutions. Stratasys uses PolyJet and Fused Deposition Modelling technologies throughout the product life cycle, from the prototyping stage to the final production stage. The automotive players inspired by Stratasys' technology include NASCAR teams and luxury auto design firms. A NASCAR team named Joe Gibbs Racing added a 3D printed dashboard insert that can accommodate instrumental devices for temperature tracking, weather sensing etc. The Stratasys technology enabled customization which helped in updating the race car drivers with real time information. Italdesign used the Stratasys J-series printer to create the marble interiors for the DaVinci concept car. With this technology, Italdesign produced four air conditioning diffusers and two door inlays in a very short time. Moving on to the aircraft customers, Lockheed Martin and BAE systems have gained advantages from Stratasys' materials and machines. The Antero high performance polymer material having electro-static dissipative (ESD) capabilities, has helped Lockheed Martin save on costs and production time along with build consistency. BAE systems has extensively used Stratasys F900 3D printers mostly for ground operations that includes prototypes, supporting tools and end products. They have been able to reduce costs and lead times.

HP is making advancements in the field AM with its Multi Jet Fusion and Jet Fusion technologies (HP Multi Jet Fusion 3D Printing Technology - Powder 3D Printer | HP® Official Site, 2021). Aereco, an industrial HVAC (heating, ventilators and air conditioners) system supplier has been an adopter of the multi jet fusion technology. Often Aereco faced problems with respect to sourcing spare parts for its jigs, fixtures and other holding tools. By adopting 3D printing, they started saving up to 90% of costs associated with production and transportation and achieved design freedom. For end use parts like the exhaust unit slider, Aereco took advantage of the versatility and quick-change capability of AM and achieved better productivity along with cost savings. Avular, a drone manufacturer utilized the capabilities of HP and Materialise to develop PCB holders, battery holders and clicking mechanisms for their drones. Avular got the benefit of design flexibility and customization. Ubi Maior, a part producer for yachts and boats adopted the HP Multi jet fusion technology to produce the conical roller cages that grip the titanium rollers tightly. With this, Ubi Maior noticed that the roller cages could withstand heavier loads with lower rotation friction.

Renishaw, a metal AM specialist uses metal powder bed fusion technology to additively produce components (Renishaw: Additive Manufacturing Case Studies, 2021). Along with metal AM systems, Renishaw also produces metal powders and supplies software related to process planning, build preparation. Bloodhound utilized Renishaw's AM250 system to improve the nose design of its supersonic car. By using Renishaw's expertise Bloodhound was able to produce prototypes in days, which otherwise would last many months. A weight reduction was achieved with the AM produced nose-tip. Transfiormers, a motorsport team reduced the weight of their front suspension component by 40% and were in a better position to adhere to tolerances to meet chassis and other kinematic requirements. This was possible to achieve because of the Renishaw metal AM technology. The Swansea university formula student team were able to meet the design challenges of the intercooler core due to Renishaw's support in the design process.

BASF is a German based materials producer which produces powders, filaments and photopolymers for AM processes like Fused filament fabrication and Powder Bed Fusion (BASF Forward AM, 2021). A Dutch bike racing team called Ten Kate racing partnered with BASF to use the ABS fusion material to produce the dashboard spacer and junction box housing. With this, they improved the speed of the production cycle and achieved better heat resistance and design flexibility. BASF's TPU powders are used in the automotive interiors. These powders are known to provide high stability, durability, surface quality, strength and flexibility. They are being used in the dashboard, headrest, seating and the armrests.