Additive Manufacturing Processes and Materials for Spare Parts

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Abstract Additive Manufacturing (AM) has shown to have a high potential to produce spare parts on demand. However, the use of AM to produce spare parts on demand faces challenges related to material availability, quality, part size, cost, and pre- and post-processing operations. From existing literature, most studies focus on a single use case. Other studies focus on the applications of using AM from a general perspective, rather than a specific AM process. This study attempts to close this knowledge gap by considering the AM of spare parts and processes by undertaking a thorough review of scientific articles regarding different AM processes and materials being utilised for spare parts. Current publications do not explore all potential materials that are available, and do not investigate a broad range of industrial sectors. It was also found that the tooling industry and use for rapid prototyping are largely left out. The study also showed that the use of Material Jetting and Binder Jetting are less frequently used for end-use spare parts and Sheet Lamination is rarely used at all. In contrast, we found that Directed Energy Deposition was most popularly used for repairing spare parts, followed by Powder Bed Fusion and Material Extrusion that are prevalent in most industries. This study revealed that further development on the use of Binder Jetting and Material Extrusion would allow for more possibilities in the use of high-value pare parts for sectors such as aerospace, automotive, energy, defence, consumer products and medical industries.

1. Introduction

Additive Manufacturing (AM) is a process that produces physical parts by adding material layer-by-layer using a 3D model data as an input [1]. Digital manufacturing processes, such as AM, Computerised Numerical Control (CNC), laser machining, laser forming, incremental sheet forming have attracted significant attention in “Just-in-Time” production of spare parts [2-4]. In this context, “spare parts” refer to components that are used to replace old or broken parts in an equipment. They are designed to be removable and replaceable and can be bought separately. Using AM processes, spare parts are usually limited to the production of components made from a single material, often plastics, metals or ceramics. The concept of “digital spare parts” involves the production of components based on using digital manufacturing technologies on demand and often at close proximity to the end-user.

AM can help address current problems related to spare parts, such as product obsolescence, criticality, and capital commitment [5-7]. The use of AM has been investigated from various perspectives to improve spare part manufacturing and supply chain management, ensuring market resilience, as well as to fulfil requirements for legacy machines. This includes reducing warehouse and maintenance requirements while improving responsiveness, product performance, and machine lifetime [8]. The aim of this paper is to conduct a thorough review of the AM industrial sector and to identify the state-of-the-art of AM produced spare parts as shown in Table 1. It is hoped that this article will provide a better understanding of the use of AM produced spares, foster further research in this area and to encourage a wider industrial adoption of AM produced spares.

To ensure relevance and to capture state-of-the-art literature, the research for papers was focused on publications from 2019-2022 regarding articles with spare parts or considering and mentioning specific AM processes with use of spare parts. Using various search engines including Scopus, Web of Science and Google Scholar, it was found that very little articles about different AM processes and materials for spare parts exist. Some papers cited challenges in adopting AM for manufacturing spare parts, such as lack of material and design knowledge [8]. In addition, most studies on AM spare part supply chains are theoretical in nature and do not consider manufacturing processes and related post-processing requirements. The search did identify a few reviews on spare parts utilising AM although they did not consider actual AM processes and materials or only used a single process as an example. In contrast, there are more reviews about using specific AM processes or for specific industry sectors. Therefore this paper aims to close this knowledge gap by focused on all AM processes and available materials used for the production of spare parts.

Table 1. Related review articles in AM sector related to spare parts and/or AM processes from 2019-2022.

	Description	Spare part focus	AM processes considered
[9]	Classification and selection of spare parts suitable for AM	Yes	PBF, BJ
[10]	Metal AM in aerospace	No	PBF, DED
[11]	AM in aerospace	No	General AM
[12]	AM in energy sector	No	General AM
[13]	AM technologies in shipbuilding	Partly	DED, MEX, PBF
[14]	AM and spare parts supply chain	Yes	General AM
[15]	AM and spare parts management	Yes	General AM
[16]	Metal PBF	No	PBF
[17]	PBF	No	PBF
[18]	AM in aerospace	No	PBF, MJ, MEX, VP, DED
[19]	AM on the supply chain of the aerospace spare parts	Yes	General AM
[20]	AM for spare parts: supply chain management	Yes	General AM
[21]	Decentralised Spare Parts Production for Aftermarket	Yes	General AM
[22]	Wire arc AM of aluminium for aerospace and automotive	No	DED
[23]	AM of polymer-based composites for automotive	No	PBF, MJ, SL, MEX, VP
Current study	AM processes and materials for spare parts	Yes	PBF, BJ, MJ, SL, MEX, VP, DED

Previous reviews studied the selection and classification of spare parts that could be potentially suitable for AM, focusing on Powder Bed Fusion (PBF) and Binder Jetting (BJ) methods [9]. Sector-specific reviews include aerospace, energy, shipbuilding and automotive sectors are available, but they do not solely focus on spare parts [10-13,18,23]. In addition, reviews that investigate specific AM processes are available [16-17,22]. Many spare part-related reviews have an operations management perspective, generalize the use of AM, and do not consider which particular AM process could be most suited for manufacturing the spare parts [14-15,19,20,21]. Some papers explored the broader difference between different AM processes but do not have a spare part focus and only looked at one industrial area, such as for aerospace or automotive sectors [18,23]. Commonly, the use of PBF for producing spare parts is studied widely [9-10,16-18, 23], followed by Material Extrusion (MEX) [13,18,23] and Directed Energy Deposition (DED) [10,13,18,22]. Other processes such as Sheet Lamination (SL) is rarely used for spare parts.

This study investigates the different AM processes and materials utilised in the industry, mainly focusing on methods that have a potential research gap in spare parts manufacturing. The study is based on the following research questions:

1. AM processes and materials: What ISO/ASTM-based AM processes and materials are utilised for manufacturing and in which sector? Is there a potential to produce spare parts? → *Section: Additive manufacturing processes*

2. Selection of parts: How do we select suitable spare parts for AM and acquire data for manufacturing? → *Sections: Selecting suitable spare parts for AM and Input of spare part data*

3. Reasoning: What possibilities and challenges do AM-fabricated spare parts pose? → *Section: Possibilities and challenges for spare parts produced via AM*

4. Future: Based on the current technological developments, what processes and applications indicate future scientific potential? → *Section: Discussion, Conclusions & Future perspectives*

Based on Table 1, none of the previous reviews considered all available AM processes and no existing papers have a focus on spare parts.

2. Additive manufacturing processes

ISO and ASTM group AM processes into seven distinct categories: 1. Material Extrusion (MEX), 2. Powder Bed Fusion (PBF), 3. Material Jetting (MJ), 4. Vat Photopolymerisation (VP), 5. Binder Jetting (BJ), 6. Directed Energy Deposition (DED), and 7. Sheet Lamination (SL) [1]. Each category has multiple derivatives, vendors, suppliers, devices and materials. The biggest challenge when undertaking a systematic review is that several different terms are sometimes used for certain technologies, including trade names, commercial names, commonly used terminology, or even terms coined independently. For example, the Material Extrusion process is often called Fused Deposition Modelling (FDM), the trade name for Stratasys, or Fused Filament Fabrication (FFF). Sheet Lamination of metals is sometimes referred as Ultrasonic Additive Manufacturing (UAM) [24-26] or Laminated Object Manufacturing (LOM). In addition, new developments challenge the current knowledge; for example, considering AM processes capable of making metal parts - in scientific literature, all processes are capable of this [25-32].

2.1 Different AM processes and materials in industrial sectors

AM is utilised in many industries, such as aerospace, marine, medical and consumer products. Certain sectors have a wider adoption when using AM and also based on the size of the market. According to the Wohlers Report in 2021 [33], the most significant industrial sectors utilising AM are aerospace (16%), automotive (16%), medical (14%), consumer electronics (13%), energy (11%) and defence (7%) (Fig. 1). Therefore, in this study, considering end-use parts, these categories were selected to represent the industrial sectors for further investigation.

These end-use domains were selected because these methods and materials can also be used for manufacturing spare parts. However, for certain end-products, such as medical pre-operative human models do not have a reference point for spare parts. Thus, this study excludes the use of AM at home, construction activities or printing of food or edible items. A scientific literature search was performed using Scopus, Web of Science and Google Scholar databases on the different AM processes utilised in various industrial sectors. Initially, the literature search focused on using ISO/ASTM process terminology with a combination of industry and sector names. When no relevant search results were found, trade names or equipment manufacturer names were then used.

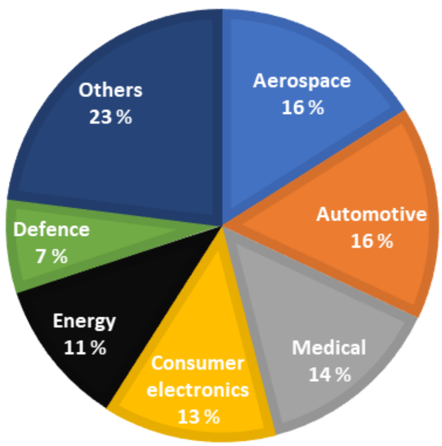


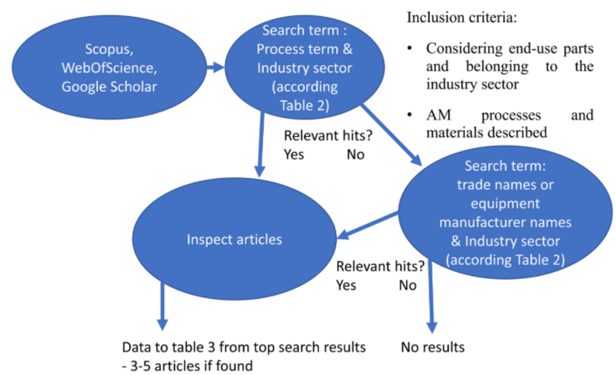
Fig. 1. Distribution of AM industry sectors utilising AM [33].

The literature search focused on gathering examples for each category and to determine which AM processes for each sector had significant gaps. When at least one or a few examples were found, the focus was moved to other processes and industry sectors. To ensure relevance, all findings from the literature search was carefully scrutinised using two criterions: (1) Does the paper belong to the industry sector, and is it considering end-use parts? (2) Are AM processes and materials described? The search terms used are listed in Table 2, and the search was performed during the period of November to December 2021, as shown in Fig. 2.

Table 2. Search terms for different AM processes in industrial sectors.

Industrial sectors	AM process	Process term	Manufacturer
"Aerospace or Automotive or Medical or Consumer products or Energy or Defence" "Car or implants or nuclear or oil & gas or military or fighters"	PBF	"powder bed fusion or PFB or selective laser sintering or SLS or direct laser sintering or DMLS"	
	MEX	"material extrusion or fused filament fabrication or FFF or fused deposition modelling or FDM"	
	VP	"vat photopolymerisation or stereolithography or SLA"	"Formlabs"
	MJ	"material jetting or polyjet or nanoparticle jetting"	"Objet"
	BJ	"binder jetting or colorjet printing"	"Zcorp or Zprinter"
	SL	"sheet lamination or LOM or laminated object manufacturing"	"Mcor or Fabrisonic"
	DED	"directed energy deposition or DED or laser engineered net shaping or LENS"	

Fig. 2. Flowchart of the literature search.



It was found that existing review articles were focused on the classification and selection of spare parts being suitable for AM [10] as well as the utilisation of different AM processes for various industries, such as aerospace, energy, marine and automotive sectors [11-15]. Generally, these studies either do not classify the use of all AM processes or review only a single AM process. They also do not distinguish between prototyping and what the actual end-use parts are. The findings of the literature search is presented in Table 3. Based on findings [33] the characteristics of different AM processes based on material form, material class, and maturity is described in Table 4.

Table 3. Characteristics of different AM processes and maturity based on the search of processes and providers from Wohlers 2021 [33].

Table 4. Different AM processes and materials in industrial sectors considering end-use parts.

	PBF	MEX	VP	MJ	BJ	SL	DED
Aerospace [34-40]	PA 2200, X20Cr13, X10CrNiTi18-10, Ti6Al4V	ABS, PEEK, PC, ND-PLA, Ultem 9085	SiC		SiC	Metal matrix composite	Ti6Al4V, TiCp/Ti6Al4V
Automotive [41-46]	PA12, Ti-45Al-4Nb-C	ABS, 316L	Acrylate, Al2O3				
Medical [47-55]	Ti-6Al-4V, PA, 316L,	PEEK	PTMC	RGD 720, RGD 875	ZP 151	Paper	Ti6Al4V
Consumer products [56-60]	PA12, TPU	PLA, TPU	Resins	ZrO2	316 SS / Bronze		
Energy [61-64]	IN939, Ti–6Al–4V	Lay-Fomm & -Fel, Gel-Lay, Conductive PLA	Thorium dioxide				SS316L
Defence [65-	Ti-6A-4V, PA12	Energetic materials					Ti

Material		PBF	MEX	VP	MJ	BJ	SL	DED
Powder	Plastics	3				3		
	Metals	3				2		3
	Ceramics	1				1		1
Filament, pellet, paste	Plastics		3					
	Metals		2					
	Ceramics		2					
Resin	Plastics			3	3			
	Metals			1	1			
	Ceramics			2	1			
Sheet	Plastics						2	
	Metals						2	
	Ceramics							
Wire	Plastics							
	Metals							3
	Ceramics							2

3: High maturity, 2: Mature, 1: Cases exist

3. Selecting suitable spare parts for AM

Different approaches can be used to produce spare parts from AM [9,70-71]. First among them is the technical approach which requires considerations such as whether the AM process can use the same or a suitable alternative material as the original spare part, whether the spare part can fit into the build chamber, whether the AM spare part can be produced according to functional requirements and geometric specifications, and the weight of the part which is sometimes used for estimating costs. [9] While opting for this approach, we should consider standard items such as bolts, nuts and bearings that are commercially impractical for production via AM [72]. In addition, electronics and assemblies can be complex, even though components from those assemblies can be made. The amount of data for spare parts that need to be analysed can be reduced by categorising and filtering out standard items, assemblies and electronics. Even though AM might be technically feasible for certain spare parts, this does not mean that they are economically viable for production using AM.

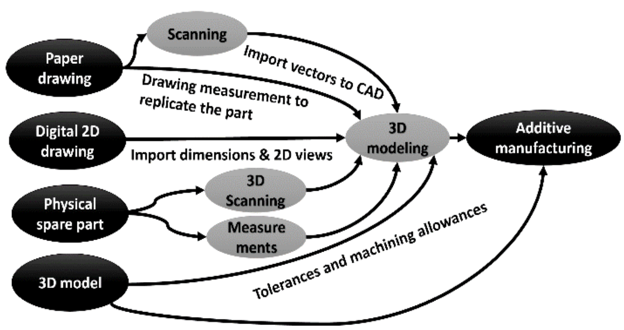
The second approach utilises the supply chain management perspective, such as demand, lead time, stock, order costs, and supply risk [70]. This approach determines the improvement potential of the supply chain and whether the improvements are economically justified and strategically feasible. It is necessary to analyse whether the parts can be fabricated using AM. If the data is available and the production is well organised, then both approaches can be used simultaneously, i.e., taking out parts that cannot be produced by AM, as well as spare parts that do not have economic potential [71]. Subsequently, certain spare parts that have the most economic potential can be turned into a viable business case.

3.1 Input of spare part data

One common problem in manufacturing spare parts is the availability of data [8]. Currently, digital data is primarily available only for newly designed spare parts where a 3D CAD file exists. Therefore, there is a need to acquire data for old and legacy spare parts, which would require 3D scanning and measurement of such parts and understanding their functional requirements, load and relation to other parts to define tolerances and materials [73]. This may require a significant amount of engineering effort, but for less demanding geometries, the use of direct 3D scanning and AM is sufficient [74-75]. If technical drawings are available, they can be used to remodel the component as the material specifications and tolerance requirements are already indicated in those drawings [76].

Conversely, while a 3D CAD model with material and tolerance annotations of new parts may exist, their manufacturing methods might differ [77]. This should be considered when defining machining allowances for spare parts. In the best-case scenario, the 3D model and documentation would include specifications on how a spare part should be produced using AM methods, which makes the process directly viable to manufacture new spare parts [72]. In other cases, having more input for the data such as by having technical drawings could be easier and much faster to reverse engineer as compared to having a single input. Fig. 3 shows different reverse engineering processes for spare parts based on input data.

Fig. 3. Different reverse engineering processes for additively manufactured spare parts based on input data



3.2 Possibilities and challenges for spare parts produced via AM

AM offers many possibilities for the production of spare parts. However, many challenges still exist, which can be chiefly categorised into technical, economic and organizational factors (Table 5). Most of these possibilities for spare parts produced using AM are related to reduced warehousing, lead time, and costs, as well as increased sustainability and local/on-demand manufacturing. The technical challenges include limited material options, tolerances, quality, build chamber size, production speed, and pre- and post-processing. From an economic and organisational perspective, cost, strategy and expertise appear to present a greater and longer-term challenge.

Table 5. Related review articles in AM sector related to spare parts and/or AM processes from 2019-2022.

	Possibilities	Challenges
Consumer electronics		
[78]	Reduction in duration of the repair process	Surface quality
Industrial & commercial machines		
[79]	Reduction in warehousing and cost-effectiveness	Expertise, high minimum order quantities, and costly after-sales strategy
[70]	Reduction in costs, improved availability, and lower carbon emissions	The limited size of possible components, inadequate quality, variable quality across AM equipment, and lack of parts data
[80]	Shortened lead times and the promise of tool-less manufacturing	High AM-piece prices and uncertain AM technology advancements
Defence		
[81]	Reduction in lead times and responsiveness, improvement in system readiness, and sustainability	Sourcing, security, and intellectual property issues
[82]	On-site inventory reductions and increased asset availability	On-site raw material storage
General		
[83]	On-demand manufacturing	Speed, volume, material range and cost, quality, automation, business strategy, education
[84]	Cost-effectiveness	Optimisation complexity
[85]	Superior sustainable performance in the supply chain	High fixed costs, such as purchasing cost of AM equipment
[86]	In-situ repair and remanufacturing enabled by the availability of digital designs; component upgradation during the repair process	Limited availability of digital designs and cost of acquiring new ones; certification of spare parts to overcome liability issues
[87]	Increased responsiveness, minimised supply disruption, cost optimisation, part complexity and sustainability	Technology awareness, intellectual property issues, costs and return on investment, strength, and physical properties of AM-produced parts
Automotive		
[88]	Products with superior performance; reduction in manufacturing and logistics time and costs	Standards regarding the certification of raw materials, machines and manufacturing processes, and final products
[89]	Centralised AM is beneficial for capacity utilisation but less favourable for short lead times and minimal downtime costs.	Scale economies in manufacturing, bundling of design, and manufacturing competencies
[90]	Improved supply-chain reliability and flexibility, reduced inventory-related costs, decreased transports, reduced lead times, increased service levels, and increased customisation possibilities	Network interdependencies and risks, ownership and information management, quality management, digital infrastructure and copyright infringement, organisational maturity and return on investment
Marine		
[91]	Local manufacturing, shorter supply chain	Methods to ensure processes and test parts—standards
Machinery & medical		
[92]	Less reliance on buffer stock and less risk of obsolescence	Cost of AM
Aerospace		
Aero spac e [93]	Up to 35% of AM parts to the spare parts inventory improves lead-time by up to 33%	Restrictions in the size of the build chamber
Process industry		
[94]	Reduction in maintenance costs and extended machine lifetimes	Tools to facilitate the identification of suitable parts and aid the optimisation Process

When discussing products produced by AM, quality and post-processing must be taken into account. Table 6 provides a general summary of different AM processes for spare parts in terms of commonality, quality and post-processing. Quality for AM is not only limited to the AM process, but also includes the design phase, machine-independent process plans (e.g., orientation and support structures), machine-dependent process plans (e.g., process parameters), post-processing, process monitoring, and certification and qualification of parts [95-96]. When comparing the differences between AM processes, the quality of the specific machine being used is important. Within the same process category, the quality can vary heavily between machine manufacturers, operators, in-house quality control and even those re-working on the CAD model.

While PBF produced parts have demonstrated excellent quality with a fairly wide range of robust materials made available (Table 4), quality-related issues still exist, such as poor density [97]. In addition, process monitoring for metal PBF is an important topic [98]. MEX is the most common AM process for low and mainstream applications (Table 4). One most significant problems for MEX produced parts is that the material properties are dependent on the print orientation where the z-axis is typically the weakest direction [99]. MJ, BJ and SL are not commonly utilised for end-products and spare parts due to the moderate quality of the end use part (Table 4). DED shows high potential for repair with good material properties and quality with a robust scientific knowledge available for process quality control and monitoring (Table 4) [100]. Many articles have studied and compared different post-processing methods for different AM processes to remove the supports structures, improve surface quality, achieve required tolerances and enhance the mechanical properties [101-103]. The most common and typical ones are listed in Table 6. To achieve high-quality parts, all steps within the process chain should be taken into account and to understand how they affect the quality of the end product.

Table 6. Analysis of different AM processes for spare parts

AM process	Spare parts	Quality	Material properties	Post-processing methods
PBF	Common	Excellent	Excellent	Plastics: bead blasting Metals: support removal, machining, heat-treatments
MEX	Common, most widespread AM process	Good	Oriented, good	Support removal: mechanical removal or dissolvable
VP	Common	Good	Good	Support removal mechanical and post-curing
MJ	Not common	Moderate	Moderate	Support removal: dissolving, water jet
BJ	Not common	Moderate	Moderate	Infiltration: epoxies, cyanoacrylate
SL	Not common	Moderate	Moderate	Manual support removal
DED	Repairing	Good	Good	Machining

4. Discussion and Conclusions

While there are many review articles available in the literature regarding the utilisation of different AM processes for spare parts, most focus on AM from a general perspective or discuss applications of only a single AM process [9,14-15,19-21]. This study closes the gap by considering AM spare parts and processes to pave way for future research directions. The limitation of this study is that it does not explore all the possible materials and industry sectors, and tooling and prototyping are not investigated. In addition, the scope of this review is only limited to papers up to 2021.

Finding published case studies related to specific industry sectors has been a challenge. Although there are many well-known case studies from the medical industry, this is not the case for other sectors. One reason for this could be that the medical field has a well-established history of scientific publishing. In addition, many articles mention common industry names in the introduction section. However, the content of the articles are often not related to these industries, which has led to irrelevant search results. Also, the production of spare parts is often viewed with commercial sensitivity especially for the aerospace and defense sector. From an industry viewpoint, there are several relevant studies on material and mechanical properties, but they do not focus on a single industry or case study. For example, the utilisation of AM for spare parts has been reported by Shell, Daimler and Deutsche Bahn [104-106]. Typical spare parts produced via AM are generally made of a single material or a material similar to the original spare part material, and the size is typically limited to the volume of the build chamber. Often the geometry of the spare parts is not optimised for AM because this will require design changes. Generally, AM spare parts are produced in low volume and are often produced for old equipment, where it is challenging to forecast the demand. In addition, most review articles are written from a management perspective or are technical studies related to the AM process utilisation such as the selection of suitable spare parts [10], AM influence on the after-sales service [14], and the transition from conventional manufacturing to AM for spare parts management [15]. Notably, the potential of different processes is not considered. Similarly, there are many reviews on specific AM processes and its utilisation, such as metal PBF [16-17] or utilisation of different AM processes in a single industry [18]. However, none of them have explored this from a spare part manufacturing perspective

This study found that the most common processes for manufacturing spare parts and end-use components are PBF, MEX and VP. This observation is related to the good quality of the PBF process, the widespread availability of MEX, and the accuracy and surface quality of VP. Generally, MJ, BJ, and SL processes are not suited for end-use component manufacturing. They have poor material properties, indicating insignificant potential for spare part manufacturing. DED is most commonly used for repairing components [107] which in this context could be considered for refurbishing spare parts. Although DED can be used to fabricate large parts, the surfaces that are produced generally require post-processing such as machining.

There is scope to extend this research to better understand how AM can be better used to produce spare parts on demand (Table 5). In an ideal scenario, parts could be locally manufactured on demand and just in time without the need for an inventory. At the same time, in the context of distributed manufacturing, the IP of the design could be more challenging to trace and may lead to copyright issues. Industries that could benefit from using AM for spares typically have a long lifespan for these products. Low-volume spares with unusual and very infrequent demand are the best candidates for spare parts to be produced with AM. Typically these sectors are energy, defence, commercial machines, aerospace and the process manufacturing industry. It should be noted that some of these industries also have stringent quality requirements and with a very long approval processes. Therefore, producing parts with a different manufacturing method should be justified, and the quality should be proven to authorities. On the other hand, this may not make economic sense for legacy products with low demand. The certification process, standards, and proof of quality should be further investigated to reduce existing barriers. Also, new products and components made by AM in these sectors will eventually increase the amount of AM spares, but will take time. Certain sectors with a shorter product lifespan, such as consumer products, could be considered from a sustainability perspective whereby the lifespan could be increased or at least supported with AM produced spare parts or even releasing 3D CAD models of the old products. All of these scenarios require more industry-related case studies.

In a conventional approach, the value of using AM is derived from using principles related to Design for AM (DfAM). This allows an optimal AM part that uses less material and with minimal support structures yet achieving better performance. As most spares parts are usually designed for coventionale manufacturing processes, there is often too much material that resides in those parts. A redesign exercise would require time and effort, and if the demand is low, it might be easiest to manufacture the spare parts as it is. This approach does not often allow Design for Assembly since other parts around the component have to remain unchanged. The design and modifications for AM and assembly cannot be fully utilised for spare parts as compared to designing new end-use parts for AM from the beginning. That is a considerable design-related barrier that should be further investigated.

4.1 Future perspective

Based on the observations in the earlier section, it can be inferred that there is a considerable potential in using BJ that has existed for many years, especially fo producing metallic spare parts. There have been significant investments in the development of BJ which allows larger build chambers, offers a more comprehensive material range based on powder metallurgy methods, such as sintering, and has the potential to be more cost-efficient. This is in line with recent reviews about metal BJ [108]. In addition, MEX for metal, continuous composite plastic and high-performance plastic is another process that should be investigated [109-111]. Composite parts can replace certain metallic materials and since MEX is already widespread, it is expected that it could be used in manufacturing metal parts even though it requires separate sintering to make the parts solid. However, the need for proof of quality, standardisation and certification may delay the use of AM produced spare parts [79,82,87,112]. One quality-related aspect is the 3D CAD file that will require modifications to achieve a suitable outcome from the AM process [113].

In summary, the research gaps for different AM processes to produce spare parts, along with the indicative industrial sectors is summarised as: (1) MEX can be utilised for composites and metal parts manufacturing as it is cost-efficient, widespread, and can replace solid metal parts. (2) BJ has the potential for metal parts manufacturing as it is cost-efficient, offers a larger build chamber and has a more comprehensive material selection. (3) Proof of quality and certification are required for both energy and defence industries, particularly in the use of PBF and BJ for metal parts manufacture and certification. (4) More case studies are needed for the automotive, energy, defence, consumer products, and electronics industries for real parts manufactured using AM and to show results based on quality testing and certification.

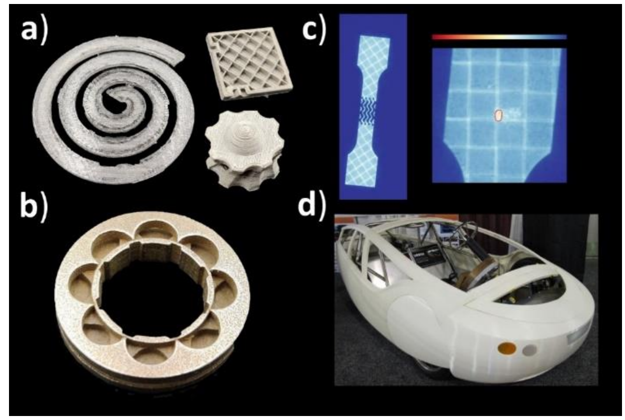


Fig. 4. Future possibilities for AM in spare parts: (a) Material extrusion – composite and metal parts. (b) Binder jetting – metal part. (c) Quality and certification – energy and defence. (d) Actual case study in automotive, energy, defence, consumer products, and electronics.

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References

[1] ISO/ASTM 52900 Additive manufacturing — General principles — Fundamentals and vocabulary. 2021.

[2] Barbosa, W.S.; Wanderley, RF; Gioia, M.M.; Gouvea, F.C.; Gonçalves, F.M. Additive or subtractive manufacturing: Analysis and comparison of automotive spare-parts. *Journal of Remanufacturing* 2021, 1-14.

[3] Casalino, G.; Ludovico, A.D.; Ancona, A.; Lugarà, P.M. In In Stainless steel 3D laser forming for rapid prototyping; *International Congress on Applications of Lasers & Electro-Optics*; Laser Institute of America: 2001; Vol. 2001, pp 808-816.

[4] Lehtinen, P.; Väisänen, T.; Salmi, M. The effect of local heating by laser irradiation for aluminum, deep drawing steel and copper sheets in incremental sheet forming. *Physics Procedia* 2015, 78, 312-319.

[5] Molenaers, A.; Baets, H.; Pintelon, L.; Waeyenbergh, G. Criticality classification of spare parts: A case study. *Int J Prod Econ* 2012, 140, 570-578.

[6] Kennedy, W.J.; Patterson, J.W.; Fredendall, L.D. An overview of recent literature on spare parts inventories. *Int J Prod Econ* 2002, 76, 201-215.

[7] Stoll, J.; Kopf, R.; Schneider, J.; Lanza, G. Criticality analysis of spare parts management: a multi-criteria classification regarding a cross-plant central warehouse strategy. *Production Engineering* 2015, 9, 225-235.

[8] Chekurov, S.; Salmi, M.; Verboeket, V.; Puttonen, T.;

Riipinen, T.; Vaajoki, A. Assessing industrial barriers of additively manufactured digital spare part implementation in the machine-building industry: a cross-organisational focus group interview study. *Journal of manufacturing technology management* 2021, 32, 909-931.

[9] Frandsen, C.S.; Nielsen, M.M.; Chaudhuri, A.; Jayaram, J.; Govindan, K. In search for classification and selection of spare parts suitable for additive manufacturing: a literature review. *Int J Prod Res* 2020, 58, 970-996.

[10] Gisario, A.; Kazarian, M.; Martina, F.; Mehrpouya, M. Metal additive manufacturing in the commercial aviation industry: A review. *J. Manuf. Syst*. 2019, 53, 124-149.

[11] Singamneni, S.; Yifan, L.V.; Hewitt, A.; Chalk, R.; Thomas, W.; Jordison, D. Additive manufacturing for the aircraft industry: a review. *J.Aeronaut.Aerosp.Eng* 2019, 8, 2.

[12] Sireesha, M.; Lee, J.; Kiran, A.S.K.; Babu, V.J.; Kee, B.B.; Ramakrishna, S. A review on additive manufacturing and its way into the oil and gas industry. *RSC advances* 2018, 8, 22460-22468.

[13] Ziółkowski, M.; Dyl, T. Possible applications of additive manufacturing technologies in shipbuilding: a review. *Machines* 2020, 8, 84.

[14] Hoffmann, M.A.; Schönheit, M. How Does Additive Manufacturing Affect the Spare Parts Supply Chain?–A Literature Review. *Logistik in Wissenschaft und Praxis* 2021, 25-43.

[15] Peron, M.; Sgarbossa, F. In In Additive Manufacturing and Spare Parts: Literature Review and Future Perspectives; *International Workshop of Advanced Manufacturing and Automation*; Springer: 2020; , pp 629-635.

[16] Bhavar, V.; Kattire, P.; Patil, V.; Khot, S.; Gujar, K.; Singh, R. In A review on powder bed fusion technology of metal additive manufacturing; *Additive manufacturing handbook*; CRC Press: 2017; pp 251-253.

[17] Singh, D.D.; Mahender, T.; Reddy, A.R. Powder bed fusion process: A brief review. *Materials Today: Proceedings* 2021, 46, 350-355.

[18] Najmon, J.C.; Raeisi, S.; Tovar, A. Review of additive manufacturing technologies and applications in the aerospace industry. *Additive manufacturing for the aerospace industry* 2019, 7-31.

[19] Debnath, B.; Shakur, M.S.; Tanjum, F.; Rahman, M.A.; Adnan, Z.H. Impact of Additive Manufacturing on the Supply Chain of Aerospace Spare Parts Industry—A Review. *Logistics* 2022, 6, 28.

[20] Mecheter, A.; Pokharel, S.; Tarlochan, F. Additive Manufacturing Technology for Spare Parts Application: A Systematic Review on Supply Chain Management. *Appl. Sci.* 2022, 12, 4160.

[21] Koller, J.; Häfner, R.; Döpper, F. Decentralised Spare Parts Production for the Aftermarket using Additive Manufacturing - A Literature Review. *Procedia CIRP* 2022, 107, 894-901.

[22] Omiyale, B.O.; Olugbade, T.O.; Abioye, T.E.; Farayibi P.K. Wire arc additive manufacturing of aluminium alloys for aerospace and automotive applications: a review. *Materials Science and Technology* 2022*,* 38(7): 391-408.

[23] Salifu, S.; Desai, D.; Ogunbiyi, O.; Mwale, K. Recent development in the additive manufacturing of polymer-based composites for automotive structures—a review. *Int J Adv Manuf Technol* 2022, 119, 6877–6891.

[24] Pei, E.; Ressin, M.; Campbell, R.I.; Eynard, B.; Xiao, J. Investigating the impact of additive manufacturing data exchange standards for re-distributed manufacturing. *Progress in Additive Manufacturing*. 2019, 4(3):331-344.

[25] Mousapour, M.; Salmi, M.; Klemettinen, L.; Partanen, J. Feasibility study of producing multi-metal parts by Fused Filament Fabrication (FFF) technique. *J. Manuf. Processes* 2021, *67*, 438–446.

[26] Levy, A.; Miriyev, A.; Sridharan, N.; Han, T.; Tuval, E.; Babu, S.S.; Dapino, M.J.; Frage, N. Ultrasonic additive manufacturing of steel: method, post-processing treatments, and properties. *J. Mater. Process. Technol.* 2018, *256*, 183–189.

[27] Herzog, D.; Seyda, V.; Wycisk, E.; Emmelmann, C. Additive manufacturing of metals. *Acta Materialia* 2016, 117, 371-392.

[28] Ait-Mansour, I.; Kretzschmar, N.; Chekurov, S.; Salmi, M.; Rech, J. Design-dependent shrinkage compensation modeling and mechanical property targeting of metal FFF. *Progress in Additive Manufacturing* 2020, 5(1), 51-57.

[29] Hehr, A.; Wenning, J.; Norfolk, M.; Sheridan, J.; Newman, J.A.; Domack, M. Selective reinforcement of aerospace structures using ultrasonic additive manufacturing. *Journal of Materials Engineering and Performance* 2019, 28(2), 633-640.

[30] Bartolo, P.J.; Gaspar, J. Metal filled resin for stereolithography metal part. *CIRP Annals* 2008, 57(1), 235-238.

[31] Li, M.; Du, W.; Elwany, A.; Pei, Z.; Ma, C. Metal binder jetting additive manufacturing: a literature review. *Journal of Manufacturing Science and Engineering* 2020, 142(9), 090801.

[32] Gibson, I.; Rosen, D.; Stucker, B.; Khorasani, M. *Material jetting in Additive Manufacturing Technologies* 2021 (pp. 203-235). Springer.

[33] Wohlers, T.T.; Campbell, I.; Diegel, O.; Huff, R.; Kowen, J. Wohlers Report 2021: 3D Printing and Additive Manufacturing Global State of the Industry. 2021, Wohlers Associates.

[34] Kestilä, A.; Nordling, K.; Miikkulainen, V.; Kaipio, M.; Tikka, T.; Salmi, M.; Auer, A.; Leskelä, M.; Ritala, M. Towards space-grade 3D-printed, ALD-coated small satellite propulsion components for fluidics. *Additive*

Manufacturing 2018, 22, 31-37.
[35] Nyman, L.; Kestilä, A.; Porri, P.; Pudas, M.; Salmi, M.; Silander, R.; Miikkulainen, V.; Kaipio, M.; Kallio, E.; Ritala, M. Constructing Spacecraft Components Using Additive Manufacturing and Atomic Layer Deposition: First Steps for Integrated Electric Circuitry. *J. Aerospace Eng.* 2021, 34, 04021049.
[36] Metel, A.S.; Grigoriev, SN; Tarasova, TV; Filatova, A.A.; Sundukov, S.K.; Volosova, M.A.; Okunkova, A.A.; Melnik, Y.A.; Podrabinnik, P.A. Influence of Post-processing on Wear Resistance of Aerospace Steel Parts Produced by Laser Powder Bed Fusion. *Technologies* 2020, 8, 73.
[37] Pirozzi, C.; Franchitti, S.; Borrelli, R.; Chiariello, A.; Di Palma, L. The Effect of Post-Processing on the Mechanical Behavior of Ti6Al4V Manufactured by Electron Beam Powder Bed Fusion for General Aviation Primary Structural Applications. *Aerospace* 2020, 7, 75.
[38] Misra, A.K.; Grady, J.E.; Carter, R. Additive Manufacturing of Aerospace Propulsion Components In Additive manufacturing of aerospace propulsion components; *Additive Manufacturing Conference,* Oct; 2015; 20150023067.
[39] Hehr, A.; Wenning, J.; Norfolk, M.; Sheridan, J.; Newman, J.A.; Domack, M. Selective reinforcement of aerospace structures using ultrasonic additive manufacturing*. Journal of Materials Engineering and Performance* 2019, 28, 633-640.
[40] Ma, G.; Yu, C.; Tang, B.; Li, Y.; Niu, F.; Wu, D.; Bi, G.; Liu, S. High-mass-proportion TiCp/Ti6Al4V titanium matrix composites prepared by directed energy deposition. *Additive Manufacturing* 2020, 35, 101323.
[41] Zareanshahraki, F.; Davenport, A.; Cramer, N.; Seubert, C.; Lee, E.; Cassoli, M.; Wang, X. Additive Manufacturing for Automotive Applications: Mechanical and Weathering Durability of Vat Photopolymerization Materials. *3D Printing and Additive Manufacturing* 2021, 8(5), 302 – 314.
[42] Juechter, V.; Franke, M.M.; Merenda, T.; Stich, A.; Körner, C.; Singer, R.F. Additive manufacturing of Ti-45Al-4Nb-C by selective electron beam melting for automotive applications. *Additive Manufacturing* 2018, 22, 118-126.
[43] Santoliquido, O.; Bianchi, G.; Dimopoulos Eggenschwiler, P.; Ortona, A. Additive manufacturing of periodic ceramic substrates for automotive catalyst supports. *International Journal of Applied Ceramic Technology* 2017, 14, 1164-1173.
[44] Yelamanchi, B.; Mummareddy, B.; Santiago, C.C.; Ojoawo, B.; Metsger, K.; Helfferich, B.; Zapka, J.; Sillani, F.; MacDonald, E.; Cortes, P. Mechanical and Fatigue Performance of Pressurized Vessels Fabricated with MultiJet Fusion™ for Automotive Applications. *Additive Manufacturing* 2021, 102048.
[45] Vinodh, S. Parametric optimisation of fused deposition modelling process using Grey based Taguchi and TOPSIS methods for an automotive component. *Rapid Prototyping Journal* 2020, 27(1), 155-175.
[46] Sargini, M.; Masood, S.H.; Palanisamy, S.; Jayamani, E.; Kapoor, A. Additive manufacturing of an automotive brake pedal by metal fused deposition modelling. *Materials Today: Proceedings* 2021, 45, 4601-4605.
[47] Akmal, JS; Salmi, M.; Hemming, B.; Teir, L.; Suomalainen, A.; Kortesniemi, M.; Partanen, J.; Lassila, A. Cumulative inaccuracies in implementation of additive manufacturing through medical imaging, 3D thresholding, and 3D modeling: A case study for an end-use implant. *Applied Sciences* 2020, 10, 2968.
[48] Huotilainen, E.; Salmi, M.; Lindahl, J. Three-dimensional printed surgical templates for fresh cadaveric osteochondral allograft surgery with dimension verification by multivariate computed tomography analysis. *The Knee* 2019, 26, 923-932.
[49] Verboeket, V.; Khajavi, S.H.; Krikke, H.; Salmi, M.; Holmström, J. Additive Manufacturing for Localized Medical Parts Production: A Case Study. *IEEE Access* 2021, 9, 25818-25834.
[50] Koivuholma, A.; Aro, K.; Mäkitie, A.; Salmi, M.; Mirtti, T.; Hagström, J.; Atula, T. Three-Dimensional Presentation of Tumor Histopathology: A Model Using Tongue Squamous Cell Carcinoma. *Diagnostics* 2021, 11, 109.
[51] Salmi, M.; Tuomi, J.; Paloheimo, K.; Paloheimo, M.; Björkstrand, R.; Mäkitie, A.A.; Mesimäki, K.; Kontio, R. Digital design and rapid manufacturing in orbital wall reconstruction. *Innovative Developments in Design and Manufacturing—Advanced Research in Virtual and Rapid Prototyping*; CRC Press: Boca Raton, FL, USA 2010, 339-342.
[52] Mäkitie, A.; Paloheimo, K.S.; Björkstrand, R.; Salmi, M.; Kontio, R.; Salo, J.; Yan, Y.; Paloheimo, M.; Tuomi, J. Medical applications of rapid prototyping--three-dimensional bodies for planning and implementation of treatment and for tissue replacement. *Duodecim* 2010, 126, 143-151.
[53] Guillaume, O.; Geven, MA; Varjas, V.; Varga, P.; Gehweiler, D.; Stadelmann, V.A.; Smidt, T.; Zeiter, S.; Sprecher, C.; Bos, R.R. Orbital floor repair using patient specific osteoinductive implant made by stereolithography. *Biomaterials* 2020, 233, 119721.
[54] Sharma, N.; Welker, D.; Aghlmandi, S.; Maintz, M.; Zeilhofer, H.; Honigmann, P.; Seifert, T.; Thieringer, F.M. A Multi-Criteria Assessment Strategy for 3D Printed Porous Polyetheretherketone (PEEK) Patient-Specific Implants for Orbital Wall Reconstruction. *Journal of Clinical Medicine* 2021, 10, 3563.
[55] Balažic, M.; Recek, D.; Kramar, D.; Milfelner, M.; Kopač, J. Development process and manufactu-ring of modern medical implants with LENS technology. *J.Achiev.Mater.Manuf.Eng* 2009, 32, 46-52.
[56] Liu, W.; Zhu, Z.; Ye, S. Industrial Case Studies of

Design for Plastic Additive Manufacturing for End-Use Consumer Products. *3D Printing and Additive Manufacturing* 2019, 6, 281-292.
[57] Solaimani, S.; Parandian, A.; Nabiollahi, N. A Holistic View on Sustainability in Additive and Subtractive Manufacturing: A Comparative Empirical Study of Eyewear Production Systems. *Sustainability* 2021, 13, 10775.
[58] Parry, E.J.; Best, JM; Banks, C.E. Three-dimensional (3D) scanning and additive manufacturing (AM) allows the fabrication of customised crutch grips. *Materials Today Communications* 2020, 25, 101225.
[59] Rojas-Nastrucci, E.A.; Nussbaum, J.T.; Crane, N.B.; Weller, T.M. Ka-band characterisation of binder jetting for 3-D printing of metallic rectangular waveguide circuits and antennas. *IEEE Trans. Microwave Theory Tech*. 2017, 65, 3099-3108.
[60] Oh, Y.; Bharambe, V.; Mummareddy, B.; Martin, J.; McKnight, J.; Abraham, M.A.; Walker, J.M.; Rogers, K.; Conner, B.; Cortes, P. Microwave dielectric properties of zirconia fabricated using NanoParticle Jetting™. *Additive Manufacturing* 2019, 27, 586-594.
[61] Wimmer, T.; Mick, Y.; Weigand, B. Experimental investigation into capabilities of laser powder bed fusion to produce wavy macro-channels from IN939. *Additive Manufacturing* 2020, 35, 101345.
[62] Thompson, S.M.; Aspin, Z.S.; Shamsaei, N.; Elwany, A.; Bian, L. Additive manufacturing of heat exchangers: A case study on a multi-layered Ti–6Al–4V oscillating heat pipe. *Additive Manufacturing* 2015, 8, 163-174.
[63] Bergeron, A.; Crigger, J.B. Early progress on additive manufacturing of nuclear fuel materials. *J. Nucl. Mater.* 2018, 508, 344-347.
[64] Kang, S.H.; Suh, J.; Lim, S.Y.; Jung, S.; Jang, Y.W.; Jun, I.S. Additive manufacture of 3 inch nuclear safety class 1 valve by laser directed energy deposition. *J. Nucl. Mater.* 2021, 547, 152812.
[65] Yang, W.; Hu, R.; Zheng, L.; Yan, G.; Yan, W. Fabrication and investigation of 3D-printed gun propellants. *Mater Des* 2020, 192, 108761.
[66] Dehoff, R.; Duty, C.; Peter, W.; Yamamoto, Y.; Chen, W.; Blue, C.; Tallman, C. Case study: additive manufacturing of aerospace brackets. *Adv Mater Processes* 2013, 171, 19-23.
[67] DeGrange, J.E.; Beilman, D.F.; Willer, R.P.; Spielman, R.L.; Taylor, T.L.; Wannemuehler, K.L.; Fink, J.; Bond, G.G. Flame-retardant Polyamide 11 and 12 Nanocomposites: Processing, Morphology, and Mechanical Properties. *Journal of Composite Materials* 2009, 7575708.
[68] Gibson, I.; Rosen, D.; Stucker, B.; Khorasani, M. In *Directed Energy Deposition; Additive Manufacturing Technologies*; Springer: 2021; pp 285-318.
[69] Muravyev, N.V.; Monogarov, K.A.; Schaller, U.; Fomenkov, I.V.; Pivkina, A.N. Progress in additive manufacturing of energetic materials: Creating the reactive microstructures with high potential of applications. *Propellants, Explosives, Pyrotechnics* 2019, 44, 941-969.
[70] Chaudhuri, A.; Gerlich, H.A.; Jayaram, J.; Ghadge, A.; Shack, J.; Brix, B.H.; Hoffbeck, L.H.; Ulriksen, N. Selecting spare parts suitable for additive manufacturing: a design science approach. *Production Planning & Control* 2021, 32, 670-687.
[71] Knofius, N.; Van der Heijden, Matthieu C; Zijm, W.H. Selecting parts for additive manufacturing in service logistics. *Journal of manufacturing technology management* 2016.
[72] Salmi, M., Partanen, J., Tuomi, J., Chekurov, S., Björkstrand, R., Huotilainen, E., ... & Mikkola, M. *Digital spare parts* 2018. http://urn.fi/URN:ISBN:978-952-60-3746-2
[73] Atzberger, A.; Montero, J.; Schmidt, T.S.; Bleckmann, M.; Paetzold, K. In In Characteristics of a metal additive manufacturing process for the production of spare parts; *Symposium on Design for X*; 2018; Vol. 29, pp 83-94.
[74] Mäkitie, A.A.; Salmi, M.; Lindford, A.; Tuomi, J.; Lassus, P. Three-dimensional printing for restoration of the donor face: A new digital technique tested and used in the first facial allotransplantation patient in Finland. *Journal of Plastic, Reconstructive & Aesthetic Surgery* 2016, 69(12), 1648-1652.
[75] Park, M. 3D printing and product repair. *Routledge Handbook of Sustainable Product Design* 2017, 236.
[76] Raja, V.; Fernandes, K.J. Reverse engineering: an industrial perspective. *Springer Science & Business Media* 2017.
[77] Ali, S.; Durupt, A.; Adragna, P.A. Reverse engineering for manufacturing approach: Based on the combination of 3D and knowledge information. In *Smart Product Engineering* 2013 (pp. 137-146). Springer, Berlin, Heidelberg.
[78] Chekurov, S.; Salmi, M. Additive manufacturing in offsite repair of consumer electronics. *Physics Procedia* 2017, 89, 23-30.
[79] Heinen, J.J.; Hoberg, K. Assessing the potential of additive manufacturing for the provision of spare parts. *J. Oper. Manage*. 2019, 65, 810-826.
[80] Knofius, N.; Van Der Heijden, M C; Zijm, W. Moving to additive manufacturing for spare parts supply. *Comput. Ind*. 2019, 113, 103134.
[81] den Boer, J.; Lambrechts, W.; Krikke, H. Additive manufacturing in military and humanitarian missions: Advantages and challenges in the spare parts supply chain. *J. Clean. Prod.* 2020, 257, 120301.
[82] Westerweel, B.; Basten, R.; den Boer, J.; van Houtum, G. Printing spare parts at remote locations: Fulfilling the promise of additive manufacturing. *Production and Operations Management* 2021, 30, 1615-1632.
[83] Khajavi, S.H.; Salmi, M.; Holmström, J. In Additive

manufacturing as an enabler of digital spare parts; *Managing 3D Printing*; Palgrave Macmillan, Cham: 2020; pp 45-60.

[84]Song, J.; Zhang, Y. Stock or print? Impact of 3-D printing on spare parts logistics. *Management Science* 2020, 66, 3860-3878.

[85]Li, Y.; Jia, G.; Cheng, Y.; Hu, Y. Additive manufacturing technology in spare parts supply chain: a comparative study. *Int J Prod Res* 2017, 55, 1498-1515.

[86]Ford, S.; Despeisse, M. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *J. Clean. Prod.* 2016, 137, 1573-1587.

[87]Rao, A. The Future of Additive Manufacturing of Spare Parts, 2021.

[88]Savastano, M.; Amendola, C.; Fabrizio, D.; Massaroni, E. In 3-D printing in the spare parts supply chain: an explorative study in the automotive industry; *Digitally supported innovation*; Springer: 2016; pp 153-170.

[89]Eggenberger, T.; Oettmeier, K.; Hofmann, E. In In Additive manufacturing in automotive spare parts supply chains–a conceptual scenario analysis of possible effects; *International Conference on Additive Manufacturing in Products and Applications*; Springer: 2017; , pp 223-237.

[90]Nybonn, A.; Halkjaer, T. Distributed Production of Spare Parts Using Additive Manufacturing Opportunities and Challenges for Volvo Group, 2018

[91]Kostidi, E.; Nikitakos, N. Is it time for the maritime industry to embrace 3d printed spare parts? *TransNav: International Journal on Marine Navigation and Safety of Sea Transportation* 2018, 12.

[92]Muir, M.; Haddud, A. Additive manufacturing in the mechanical engineering and medical industries spare parts supply chain. *Journal of Manufacturing Technology Management* 2018, 29(2), 372-397.

[93]Togwe, T.; Eveleigh, T.J.; Tanju, B. An additive manufacturing spare parts inventory model for an aviation use case. *Eng. Manage. J.* 2019, 31, 69-80.

[94]Cardeal, G.; Sequeira, D.; Mendonça, J.; Leite, M.; Ribeiro, I. Additive manufacturing in the process industry: A process-based cost model to study life cycle cost and the viability of additive manufacturing spare parts. *Procedia CIRP* 2021, 98, 211-216.

[95]Kim, D.B.; Witherell, P.; Lu, Y.; Feng, S. Toward a digital thread and data package for metals-additive manufacturing. *Smart and sustainable manufacturing systems* 2017, 1(1), 75.

[96]Seo, G.; Ahsan, M.R.; Lee, Y.; Shin, J.H.; Park, H.; Kim, D.B. A functional modeling approach for quality assurance in metal additive manufacturing. *Rapid Prototyping Journal* 2021, 27(2), 288-303.

[97]Zhao, X.; Wang, T. Laser Powder Bed Fusion of Powder Material: A Review.*3D Printing and Additive Manufacturing* 2022, ahead of print, http://doi.org/10.1089/3dp.2021.0297

[98]Malekipour, E.; El-Mounayri, H. Common defects and contributing parameters in powder bed fusion AM process and their classification for online monitoring and control: a review. *The International Journal of Advanced Manufacturing Technology*, 2018, 95(1), 527-550.

[99]Goh, G.D.; Yap, Y.L.; Tan, H.K.J.; Sing, S.L.; Goh, G.L.; Yeong, WY Process–structure–properties in polymer additive manufacturing via material extrusion: A review. *Critical Reviews in Solid State and Materials Sciences*, 2020, 45(2), 113-133.

[100]Liu, M.; Kumar, A.; Bukkapatnam, S.; Kuttolamadom, M. A review of the anomalies in directed energy deposition (DED) Processes & Potential Solutions-part quality & defects. *Procedia Manufacturing*, 2021, 53, 507-518.

[101]Kumbhar, N.N.; Mulay, A.V. Post processing methods used to improve surface finish of products which are manufactured by additive manufacturing technologies: a review. *Journal of The Institution of Engineers (India): Series C*, 2018, 99(4), 481-487.

[102] Peng, X.; Kong, L.; Fuh, J.Y.H.; Wang, H. A Review of Post-Processing Technologies in Additive Manufacturing. *J. Manuf. Mater. Process.* 2021, 5, 38.

[103]Gibson, I.; Khorasani, A.M. Metallic Additive Manufacturing: Design, Process, and Post-Processing. *Metals* 2019, 9, 137.

[104]Shell A digital future for spare part management. https://www.shell.com/energy-and-innovation/digitalisation/a-digital-future-for-spare-part-management.html.

[105]Deutsche Bahn 3D printing at DB. https://www.deutschebahn.com/en/Digitalization/technology/New-Technology/3d_printing-3520386.

[106]Daimler Trailblazing future technology Spare parts for trucks and buses made in a 3D printer. https://www.daimler.com/sustainability/corporate-environmental-protection/3d-print.html.

[107]Kim, Y.; Kwon, K.; Mun D. Mesh-offset-based method to generate a delta volume to support the maintenance of partially damaged parts through 3D printing. *Journal of Mechanical Science and Technology*, 2021, 35, 3131–3143.

[108]Li, M.; Du, W.; Elwany, A.; Pei, Z.; Ma, C. Metal binder jetting additive manufacturing: a literature review. *Journal of Manufacturing Science and Engineering*, 2020, 142(9).

[109]Suwanpreecha, C.; Manonukul, A. A review on material extrusion additive manufacturing of metal and how it compares with metal injection moulding. *Metals*, 2022, 12(3), 429.

[110] Zhuo, P.; Li, S.; Ashcroft, I. A.; Jones, A. I. Material extrusion additive manufacturing of continuous fibre reinforced polymer matrix composites: A review and outlook. *Composites Part B: Engineering*, 2021, 224, 109143.

[111]Gupta, V.; Thiruselvam, N.I.; Kulkarni D.M.; Chaudhari, V.V; Suraj, S. Anisotropy and deformation heterogeneity in additive manufactured carbon-reinforced PEEK. *Journal of Mechanical Science and Technology*, 2023 37, 2871–2880
[112]Cha, C.K.; Wong, C.H.; Yeong, WY Standards, quality control, and measurement sciences in 3D printing and additive manufacturing. 2017, Academic Press.
[113]Jee, H. Preparation of “Ready-Made STL (RMS)” for build assurance in additive metal manufacturing (AMM): A review *Journal of Mechanical Science and Technology* 2019, 3, 5643–5652.

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