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In search for classification and selection of spare parts suitable for additive manufacturing: a literature review

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This paper reviews the literature on additive manufacturing (AM) technologies and equipment, and spare parts classification criteria to propose a systematic process for selecting spare parts which are suitable for AM. This systematic process identifies criteria that can be used to select spare parts that are suitable for AM. The review found that there is limited research that addresses identifying processes for spare parts selection for AM, even though companies have identified this to be a key challenge in adopting AM. Seven areas for future research are identified relating to the methodology of spare parts selection for AM, processes for cross-functional integration in selecting spare parts for AM, broadening the spare parts portfolio that is suitable for AM (by considering usage of AM in conjunction with conventional technologies), and potential impact of AM on product modularity and integrality.

Keywords: classification and selection of spare parts; additive manufacturing; literature review

1. Introduction

Additive manufacturing (AM) can be economically attractive, particularly for low volume spare parts production as it provides flexibility in producing spare parts as and when needed, unlike conventional manufacturing, wherein high volumes and therefore, higher inventories are needed, to recoup high initial investments in tooling (d'Aveni 2015). For example, Lego, the Danish toy manufacturer spends 20 million Euros on spare parts for their equipment, and they estimated a potential saving of 1.2 million Euros by producing some of those spare parts using AM. Such savings are possible as large majority of those spare parts are consumed in very low quantities over the last 5 years with some having no consumption at all, but Lego is forced to keep inventories because of minimum order quantities requirements as dictated by suppliers of those spare parts (Hadar 2018). Also, companies like Daimler have started using AM for spare parts manufacturing. Daimler initially used AM to make spare parts for older trucks. After it became proficient with the technology, it started producing specialised parts for newer low-volume truck models as well. As the number of segments served grows, and the number of units sold per segment increases, there will be need for enough parts to be produced to become a profitable aspect of the business (d'Aveni 2018).

Spare parts management is especially challenging because it involves high variety, low volume parts (Danas, Roudsari, and Ketikidis 2006; Knofius, van der Heijden, and Zijm 2016) and is often also characterised by high service requirements coupled with extremely sporadic and unpredictable demand patterns. The financial impact in case of stock-outs, and the prices for individual parts often tend to be high (Cohen and Ernst 1988; Durão et al. 2017; Huiskonen 2001). Therefore, it is common practice to hedge against stock-outs by incurring large investments in spare parts inventories of critical parts (Bergman et al. 2017). Carrying such high inventory levels of spare parts that are expensive also results in high depreciation and obsolescence costs, all of which could impede the profitability for companies (de Souza et al. 2011).

Additive manufacturing (AM) has been identified as having the potential of manufacturing spare parts with an advantage of providing faster delivery without holding high inventory levels (Pérès and Noyes 2006; Holmström et al. 2010; Holmström and Partanen 2014). Use of AM for spare parts manufacturing is potentially useful in industries that face penalties or negative consequences for late deliveries (Holmström, Liotta, and Chaudhuri 2017). Such industrial contexts include replacement parts for mining, oil exploration firms (Weller, Kleer, and Piller 2015), and wind energy farms, to name a few.

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In all these cited cases, site locations tend to be remote and production downtimes could be costly (Lipson and Kurman 2013). Usage of AM in the spare parts supply chain has been studied by several authors (Muir and Haddud 2018; Ghadge et al. 2018; Li et al. 2017; Holmström et al. 2016; Zanardini et al. 2016; Khajavi, Partanen, and Holmström 2014). Applying AM technologies in after-sales service supply chains can support the maintenance process of advanced capital goods throughout their lifecycles, which often spans several decades (Knofius, van der Heijden, and Zijm 2016). There have also been studies related to legal aspects and patent protection of spare parts produced using AM (Ballardini, Flores Ituarte, and Pei 2018) and on how AM will challenge the traditional forms of intellectual property (IP) protection (Kurfess and Cass 2014).

There have also been literature reviews related to AM. For example, Khorram Niaki and Nonino (2017) in their literature review on the topic identified the following eight major research streams in AM: (i) AM technology selection; (ii) supply chain considerations; (iii) product design considerations; (iv) production cost models; (v) environmental aspects; (vi) strategic challenges; (vii) manufacturing systems, and (viii) open-source innovation/business models and economics. Gardan (2016) reviewed the most prominent AM technologies, and identified new trends relating to new applications, topological optimisation, file exchange and development of standards. Uriondo, Esperon-Miguez, and Perinpanayagam (2015) provided a review of present and future applications of AM for the aerospace sector. As can be seen from these research works, even though the topic of AM is relatively new, there is already an emerging body of literature on the topic.

Despite these studies on AM, there has been little attention paid to the issue of selection of spare parts that are suitable for AM. This lack of attention paid to spare parts manufacturing that is suitable for AM can be potentially explained due to a lack of awareness of the capabilities of AM among supply chain professionals, logisticians, and design engineers, all of whom are responsible in some way to address logistical issues to improve after-sales service supply chains (Knofius, van der Heijden, and Zijm 2016). A key challenge faced by companies that are considering adopting AM for spare parts manufacturing is the difficulty in identifying the most suitable parts which can be produced using AM (Chaudhuri et al. 2017). AM is suitable for spare parts manufacturing to offset the inventory costs over the life time of usage of these parts but will require investments in generating the printable files of the spare parts (Holweg 2015). Hence, the companies which are willing to explore the possibility of using AM for spare parts manufacturing must first identify the most appropriate spare parts, that are suitable for AM. Thus, there is a need for systematic research on classifying spare parts, and then understanding the characteristics that make the classified spare parts, most suitable for AM. This research addresses these needs by specifically raising and addressing the following research questions:

(1) What are the specific AM technologies and equipment that can be used to produce different spare parts?
(2) What criteria can be used to first classify the spare parts?
(3) How can the classified spare parts, that are most suitable for AM, be identified?

2. Systematic literature review

2.1. Review process

To ensure transparency and reproducibility, a systematic review was conducted. The overall structure of this review is tailored similar to literature reviews in the field of operations and supply chain management (Cooper 1988; Tranfield, Denyer, and Smart 2003; Vom Brocke et al. 2009; Seuring and Gold 2012). This structure consists of three iterative stages: (1) planning the review; (2) conducting the review; and (3) reporting and dissemination. The first stage requires defining the literature search strategy by using a common taxonomy (Cooper 1988 and Vom Brocke et al. 2009). The second stage conducts the content analysis of the resulting literature, as per established guidelines (Seuring and Gold 2012). The third stage pertains to synthesising the findings (Tranfield, Denyer, and Smart 2003).

2.1.1. Planning the review

Prior to the structured review, significant time was invested in conducting a non-structured explorative literature search to identify topics and keywords of common occurrence. This experience stressed the need to begin with a broad conceptualisation of the topical areas (such as supply chain, spare parts and AM) including assessment of gaps where knowledge may be needed (Vom Brocke et al. 2009). Therefore, a conceptual framework as shown in Figure 1 was developed to focus the literature review in a directed fashion. The literature search was conducted using the databases EBSCO, ProQuest, and Science Direct due to their extensive coverage of literature and their high reputation within the core subject areas.

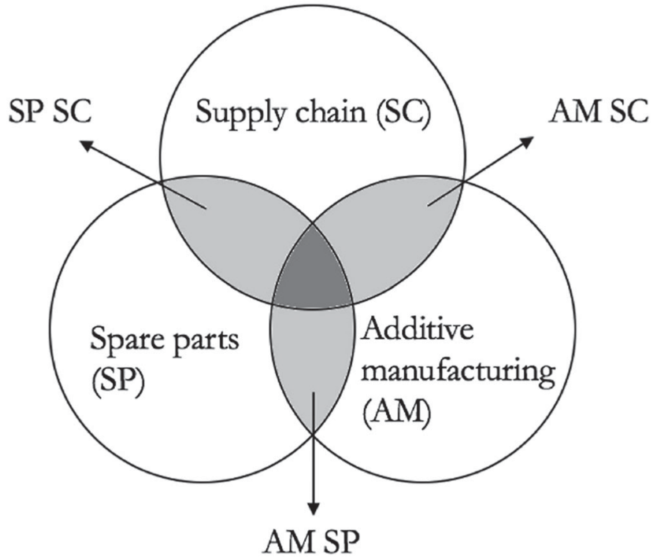

Figure 1. Concept mapping of core subject areas.

2.1.2. Conducting the review

Keywords were identified through an unstructured literature search. From the identified keywords, the appropriate search strings were identified, by combining keywords including synonyms with Boolean search modifiers and operators. Table 1 contains the search strings for each domain of interest, the databases where the search strings were used, and a specification scheme for the search fields for each database.

Only scholarly, i.e. peer-reviewed journal articles were used in this review. Practitioner magazines or newspaper articles were not included. The search strings were used to perform literature search in the selected databases. The resulting literature from the search were either included or excluded for further assessment (Tranfield, Denyer, and Smart 2003). The inclusion and exclusion process was divided into subsequent stages with specific criteria for their inclusion or exclusion. The criteria used are reported in Table 2.

In phase 1, 623 papers were identified from the three databases using the developed search strings. In phase 2, duplicate papers *within* each search string were removed from the results. In phase 3, duplicates were removed *across* search strings. For example, fourteen papers appeared in the three search strings presented in the conceptual model shown in Figure 1. In phase 4, the abstracts were read to exclude papers that did not focus on metal or plastic parts. This is because the initial review found that these papers were vastly different and had little to no relevance to our research questions. In phase 5, the above criteria from phase 4 were reused along with an exclusion criteria relating to the direct relevance of the papers to the research questions. In phase 6, a content-based backward literature search was conducted in which papers from the reference list of the already selected papers were evaluated for relevance to the research questions. To manage subjectivity between individual researchers, exclusion phase 4–6 was conducted jointly via mutual discussions among the first and second authors of this paper. The papers' relevance in relation to the research questions was the primary criteria used for exclusion/inclusion decisions. The outcome after the inclusion and exclusion process was a set of papers to be further analysed. Table 3 provides a detailed overview of the literature gathered from each search string, and the outcome of each phase. In phase 4, assessment of abstracts were performed on 312 papers that emerged from phase 3. In phase 5, full assessments, i.e. reading the paper in full, were performed on the 186 papers that emerged from phase 4. After the full-read assessment in phase 5, 57 papers qualified for the content analysis. Inter-rater reliability to assess the validity of the inclusion of papers was calculated (Voss, Tsikriktsis, and Frohlich 2002). Both the raters decided to include 57 papers and exclude 546 papers while there were disagreements on remaining 20 papers. After discussing the remaining 20 papers with the other three authors, it was decided to include the 57 papers for review. Thus, Inter-rater reliability calculated using Cohen's κ was 82.6. In addition to these papers, 45 more papers were captured through the backward literature search process. Overall, papers that were identified to be related to the classification criteria accounted for the vast majority of included papers. Appendix 1 reports the final list of included papers in this literature review.

Table 1. Core subject area, search strings, databases and search fields.

Core subject area	Search strings	Databases	Search field
Additive Manufacturing & Spare Parts	('additive manufacturing' OR 'direct manufacturing' OR '3d printing' OR '3d-printing' OR '3-d printing' OR 'digital manufacturing' OR 'rapid manufacturing' OR 'three-dimensional printing' OR 'three dimensional printing' OR 'freeform fabrication' OR 'solid free form fabrication' OR 'rapid prototyping' OR 'additive fabrication' OR 'additive production' OR 'generative manufacturing') AND ('spare part' OR 'spare parts' OR 'replacement part' OR 'replacement parts' OR 'service part' OR 'service parts' OR 'repair part' OR 'repair parts')	EBSCO ProQuest Science Direct	Abstract Anywhere except full text Abstract, title, keywords
Additive Manufacturing & Supply Chain	('additive manufacturing' OR 'direct manufacturing' OR '3d printing' OR '3d-printing' OR '3-d printing' OR 'digital manufacturing' OR 'rapid manufacturing' OR 'three-dimensional printing' OR 'three dimensional printing' OR 'freeform fabrication' OR 'solid free form fabrication' OR 'rapid prototyping' OR 'additive fabrication' OR 'additive production' OR 'generative manufacturing') AND ('supply chain' OR 'supply chains')	EBSCO ProQuest Science Direct	Abstract Anywhere except full text Abstract, title, keywords
Spare Parts & Supply Chain	('spare part' OR 'spare parts' OR 'replacement part' OR 'replacement parts' OR 'service part' OR 'service parts' OR 'repair part' OR 'repair parts') AND ('supply chain' OR 'supply chains')	EBSCO ProQuest Science Direct	Abstract Anywhere except full text Abstract, title, keywords
Spare Parts & Classification	('spare part' OR 'spare parts' OR 'replacement part' OR 'replacement parts' OR 'service part' OR 'service parts' OR 'repair part' OR 'repair parts') AND ('classification' OR 'segmentation' OR 'ABC')	EBSCO ProQuest Science Direct	Abstract Anywhere except full text Abstract, title, keywords

The column 'Search field' is unique for each database, explaining the difference among them.

Table 2. Criteria used for the inclusion/exclusion process.

Phase	Inclusion and/or exclusion criteria
1	Execution of literature searches with developed search strings.
2	Exclusion of non-available papers and duplicates within each search string.
3	Exclusion of duplicates across search strings to establish a new search category (AM + SP + SC) containing papers appearing under all three search strings.
4	Execution of abstract assessments, and exclusion of papers without relevance.
5	Execution of full-read assessments, and exclusion of papers without relevance
6	Execution of backwards literature search based on a content analysis of the resulting papers from phase 5.

2.1.3. Dissemination outlets over time

The characteristics of the literature selected from each core search area are illustrated in Figures 2 and 3 in terms of the number of publications over time, and the publication outlets. The papers' year of publication ranged from 1986 to 2017, with a significant increase in publications in recent years (Figure 2). A large contributor to this was the increased focus on the impact of AM in supply chain management. Several journals are represented as dissemination outlets for research on AM (Figure 3).

Table 3. Outcome of inclusion/exclusion phase 1–7 related to each search category.

	1st	2nd	3rd	4th	5th	6th	Total
AM + SP	52	35	21	8	6		6
AM + SC	187	95	81	61	25		25
SP + SC	274	156	142	78	7		7
AM + SP + SC			14	10	7		7
SP + Classification	110	58	54	29	12		12
Backwards						45	45
Outcome	623	344	312	186	57	45	102

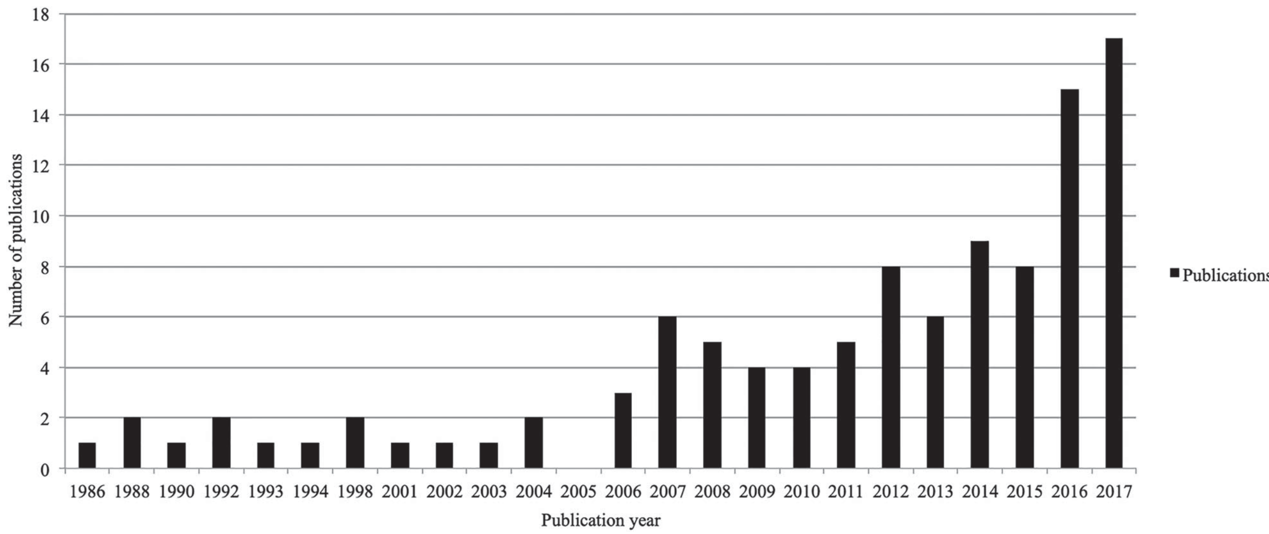

Figure 2. Distribution of literature over time.

3. Content analysis of the literature review

The content analysis of the literature review is divided into three sections; one focusing on the general and technical aspects of AM in terms of technologies, applications, and limitations, one focusing on spare parts management and identification of classification criteria, and finally one focusing on the intersection between AM and spare parts.

3.1. Terminologies used in the AM technologies literature

Before identifying spare parts that are suitable for AM, it is important to understand the different terminologies used for AM technologies. The review showed that various terminologies and definitions relating to AM exist in the literature. The AM-related terminologies used in our literature sample are reported in Figure 4.

Most of the terminologies were used to define technologies, machines, processes, techniques, methods, concepts, or to identify applications. ASTM International defines AM as ‘a process of joining materials to make objects from three dimensional (3D) model data, usually depicted as ‘layer upon layer’, as opposed to subtractive manufacturing methodologies which take away layers. The synonyms for AM include additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, and freeform fabrication (ASTM International 2013).

Additive manufacturing (AM) is the most commonly used terminology of the considered terminologies, appearing in most AM-related papers. AM has been defined as a technology (Lindemann et al. 2012; Khajavi, Partanen, and Holmström 2014; Holmström and Partanen 2014) as a group of technologies (Attaran 2017), and as a process (Berman 2012; Knofius, van der Heijden, and Zijm 2016; Durão et al. 2017).

Rapid prototyping has been referred to as a technology (Khajavi, Partanen, and Holmström 2014; Lindemann et al. 2012), as a process (Achillas et al. 2014; Rogers, Braziotis, and Pawar 2017; Strong et al. 2017) and as an application of AM-related technologies (Gress and Kalafsky 2015; Jha 2016; Feldmann and Pumpe 2017). Similarly, the literature refers

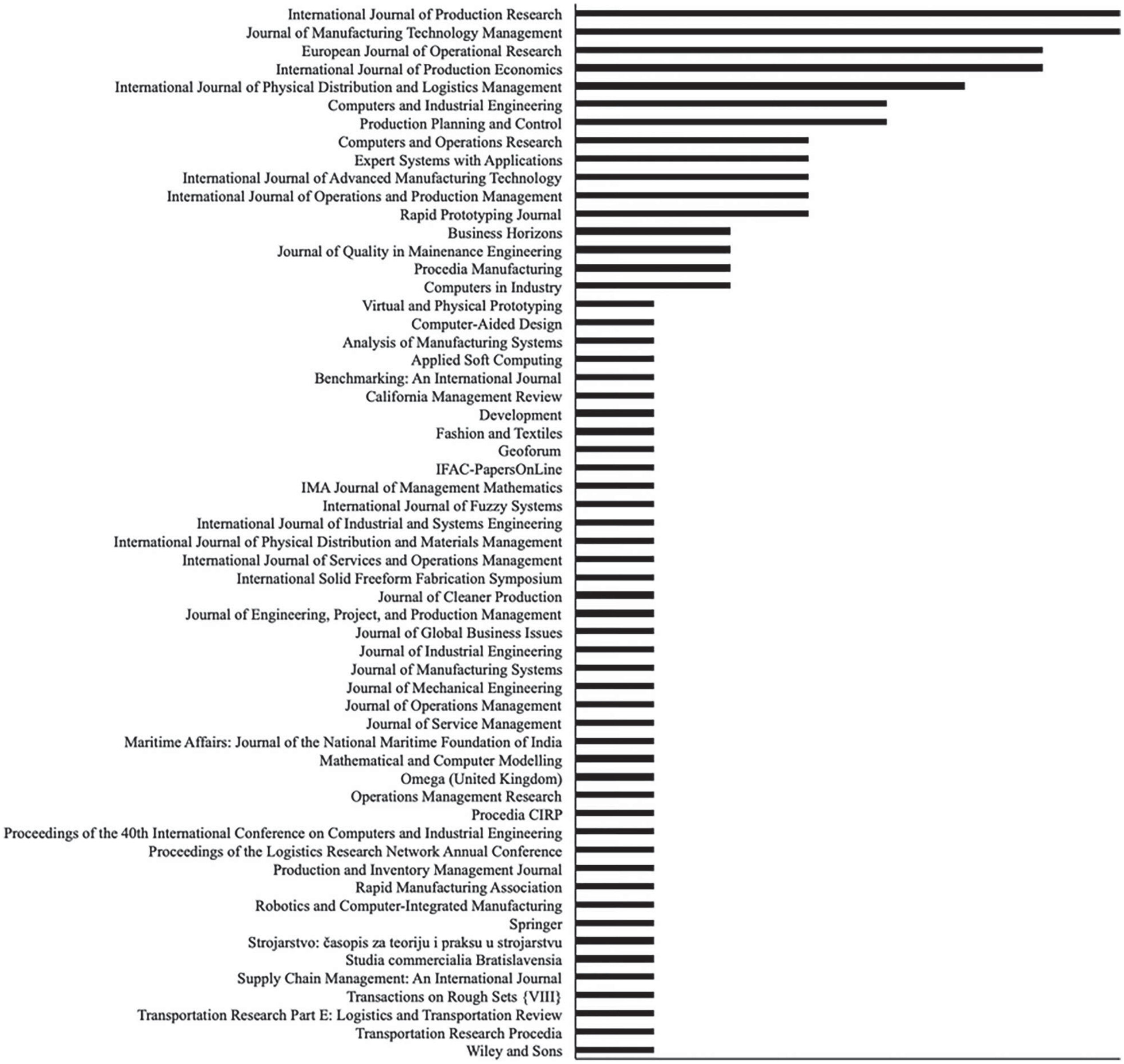

Figure 3. Distribution of literature over publication outlets.

to rapid manufacturing as a technology (Lindemann et al. 2012; Sasson and Johnson 2016), as a process (Huang et al. 2013; Oettmeier and Hofmann 2016; Ryan et al. 2017), and as an application of AM-related technologies (Meisel et al. 2016; Attaran 2017; Ortt 2017). Direct digital manufacturing (DDM) has been referred to as a technology (Attaran 2017; Sasson and Johnson 2016; Sun and Zhao 2017), and as a process (Holmström, Liotta, and Chaudhuri 2017; Holmström et al. 2016; Oettmeier and Hofmann 2016). Similarly, direct manufacturing has been described as a technology (Khajavi, Partanen, and Holmström 2014; Li et al. 2017), and as a process (Holmström, Liotta, and Chaudhuri 2017; Oettmeier and Hofmann 2016). Other terminologies used in the literature are layer or layer-by-layer manufacturing (Attaran 2017; Zanardini et al. 2016), freeform fabrication (ASTM International 2013; Strong et al. 2017; Sun and Zhao 2017), additive fabrication (ASTM International 2013; Attaran 2017; Strong et al. 2017), generative manufacturing (Hasan, Rennie, and Hasan 2013; Oettmeier and Hofmann 2016), and 3D manufacturing (Berman 2012; Sasson and Johnson 2016; Sun and Zhao 2017). In this paper, we used the most common terminologies and definitions in the literature to identify the different technologies and equipment used in AM.

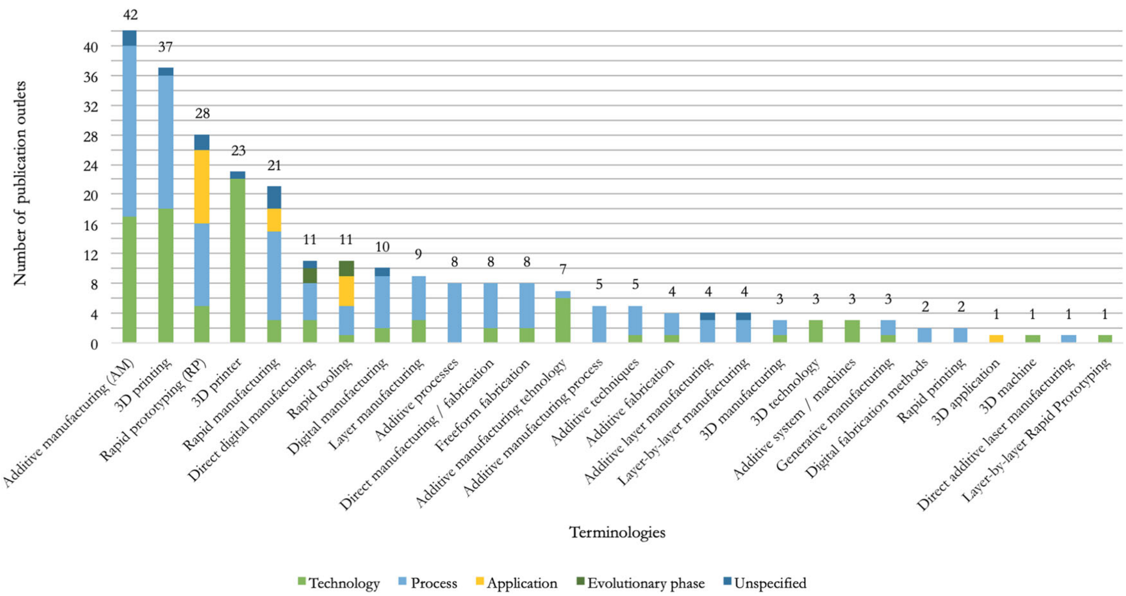

Figure 4. AM-related terminologies and their usage across papers. (Also, see Appendix 2 for details on how the different terminologies had been used in academic research).

3.1.1. AM technologies and equipment manufacturers

Selection of spare parts that are suitable for AM will depend on the characteristics of AM technologies and the equipment. Based on the understanding of different AM terminologies, we proceeded to develop an overview of the different AM technologies and AM equipment. This overview will help companies determine the limits of the AM technologies and equipment, and select the spare parts that are most suitable for AM, while considering their current capabilities and limitations of the technologies.

The different AM technologies utilise a specific mechanism to build objects layer by layer, and have distinct advantages and disadvantages. The major patented AM technologies are briefly reviewed below. The ISO/ASTM 52900:2015 standard was created in 2015 to standardise all terminology as well as classify different process categories and associated AM technologies (ISO/ASTM 2015). Similar terminology standardisation is provided by ISO (2014). ISO (2015) provides explanations for the process fundamentals of AM, including types of materials that can be used in different process categories. Together, these standards serve an important role in highlighting the difference between characteristics of different AM technologies, process, and terminologies, as well as current limitations of different process categories. Hence, the standards must be considered before selecting technologies and for identifying spare parts that are suitable for AM.

The seven AM process categories (and the associated AM technologies in parentheses) are as follows:

1. Material extrusion (Fused Deposition Modelling),
2. Vat Polymerisation (Stereolithography and Direct Light Processing),
3. Powder Bed Fusion (Selective Laser Sintering, Selective Direct Metal Laser Sintering, Selective Laser Melting, Electron Beam Melting),
4. Material Jetting (material jetting and Drop On Demand),
5. Binder Jetting (Binder Jetting),
6. Direct Energy Deposition (Laser Engineering Net Shaping and Laser Based Metal Deposition),
7. Sheet Lamination (Laminated Object Modelling and Ultrasonic Additive Manufacturing)

Because a review of all the above processes and technologies are beyond the scope of this paper, we review the most common AM technologies, the materials used, and their advantages and disadvantages. We also identify which of the above processes and technologies will be most suitable for spare parts.

Fused deposition modelling (FDM): This technology extrudes and deposits ultra-thin layers of thermoplastic material. By heating the material to 1°C above its melting point, it solidifies immediately to the previous layer when added. FDM has an accuracy of $\pm$ 0.05 mm, produces a seam line between layers, requires support materials in the process, has long build time, and suffer from delamination due to temperature fluctuations. Thermoplastics that require better engineering properties require a higher temperature to be heated to a malleable state and hence are more difficult to print. Industrial FDM printers work in a tightly controlled environment limiting likelihood of warping and distortion. Most industrial machines also use dual extrusion allowing support structures to be printed in dissolvable materials. But, most suitable applications of FDM are in investment casting patterns, jigs and fixtures and prototypes (Redwood, Schoffer, and Garrett 2018). One recent technological development among the extrusion processes is Continuous Filament Fabrication (CFF) by MarkForged, which uses a second print head and reinforces the printed thermoplastic material by embedding continuous strands of carbon fibres or fibreglass (Redwood, Schoffer, and Garrett 2018).

Stereolithography (SLA) and Direct Light Processing (DLP): Vat polymerisation is a process in which a liquid photopolymer in a vat is selectively cured by light activated polymerisation. SLA uses a photosensitive monomer resin as well as a UV laser to build parts layer by layer. It uses mirrors known as galvanometers to rapidly aim a laser beam across a vat. The laser beam solidifies the pattern by tracing the cross-section of the part on the surface on the liquid. After solidification of each layer, the supporting foundation beneath the part is moved down to cover the part with a new layer of resin, where a new layer is solidified by the UV laser. SLA creates a good surface finish, and when the object is complete, supporting materials must be removed manually. Drawbacks of this technology are relatively small build chambers, high cost of the photopolymer, and limited compatible materials. DLP uses a similar method but uses a digital light projector screen to flash a single image of each layer at once. Thus, it can have faster print times compared to SLA. SLA and DLP use thermoset photopolymers to produce the parts. These technologies produce dimensionally accurate parts with high details, intricate features and accurate tolerances. Its primary applications are in jewellery, dental and hearing aids industries. Recent technological development in vat polymerisation is Continuous Direct Light Processing Method which uses a continuous upward motion of the build plate but can work with specific photopolymers (Redwood, Schoffer, and Garrett 2018).

Selective laser sintering (SLS): Powder Bed Fusion process use thermal energy to selectively fuse regions of powder bed. Among the Powder Bed Fusion technologies, SLS uses a laser to fuse particles of build materials layer by layer on top of each other (Gao et al. 2015). After sintering each layer, a layer of build material is drawn across the whole powder bed. A laser then sinters the layer of material at those areas that corresponds the geometry of the part at a given cross-section of the part. SLS can produce parts from any material that can be pulverised, including polymers, metals, ceramics, and glass. Post-curing is not required, the build time is fast, and complex parts can be manufactured. Drawbacks are that SLS is that surface finish is not as good as compared to SLA, and that material changeover is difficult. It has long lead times, require post-processing, requires skilled operators and advanced material handling systems (Redwood, Schoffer, and Garrett 2018). Materials with low thermal conductivity are suitable for Powder Bed Fusion processes. Thus, for polymer-based SLS, polyamides are almost exclusively used. Interested readers may refer to Tiwari et al. (2015) for detailed description and analysis related to choice of materials for SLS. To further enhance mechanical properties, heat and chemical resistance of parts, polyamides like nylon can be combined with aluminium, glass, carbon or graphite. It does not require support structures. SLS is best suited for producing strong functional parts with complex geometries and consistent surface finish. Hence, its primary applications are in functional parts, low volume part production and complex ducting. Thus, SLS can be considered as a potential technology for spare parts. A recent development in a technology similar to SLS is Multi Jet Fusion developed by Hewlett Packard (HP), which uses a detailing agent. The detailing agent reduces fusing at the boundary of the parts to produce features with sharp and smooth edges.

Direct Metal Laser Sintering (DMLS) and Selective Laser Melting (SLM) use similar methods as SLS. DMLS heats the metal powder to a point so that it can fuse together at a molecular level while SLM uses the laser to melt the metal powder completely to form a homogeneous part. Thus, DMLS produced parts from metal alloys while SLM uses single element metals like titanium. DMLS and SLM can produce complex parts with geometries which traditional manufacturing technologies cannot produce. But, costs of the processes are high and build sizes are also limited. Usually design for AM can make a part a suitable candidate for DMLS/SLM. DMLS sand SLM are used for dental, medical, automotive and aerospace applications.

Material Jetting: Material Jetting is a process in which droplets of materials are selectively deposited and cured on a build plate. Material jetting operations deposit build materials in a rapid line-wise fashion. Thus, multiple parts can be built in a single line with no effect on build speed. Thermoset photopolymers are used in material jetting which are cured by UV light. Hence, materials with low viscosity are most suitable. Parts produced using material jetting are dimensionally very accurate, have very smooth surfaces. But, the parts produced have poor mechanical properties and are brittle. Hence, the technology is suitable for prototypes, and low-run injection moulds, and are not ideally suited for spare parts of industrial products.

Binder Jetting: It is a process in which a liquid binding agent selectively binds regions of a powder bed. Binder jetting moves a print head over the powder surface depositing binder droplets that bind the powder particles together to produce each layer of the part. The process does not use any heat and thus parts do not suffer from residual stresses. Operating costs

Table 4. Summary of AM technologies suited for spare parts production.

AM technology	Most common materials	Part Size	Mechanical properties	Dimensional accuracy
SLS	Thermoplastic powders (Nylon 6, 11,12, ABS, PEEK)	Average build volume of 300x 300 × 300 mm and bigger machines with 750 × 550 × 550 mm	Good	+ or − 0.3% with a lower limit of + or − 0.3 mm
DMLS	Metal powders (stainless steel and alloys)	Small (maximum of 250 × 150 × 150 mm)	Very good	+ or − 0.1 mm
SLM	Metal powders (aluminium, titanium)	Small (maximum of 250 × 150 × 150 mm)	Very good	+ or − 0.1 mm
Binder Jetting	Sandstone, stainless steel, Inconel alloy, Tungsten carbide	Large (up to 1800x 1000 × 700 mm)	Not as good as DMLS/SLM	+ or − 0.2 mm (metal) or + or – 0.3 mm (sand)

Adapted from Redwood, Schoffer, and Garrett (2018).

are low and large parts can be printed. Mechanical properties of parts of the parts coming directly out of the print bed are low and secondary processes are needed to achieve the desired properties.

Laser engineered net shaping (LENS): Direct Energy Deposition is a process in which focused thermal energy is sued to fuse materials by melting as they are deposited. LENS, one of the technologies following the above process builds objects by focusing a high-powered laser beam on top of a substrate, whereby a molten pool is created, in which metal powder is injected to build layers. The supporting foundation beneath the laser beam is moved down as each layer is build, by which the desired geometry is created. LENS offers appropriate control of manufacturing parameters, and desirable geometric and material properties. Apart from being used to manufacture new parts, it can also be used to repair parts. Drawbacks of this technology are that parts that are produced with LENS technology require postproduction, as they must be cut from the build substrate, and have rough surfaces.

Laminated object manufacturing (LOM): Sheet lamination is a process in which sheets of material are bonded to form a part. LOM is a technology uses adhesive-coated sheet materials for sequentially laminating and cutting of 2D cross-sections on top of each other to create 3D objects. A laser beam is used for cutting each layer, with a cutting depth corresponding exactly to the thickness of each layer. LOM can be used to manufacture objects in paper, metals, plastics, fabrics, synthetic materials, and composites. Drawbacks of the technology are dimensional instability, lack of product quality due to internal cavities, and postproduction requirements.

The above overview of AM processes and technologies show that SLS, DMLS, SLM and Binder Jetting are most suitable for producing functional parts and spare parts for industrial use. Multiple factors need to be considered before a company can make such a choice. Process and material design, and part related characteristics (performance, supply and demand issues) are some of the factors that will guide the decision making for the choice of AM technologies and equipment for spare parts production. The process and material design domain includes the elements that describe the printing process, such as printing technology, printing material, and printing parameters. The design-related domain includes the elements that describe the design model, such as design features and surfaces (Wang et al. 2018). The part-related domain includes the elements that describe the performance of the printed part, such as general properties (e.g. tensile strength and surface finish), quality of features, supply characteristics (e.g. lead time), and demand characteristics (e.g. predictability of demand). Factors in the process and material-related domains and design-related domain could influence attributes in the part related characteristics. With an understanding of advantages and disadvantages and their potential trade-off relationships, companies can choose appropriate AM equipment to achieve the desired objectives (Wang et al. 2018). For example, metal binder jetting can be much cheaper compared to DMLS or SLM. However, parts produced using binder jetting will not be able to meet strict tolerances and mechanical properties. Also, DMLS and SLM can have high lead times and build size restrictions. Thus, for a larger sized part without load bearing and hence high mechanical property requirements, binder jetting can be suitable, while for smaller alloy parts which have high mechanical property requirements, DMLS can be considered as most suitable. Materials which can be used for AM, have to be carefully examined for their different properties such as dimensional stability, strength, viscosity, and resistance to heat and moisture (Joshi and Sheikh 2015). We summarise the AM technologies and materials, which can be used for spare parts production in Table 4.

A list of 37 companies offering industrial additive systems and equipment has been reported (Wohlers Associates 2018). A detailed overview of the flagship equipment used in each company is given in Appendix 3. For example, details on build envelope, layer thickness, materials, and build speed are reported. Also, the post-processing requirements, along with critical

Table 5. Criteria and methods used in ABC classification literature.

	Lead-time	Unit cost	Criticality	Annual dollar usage	Demand volume/rate/variability	Commonality	Substitutability	Repairability	Durability	No. of suppliers	Stockability	Warehouse space	Production availability	Perishability	Inventory cost	Lifecycle stage	Probability of failure	Demand predictability	Obsolescence	Last use date	Other criteria applied	Method used
Flores and Whybark (1986)	✓	✓	✓	✓	✓	✓	✓	✓											✓			Bi-criteria
Duchessi, Tayi, and Levi (1988)*	✓		✓												✓		✓				✓	Bi-criteria
Ernst and Cohen (1990)*	✓	✓	✓															✓				Statistical clustering
Petrović and Petrović (1992)*		✓	✓					✓					✓								✓	SPARTA II
Flores, Olson, and Dorai (1992)	✓	✓	✓	✓																		AHP
Partovi and Burton (1993)*	✓	✓	✓		✓																	AHP
Gajpal, Ganesh, and Rajendran (1994)*	✓		✓			✓							✓									AHP
Guvenir and Erel (1998)	✓	✓		✓	✓	✓	✓	✓	✓		✓										✓	GA
Partovi and Anandarajan (2002)*	✓	✓			✓																✓	BPNN and GANN
Braglia, Grassi, and Montanari (2004)*	✓	✓	✓		✓		✓	✓		✓		✓		✓					✓		✓	MASTA and AHP
Danas, Roudsari, and Ketikidis (2006)*	✓	✓	✓		✓		✓			✓	✓	✓		✓								MASTA
Ramanathan (2006)	✓	✓	✓	✓																		Weighted linear optimisation model
Bhattacharya, Sarkar, and Mukherjee (2007)	✓	✓			✓									✓	✓							TOPSIS
Ng (2007)	✓	✓		✓																		Weighted linear optimisation model
Rezaei (2007)	✓	✓			✓						✓										✓	FAHP
Zhou and Fan (2007)	✓	✓		✓																		Weighted linear optimisation model
Cakir and Canbolat (2008)	✓	✓	✓		✓	✓	✓															FAHP
Chen et al. (2008a)	✓	✓	✓	✓																		Weighted Euclidean distance
Chen et al. (2008b)*	✓	✓	✓	✓																		DRSA
Jamshidi and Jain (2008)		✓		✓	✓																	Exponential Smoothing Weights

Persson and Saccani (2009)*			✓		✓											✓					✓	Discrete event simulation
Çebì, Kahraman, and Bolat (2010)	✓	✓			✓		✓														✓	Modified FAHP
Hadi-Vencheh (2010)	✓	✓		✓																		Extended weighted linear optimisation model
Razaei and Dowlatshahi (2010)	✓	✓			✓				✓													Fuzzy Logic
Chen (2011)	✓	✓		✓																		Peer-estimation approach
Hadi-Vencheh and Mohamadghasemi (2011)	✓			✓								✓			✓							FAHP-DEA
Yu (2011)	✓	✓	✓	✓																		BPN, SVM, and *k*-NN
Chen (2012)*	✓	✓	✓	✓																		TOPSIS
Mohammaditabar, Ghodsypour, and O'Brien (2012)	✓	✓		✓																		Simulated annealing
Molenaers et al. (2012)*	✓		✓							✓							✓				✓	VED and AHP
Torabi, Hatefi, and Saleck Pay (2012)	✓	✓	✓	✓																		Modified DEA
Zeng, Wang, and He (2012)*	✓					✓		✓		✓			✓			✓		✓				Fuzzy Comprehensive Evaluation and GRA
Kabir and Hasin (2013)		✓	✓		✓				✓											✓		Integrated FAHP and ANN
Kabir and Hasin (2013)		✓	✓		✓				✓											✓		Integrated Fuzzy Delphi and FAHP
Keskin and Ozkan (2013)	✓	✓	✓	✓																		FCM
Hatefi, Torabi, and Bagheri (2014)	✓	✓	✓	✓																		Modified weighted linear optimisation model
Lolli, Ishizaka, and Gamberini (2014)	✓		✓	✓																		AHP-K
Park, Bae, and Bae (2014)	✓	✓		✓																		CE-WLO
Soylu and Akyol (2014)	✓	✓	✓	✓																		UTADIS
Sarmah and Moharana (2015)*	✓	✓	✓	✓		✓																Fuzzy rule-based model
Antosz and Ratnayake (2016)*	✓	✓	✓		✓					✓	✓										✓	Scoring-based ABC model
Baykasoglu, Subulan, and Karaslan (2016)*	✓		✓	✓					✓												✓	Fuzzy LAM
Liu et al. (2016)	✓	✓		✓																	✓	ELECTRE III
Teixeira, Lopes, and Figueiredo (2017)	✓	✓	✓																			Extended VED
Hu et al. (2017)*	✓	✓	✓	✓																		DRSA
Total	40	37	29	25	16	6	6	5	5	5	4	3	3	3	3	2	2	2	2	2	12	

factors that need to be considered while choosing the most appropriate AM process and equipment are provided. AM equipment and systems can be differentiated on the basis of underlying technologies, and applications. For metal AM systems, build envelopes varies from 200 mm × 200 mm × 380 mm (Arcam EBM 2018) to 5791 mm × 1219 mm × 1219 mm (Sciaky 2018). For plastic AM systems, build envelopes varies from 180 mm × 230 mm × 200 mm (Tiertime 2018) to 2800 mm × 2400 mm × 2300 mm (Voxeljet 2018). The AM systems also vary on layer thickness, materials they can use, and build speed. The latter depends on the materials used. For AM systems produced with sand, the maximum print speed identified is 400 l/h (Exone 2018). For plastic, the maximum print speed identified is 15 l/h (Farsoon Technologies 2018), and for metal it is 250 cm3/h (Irepa Laser 2018).

In summary, multiple AM technologies and different types of equipment are currently available. Companies planning to manufacture spare parts using AM, must consider the capabilities and limitations of the technologies in terms of build volume, build speed, materials flexibility, post-processing requirements and the spare part's design and supply requirements to determine feasibility of manufacturing the spare parts using AM.

3.2. Spare parts classification criteria and methods

After analysing AM technologies and capabilities of the equipment, we need to understand the criteria, which can be used to classify spare parts and assess their suitability for AM. As limited research exists on classification of spare parts that are suitable for AM, the broader literature on spare parts classification is reviewed in this section. In order to reduce the complexity involved in managing thousands of spare parts, it is common practice to classify the parts according to their similarities (Silver, Pyke, and Peterson 1998). From the traditional single-criterion ABC-classification based on annual dollar usage (average unit price × annual demand volume) to the advanced multi-criteria methods, a wide range of classification schemes have been proposed. The criteria used for these classifications vary according to the context in which they were used. Our review revealed that about twenty criteria were applied for classification purposes more than once in the literature. The distribution of different criteria used in the literature is reported in Table 5. Additionally, another twenty-one criteria were mentioned at least once, which were distributed across twelve 12 papers, and reported as 'other criteria'. This 'other' category contained the following criteria: Stock-out cost, part weight, part volume, availability of spares-consumables, irreplaceability, scarcity, order size requirement, ordering cost, masked time, supply certainty, competition, payment terms, maintenance type, availability of technical specifications, failure type, machine category, spare part exchange time, exchange process complexity, special qualifications required, availability, and turnover rate. As the count at the bottom of Table 5 shows, the most frequently used criteria to classify spare parts are lead-time, unit cost, criticality, and annual dollar usage. The fifth most used criteria was demand volume, which is a little different, as any two of the three criteria (unit cost, demand volume, and annual dollar usage) can be used to calculate the other criterion. This dependency is also evident for several other criteria, and when selecting the criteria to use for selecting spare parts that are suitable for AM, these dependencies and relationships need to be carefully evaluated because all the criteria mentioned may not be necessarily independent.

An overview of how the methodologies used for classification was developed from bi-criteria analysis to various multi-criteria decision support tools is reported in Table 5. The classification schemes utilised some of these techniques: pairwise comparison, a distance-based method, outranking, compromise ranking, weighted linear optimisation, and rule-based decision making.

Several papers have benchmarked methods against those developed earlier by using the same data and criteria (Hadi-Vencheh 2010 and Hatefi, Torabi, and Bagheri 2014). Some of these methods can also be used for classification of spare parts suitable for AM. However, having a large number of criteria and parts may require that the patterns amongst the most suitable parts be identified using suitable machine learning based classification schemes and clustering techniques in order to save time in the screening process.

The technical characteristics of parts, which can be considered for spare parts selection for AM, are material type, and part size (Knofius, van der Heijden, and Zijm 2016; Lindemann et al. 2015). Measuring part size in a cubic measure can be used to determine the speed of printing a specific part, but it does not indicate whether a part can be printed by specific AM technologies. Additional characteristics in cases where parts redesign need to be considered can be advantages of using existing materials, possibility for improvement of part characteristics via design optimisation, reduced material consumption and faster processing times (Lindemann et al. 2015).

Our review revealed that 17 out of 45 papers, either focussed entirely on spare part classification, or discussed spare parts in relationship to the criteria mentioned in this paper. Those papers are marked with an asterisk in the first column in Table 5. The five criteria applied in the spare parts context included: number of suppliers, production availability, life cycle stage, probability of failure, and demand predictability. All the above-mentioned criteria are related to downtime reduction and supply risk, which are especially important in a spare parts context. Therefore, these findings suggest that special attention should be placed on these five criteria when selecting the criteria for ranking spare parts that are suitable for AM.

3.3. *Selecting spare parts that are suitable for AM*

In this section, we reviewed the literature, which considered selection of spare parts for AM. Despite many studies considering AM in the context of supply chain, only two studies considered how companies should identify appropriate part family candidates to be manufactured with AM technologies, with only one of them actually focusing on spare parts. Knofius, van der Heijden, and Zijm (2016) presented a methodology for ranking spare parts relative to each other, according to their potential value when produced with AM. The proposed method designed to rank large numbers of spare parts was a top-down approach, using data available in standard information systems (Knofius, van der Heijden, and Zijm 2016). Knofius, van der Heijden, and Zijm 2016 proposed several opportunities for improvement in spare parts management offered by AM, together with the attributes of multiple spare parts affecting those opportunities. As the proposed method was intended to be used by companies across multiple industries, a more complete description of potential attributes would have created a flexible methodology for users. Such a flexible methodology can configure individual company objectives in accordance with attributes of alternative spare parts. For example, the company objectives used to select the spare parts cited in the Knofius, van der Heijden, and Zijm (2016) study were securing supply, reducing downtime and reducing costs. This study used analytical hierarchy process (AHP) as the procedure for selecting the parts. The details for selecting this particular methodology was not specified, while alternate methods could have been used. Lindemann et al. (2015) presented a methodology for identification of appropriate part candidates to be redesigned and manufactured with AM technologies, considering the entire life cycle of products. According to Lindemann et al. (2015), introducing AM technologies into businesses is a learning process and not a 'plug and play' solution. Many companies are testing AM technologies on a sample of parts from their current product portfolios (Lindemann et al. 2015). However, due to the current state of AM technologies, they cannot be used to manufacture all kinds of parts (Lindemann et al. 2015). In fact, in most cases, when considering AM for parts currently being produced with conventional manufacturing technologies, a technology switch is not enough, unless part redesign is also simultaneously taken into account (Lindemann et al. 2015). They suggest a three-phased workshop-based method with inclusion of AM experts, that tries to reduce the time-consuming effort of information collection before parts are selected. However, their proposed method is only suited for bottom-up assessment of parts with regards to their potential value when redesigned and manufactured with AM technologies.

In conclusion, our review showed that only two studies have proposed methods for evaluating and selecting spare parts for AM. One of the suggested method takes a top-down approach, using data available in standard information systems, and focused on ranking of spare parts based on their current functionality, according to their potential value when manufactured with AM. The other study takes a bottom-up approach for identification of spare parts qualified for redesign and functional integration with other spare parts, where after manufactured with AM. The review showed that there is a need for in-depth research and development of a framework and methodology for selecting spare parts, suitable for AM.

4. Discussion and future research directions

Spare parts management is characterised by parts of high variety, low demand volume, sporadic and unpredictable demand, high service requirements, high financial consequences of stock-outs, and high prices for individual parts. To meet customer requirements of fast response times, many original equipment manufacturers (OEMs) make significant investments in spare parts inventories. To reduce complexity, spare parts are classified according to similar characteristics. 38 criteria for spare parts classification were identified from the literature review. 16 criteria, were mentioned more than once, and were identified in papers focusing on classification of spare parts. Five criteria most relevant to classification of spare parts were identified to be: probability of failure, number of suppliers, demand predictability, stock-out cost, and production availability. All of these criteria were related to downtime reduction and supply risk.

AM has the potential to manufacture spare parts, reduce delivery lead time and reduce inventory. AM technologies, suitable for industrial spare parts production, along with 37 companies offering industrial AM systems and equipment were identified in this paper. Among those applicable for manufacturing of spare parts in metal build envelopes varied significantly. The review shows that there is a dearth of research on selecting spare parts, suitable for AM. Detailed understanding of different spare parts classification criteria and the assessment of capabilities of available AM technologies need to be considered while taking into account the specific application context before finalising the most appropriate method to select the spare parts, most suitable for AM. Companies not using relevant spare parts classification criteria and a systematic data-driven process of identifying most suitable spare parts for AM, are likely to miss some potential aspects and spend a lot of time in conducting such an exercise. There is limited research addressing this issue. Therefore, this review is useful, and in particular, has paved the way to help identify missing themes and promising opportunities for future research. These opportunities for future research are highlighted below:

Research direction #1: spare parts screening for AM with limited data availability

Suitable data to pre-screen parts and score them on their suitability for AM may not be easily available. One reason for the above is that some of the data may reside in an Enterprise Resource Planning (ERP) system while data about design may reside in a different Product Life Cycle Management (PLM) System. Thus, different functions within a company will have access to the desired data. For some organisations, only limited amount of required data may be available if the products are old and if drawings do not exist. Many small and medium enterprises may also have limited data availability. For such contexts, it is important to develop processes to systematically identify the required parts through a bottom-up approach by utilising the experiences of service and maintenance technicians. Organisations like Deutsche Bahn have adopted such an approach (Brickwede 2017), and yet there is limited research to formalise and generalise this process and make it applicable for different contexts.

Research direction #2: cross-functional process for selecting spare parts suitable for AM

For organisations, where the required data may be available and can be combined, a formal process is required. This process includes: validation of data, creating cut-offs for screening the parts, and scoring the parts. This requires a cross-functional effort across the organisation, which may also involve external or internal AM experts. Finally, business cases need to be developed for the identified spare parts by comparing AM with existing manufacturing technologies over the lifecycle of the product. There is limited literature on developing a comprehensive process involving multiple functions to identify the criteria to be used to determine the suitability of a spare part using AM, to score and select those parts and then to develop the business case that justifies the investment.

Research direction #3: methodology for spare parts selection for AM

Scoring the parts on suitability for AM is a multi-criteria decision making problem (MCDM) and there can be multiple MCDM approaches which can be used, which will depend on the nature of relationships between the criteria and the form in which the data is available. For example, such approaches may involve quantitative or subjective judgment by experts or a combination of both judgments. Many of the criteria that can be used to determine suitability of spare parts for AM may be inter-related. Therefore, considering such dependencies among the criteria when scoring spare parts with respect to objectives is paramount in ensuring a valid scoring framework. This issue has not been addressed in the existing literature. Multiple methods need to be applied, and the ensuing results validated with the experts. Currently, there are no clear guidelines available in the literature in terms of choosing appropriate methodologies. Future research should be directed on developing guidelines to choose the most appropriate method depending on the context.

Research direction #4: understanding characteristics of spare parts suitable for AM

Evaluating a large portfolio of spare parts across multiple criteria is a time-consuming process. As more products are launched and their spare parts added to the portfolio, companies would like to avoid repeating the entire evaluation process. Thus, there is a need to understand the characteristics of spare parts which are most suitable for AM compared to the less suitable ones, and use those to decide whether any new part is suitable for AM or not. As the companies identify more spare parts, which can be manufactured using AM, analysis of characteristics of those parts and identifying patterns using different machine learning techniques is important. This will facilitate feature and characteristic recognition of parts to identify parts which are feasible to be printed and then also matching them with the most appropriate AM technology and equipment. This can ensure that the entire spare parts selection process for AM need not be repeated when new products are developed and new parts are added to the spare parts population. Commercial versions of such software which have been recently developed include Partfinder by enter2net.de, and AM Part Identifier by 3yourmind.

Research Direction #5: design for AM and impact on part selection

This review focused only on spare parts selection for AM. If parts for existing or new products are considered along with options for design for AM, the process of selection of parts can become complex. This is so because some individual parts with existing designs may not be suitable, but could have potential if those are redesigned or combined to create an integral product architecture. In such cases, technical performance measures such as weight reduction, strength and durability of the parts will also have to be considered. Future research should be directed at the parts selection problem with design for AM in mind. The options for design for AM could be amenable to a combination of a top-down data-driven approach and the bottom-up expert opinion driven approach which is extends the workshop based bottom-up approach proposed by Lindemann et al. (2015).

Research direction #6: impact of AM on product modularity and integrality

The influence of AM on product modularity and integrality is important to understand. This influence has an effect on product development strategies, product performance as well as on supply chain performance. This area is expected to be an interesting field of research in the coming years, with an increased use of AM that could make integral design a favourable approach for certain parts, even though the current design may prefer a modularity approach. Considering design changes will require companies to evaluate whether to combine individual parts and how many of those to combine considering multiple performance objectives such as lead time reduction, inventory cost reduction, supply risk reduction, product quality improvement, or reduction in carbon footprint. Selecting spare parts for AM can trigger redesign decisions. Product modularity and integrality considerations need to be taken into account. For example, replacing a single spare part using AM may not be economically justified for modular products, but creating an integral design, which can be produced using AM, may make it feasible. But, there can be additional costs involved. Hence, there is a need for research to explore the various trade-offs related to production of spare parts by AM and their implications on product modularity and integrality.

Research direction #7: considering usage of AM in conjunction with conventional manufacturing technologies for spare parts production

AM technologies can also be used to produce tools and moulds with the finished part that is being produced using existing technologies such as injection moulding (Charalambis et al. 2017). This can open up possibilities of low-volume spare parts production using existing technologies (currently suitable for only high volumes). Such usage of AM in conjunction with conventional technologies (for example, using injection moulding) will help in combining superior finish and materials flexibility associated with injection moulding. In this way, design complexity can be handled via AM and it is likely that low volume spare parts production can become more economical even for complex designs. In some cases, injection moulding alone is may not be a favourable option, and AM alone may not be feasible. This could be because of limited choices in materials, and inferior finish quality. This argument is also in line with Gao et al. (2015) and Holweg (2015), who commented that AM should be viewed as a complement to conventional manufacturing. AM can be exploited due to its unique capabilities in making existing products better, and for the ability to manufacture entirely new ones that previously could not be made. Thus, the future research on spare parts selection for AM should also consider the above option of using AM in combination with conventional manufacturing technologies.

5. Conclusions

The objective of this review was to create a foundation that companies can use to develop methodologies to identify spare parts, which are most suitable for AM. We conducted a systematic review of the literature with the following specific goals. First, to document the different AM technologies and terminologies, which can be used as inputs to the part selection process. Second, to identify the criteria, which can be used to classify spare parts and select the most suitable ones, which can be manufactured using AM. Third, to identify the methodologies which can be used to identify the most suitable spare parts. As the literature relating to selecting parts suitable for AM is limited, we relied on the broader spare parts classification literature to identify the criteria, that can be used to select spare parts suitable for AM. We supplemented the knowledge base by creating a database of AM equipment manufacturers and by reviewing the different capabilities of the equipment.

In line with these objectives, this review makes two contributions. First, the review showed that multiple criteria can be used to classify spare parts to assess their suitability for AM. Their suitability will depend on the context, and thus each company should choose the most appropriate spare parts, which are relevant for their business and for which data can be made available. Usually, redesign of spare parts to be suitable for AM is not an option. Therefore, the technical characteristics that are most appropriate to classify spare parts are dimension, weight of the products, and material specifications. A key consideration in the selection of spare parts suitable for AM is also defining the objectives that a company may want to achieve by using AM for spare parts manufacturing. For example, it could be downtime reduction, inventory reduction, lead time reduction, or supply risk reduction, to name a few. The basis for which each part is evaluated on the chosen criteria, could help achieve the sought after objectives of the company. Hence, companies must define the objectives upfront. The objectives most frequently mentioned in the literature are lead-time reduction, inventory cost reduction (Muir and Haddud 2018; Ghadge et al. 2018; Khajavi, Partanen, and Holmström 2014), supply risk reduction, and downtime reduction. However, the extant literature has paid limited attention to examining the relationships between parts classification factors and company objectives.

Second, this review identified future research opportunities in the nascent field of spare parts suitable for AM. We identified seven future research directions relating to several domain areas. They include: methodology for spare parts selection; processes to be followed by companies to conduct assessments for suitability of spare parts; impact of AM on product modularity and integrality, in particular, for parts with redesign options; and considering options that utilise benefits of existing conventional technologies and AM for spare parts production.

AM is now actively considered by industrial manufacturers for spare parts as well as production of parts for new products. Still, there are limited examples of such parts, which have been used in practice in a product. As companies attempt to adopt AM, there will be some failures. Analysing such failures and by engaging with both equipment and material manufacturers, new solutions could be obtained either in new or customised material development. For instance, this can happen by automating the AM process thereby improving productivity, or by improving or reducing post-processing tasks. As the AM processes are still evolving, there are plenty of opportunities to capture real-time data from AM processes, analysing this data and simulating AM processes to optimise process parameters for specific applications. Hence, inter-connectedness of AM processes and distributed quality-assurance will be key to AM's future adoption for industrial applications. Another key enabler will be development and continuous updating of standards for AM produced parts for each industry. This could lead to development of AM qualification and process certification guidelines (AM-motion 2018).

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendices

Appendix 1. Literature included in the review.

Search category	Literature	No.
AM + SP	(Berman 2012; Durão et al. 2017; Jha 2016; Pérès and Noyes 2006; Pour and Zanoni 2017; Zanardini et al. 2016)	6
AM + SC	(Achillas et al. 2014; Attaran 2017; Ben-Ner and Siemsen 2017; Durach, Kurpjuweit, and Wagner 2017; Feldmann and Pumpe 2017; Gao et al. 2015; Gress and Kalafsky 2015; Hasan, Rennie, and Hasan 2013; Holmström et al. 2016; Holmström, Liotta, and Chaudhuri 2017; Holmström and Partanen 2014; Huang et al. 2013; Joshi and Sheikh 2015; Khorram Niaki and Nonino 2017; Kothman and Faber 2016; Oettmeier and Hofmann 2016; Ortt 2017; Rogers, Baricz, and Pawar 2016; Rogers, Braziotis, and Pawar 2017; Ryan et al. 2017; Rylands et al. 2016; Strong et al. 2017; Sun and Zhao 2017; Wagner and Walton 2016; Woodson 2015)	25
SP + SC	(Behfard et al. 2015; Bergman et al. 2017; Danas, Roudsari, and Ketikidis 2006; de Souza et al. 2011; Huiskonen 2001; Van Utterbeeck et al. 2009; Wagner and Lindemann 2008)	7
AM + SP + SC	(Holmström et al. 2010; Khajavi, Partanen, and Holmström 2014; Knofius, van der Heijden, and Zijm 2016; Li et al. 2017; Liu et al. 2014; Meisel et al. 2016; Sasson and Johnson 2016)	7
SP + Classification	(Antosz and Ratnayake 2016; Baykasoglu, Subulan, and Karaslan 2016; Braglia, Grassi, and Montanari 2004; Duchessi, Tayi, and Levy 1988; Ernst and Cohen 1990; Gajpal, Ganesh, and Rajendran 1994; Hu et al. 2017; Molenaers et al. 2012; Persson and Saccani 2009; Roda et al. 2014; Sarmah and Moharana 2015; Teixeira, Lopes, and Figueiredo 2017)	12
Backward search	(ASTM International 2013; Atzeni and Salmi 2012; Bhattacharya, Sarkar, and Mukherjee 2007; Cakir and Canbolat 2008; Çebì, Kahraman, and Bolat 2010; Chen 2012; Chen 2011; Chen et al. 2008a; Chen et al. 2008; Cohen and Ernst 1988; Flores, Olson, and Dorai 1992; Flores and Whybark 1986; Gibson, Rosen, and Stucker 2009; Guvenir and Erel 1998; Hadi-Vencheh 2010; Hadi-Vencheh and Mohamadghasemi 2011; Hatefi, Torabi, and Bagheri 2014; Hopkinson and Dickens 2003; Jamshidi and Jain 2008; Kabir and Hasin 2013; Keskin and Ozkan 2013; Lindemann et al. 2012; Lindemann et al. 2015; Liu et al. 2016; Lolli, Ishizaka, and Gamberini 2014; Mohammaditabar, Ghodsypour, and O'Brien 2012; Ng 2007; Park, Bae, and Bae 2014; Partovi and Anandarajan 2002; Partovi and Burton 1993; Petrović and Petrović 1992; Petrovic et al. 2011; Ramanathan 2006; Razaei and Dowlatshahi 2010; Rezaei 2007; Ruffo, Tuck, and Hague 2007; Silver, Pyke, and Peterson 1998; Soylu and Akyol 2014; Torabi, Hatefi, and Saleck Pay 2012; Tuck, Hague, and Burns 2007; Walter, Holmström, and Yrjölä 2004; Weller, Kleer, and Piller 2015; Yu 2011; Zeng, Wang, and He 2012; Zhou and Fan 2007)	45

Appendix 2. Terminologies and their usage across literature. Terminologies appearing under keywords were not counted, as these were not directly used by the authors. The terminologies Manufacturing and Production were assumed synonyms.

	3D application	3D machine	3D manufacturing	3D printer	3D printing	3D technology	Additive fabrication	Additive layer manufacturing	Additive manufacturing (AM)	Additive manufacturing process	Additive manufacturing tehnology	Additive process	Additive system / machines	Additive techniques	Digital fabrication methods	Digital manufacturing	Direct additive laser manufacturing	Direct digital manufacturing (DDM)	Direct manufacturing / fabrication	Freeform fabrication	Generative manufacturing	Layer manufacturing	Layer-by-layer manufacturing	Layer-by-layer rapid prototyping	Rapid manufacturing	Rapid printing	Rapid prototyping (RP)	Rapid tooling
Achillas et al. (2014)					T				T			*P*		T						*P*		*P*			*P*		*P*	*P*
ASTM International (2013)				T	*P*		*P*	*P*	*P*		T	*P*	T	*P*						*P*		*P*					A	A
Attaran (2017)				T	*P*		T		T		T							T				T			A		A	
Atzeni and Salmi (2012)									*P*		T	*P*	T	*P*	*P*	*P*			*P*		*P*						T	*P*
Ben-Ner and Siemsen (2017)				T	T				T			*P*														*P*		
Berman (2012)	A	T	T		*P*	T			*P*	*P*								E									*P*	E
Durach, Kurpjuweit, and Wagner (2017)				T	T				T	*P*						T												
Durão et al. (2017)									*P*																			
Feldmann and Pumpe (2017)					*P*				T	*P*																	A	
Gao et al. (2015)				T	T				T																			
Gress and Kalafsky (2015)					*P*				*P*		T																A	
Hasan, Rennie, and Hasan (2013)				T	T				*P*												T	T			U		U	
Holmström et al. (2010)																									*P*		*P*	A
Holmström and Partanen (2014)					T				T							*P*												
Holmström et al. (2016)					*P*				*P*									*P*									*P*	
Holmström, Liotta, and Chaudhuri (2017)					T				T									*P*	*P*						U		*P*	*P*
Hopkinson and Dickens (2003)												*P*										*P*			*P*		*P*	
Huang et al. (2013)				T	T				*P*	*P*							*P*								*P*		*P*	

Jha (2016)		T	T	T			*P*																		A	
Joshi and Sheikh (2015)		T	*P*				*P*		T											T						
Khajavi, Partanen, and Holmström (2014)			T				T							T			T								T	
Khorram Niaki and Nonino (2017)		T	T				*P*									E		*P*		*P*	*P*					E
Knofius, van der Heijden, and Zijm (2016)							*P*																			
Kothman and Faber (2016)		T	T				T	*P*																		
Li et al. (2017)			T				T		T								T								U	
Lindemann et al. (2012)							T																T		T	
Liu et al. (2014)							*P*																			
Meisel et al. (2016)		T	*P*				*P*																A			
Oettmeier and Hofmann (2016)			*P*				*P*			*P*				*P*		*P*	*P*		*P*				*P*		A	
Ortt (2017)		T	T				T																A			
Pérès and Noyes (2006)			*P*									*P*					*P*	*P*					T		T	T
Petrovic et al. (2011)			*P*		*P*	*P*	T				T						*P*	*P*			*P*		*P*		T	*P*
Pour and Zanoni (2017)							U		*P*																	
Rogers, Baricz, and Pawar (2016)		T	*P*				*P*							*P*		U							*P*		A	A
Rogers, Braziotis, and Pawar (2017)			*P*				U																		*P*	
Ruffo, Tuck, and Hague (2007)			T																				*P*		*P*	
Ryan et al. (2017)		T	*P*				*P*																*P*			
Rylands et al. (2016)		T	*P*				*P*														*P*		*P*		A	
Sasson and Johnson (2016)	*P*	T	T	T			*P*			*P*						T							T			
Strong et al. (2017)		T	*P*		*P*	*P*	*P*			*P*		*P*		*P*		*P*		*P*		*P*					*P*	
Sun and Zhao (2017)	*P*	T	T				T						*P*	*P*		T		T								
Tuck, Hague, and Burns (2007)							*P*							*P*									*P*	*P*		
Wagner and Walton (2016)			*P*			U	T							U												
Walter, Holmström, and Yrjölä (2004)		T																T				T	*P*		*P*	A
Weller, Kleer, and Piller (2015)		T	T				T									*P*	*P*			*P*			U		A	
Woodson (2015)		U	*P*				*P*																			
Zanardini et al. (2016)		T	U				*P*														U				A	

A – Application, *P* – Process, T – Technology, E – evolutionary phase, U – unspecified.

Appendix 3. AM equipment and systems manufacturers 2018. Manufacturers were identified through Wohlers Associates (2018).

Manufacturer	Model	Build size (mm)	Layer thickness	Material class	Material details	Build speed
3D Systems	ProX DMP 320	275 × 275 × 420	2–60 µm	Metal	LaserForm® Ti Gr. 12 LaserForm® Ti Gr. 52 LaserForm® Ti Gr. 232 LaserForm® Ni7183 LaserForm® Stainless 316L3	N/A
3D Systems	ProJet MJP 5600	518 × 381 × 300	13–16 µm	Plastic (multi)	Rigid Plastic Black, Rigid Plastic White, Rigid Plastic Clear, Elastomeric Black, Elastomeric Natural, multi-material composites	N/A
3D Systems	ProX SLS 6100	381 × 330 × 460	0.08–0.15 mm	Plastic	Plastics, composites, elastomer and CastForm® PS (powders)	2.7 l/hr
3DCeram	CERAMAKER 900	300 × 300 × 100	30 µm	Ceramic	N/A	N/A
Agilista	N/A	N/A	N/A	N/A	N/A	N/A
Arcam AB	Arcam A2X	200 × 200 × 380	250 µm	Metal	Titanium Ti6Al4V, Titanium Ti6Al4V ELI, Titanium Grade 2, Cobalt-Chrome, ASTM F75, Nickel Alloy 718	N/A
Arcam AB	Q20plus	350 × 380 (Ø/H)	140 µm	Metal	Titanium Ti6Al4V, Titanium Ti6Al4V ELI, Titanium Grade 2, Cobalt-Chrome, ASTM F75, Nickel Alloy 718	N/A
Asiga	N/A	N/A	N/A	N/A	N/A	N/A
Carima	DM250	250 × 140 × 280	130 µm	Plastic	Various Photopolymer Resin	N/A
CMET	ATOMm-8000	800 × 600 × 400	0.05 mm	Plastic	Resins	N/A
Concept Laser	X LINE 2000R	800 × 400 × 500	30–150 µm	Metal	Aluminium (AlSi10Mg) Titanium alloy (TiAl6V4 ELI) Nickel-based alloy (Alloy 718)	120 cm3/h
DWS	XPRO S	300 × 300 × 300	10–100 µm	Plastic	Polymers and flexible materials	N/A

EnvisionTEC	SLCOM 1	30” × 24” × 24”	0.1-1.0 mm	Plastic	Polymer matrices. Can be reinforced with fibres like: Carbon Fibre, Fibreglass, Aramid Fibre (i.e. Kevlar), PBO (i.e. Zylon), along with metal fibres like steel, aluminium or titanium	N/A
EnvisionTEC / Viridis3D	RAM 336	3’ × 3’ × 6’	200-500µ	Sand		1.5–2.5 vertical inch/h
EOS	EOS M 400–4	400 × 400 × 400 incl. build plate	100 µm	Metal	EOS Aluminium AlSi10Mg, EOS Nickel Alloy IN718, EOS Nickel Alloy HX, EOS MaragingSteel MS1, EOS StainlessSteel 316L, EOS Titanium Ti64, EOS Titanium TiCP Grade 2	N/A
EOS	EOS *P* 770	700 × 380 × 580	0.06-0.18 mm	Plastic	Alumide, PA 1101, PA 1102 black, PA 2200, PA 2201, PA 3200 GF, PrimeCast 101, PrimePart FR (PA 2241 FR), PrimePart PLUS (PA 2221)	Up to 2 × 10 m/s
ExOne	Exerial™	1200 × 2200 × 700	280–500 µm	Sand	N/A	300–400 L/h
ExOne	M-Print™	400 × 250 × 250	Min. 0.15 mm	Metal	Currently available metals include 420 & 316 stainless steel, sand and other casting media also available.	30–60 s/layer
ExOne	M-Flex™	400 × 250 × 250	Min. 0.15 mm	Metal	420 & 316 stainless steel & bronze, bronze and tungsten. Soda lime (semi-opaque) glass, sand and other casting media also available.	30–60 s/layer
Farsoon	HT1001P	1000 × 500 × 450	0.06–0.3 mm	Plastic	FS3300PA, FS3250MF, FS3400CF, FS3400GF, FS6028PA, (PA6)	15 L/h
Farsoon	FS421M	420 × 420 × 420	0.02–0.1 mm	Metal	316L, 17-4PH, CoCr, Ti64, AlSi10Mg, 18Ni300, 420, Cu90Sn10, IN625, IN718, Ta, W	N/A

(*Continued*).

Appendix 3. Continued.

Manufacturer	Model	Build size (mm)	Layer thickness	Material class	Material details	Build speed
Formlabs	N/A	N/A	N/A	N/A	N/A	N/A
InssTek, Inc.	MX-Grande	2000 × 1000 × 1000	N/A	Metal (multi)	Inconel, Steel	N/A
InssTek, Inc.	MX-1000	1000 × 800 × 650	N/A	Metal (multi)	N/A	N/A
Irepa Laser	Magic LF 6000	1500 × 800 × 800	N/A	Metal (multi)	N/A	250 cm^3/h
Lithoz	CeraFab 8500	76 × 43 × 170	10–100 µm	Ceramics	N/A	100 slices/h
Luxexel	Luxexcel 3D printing technology	N/A	N/A	Luxexcel VisionClear	N/A	N/A
MakerBot Industries	Replicator +	N/A	N/A	N/A	N/A	N/A
Matsuura	Lumex Avance-25 hybrid	N/A	N/A	N/A	N/A	N/A
Mcor Technologies	Mcor IRIS	N/A	N/A	N/A	N/A	N/A
Microfabrica	EFAB technology	N/A	N/A	N/A	N/A	N/A
OPM Laboratory	OPM250L	250 × 250 × 250	N/A	Metal	N/A	N/A
Optomec	LENS 850-R	900 × 1500 × 900	N/A	Metal	Inconel alloys, stainless steels, titanium alloys	Up to 0.5 kg/hr
Prodways	ProMaker L7000	800 × 330 × 200	25–150 µm	Plastic	Resins	2.5 kg/h
ReaLizer	SLM 300i	300 × 300 × 300	20–100 µm	Metal	CoCr, Titanium, Steel alloys	N/A
Renishaw	RenAM 500M	250 × 250 × 350	N/A	Metal	Titanium, Ti6Al4VAluminium, AlSi10Mg alloyCobalt chromium, CoCrStainless steel, 316LNickel alloys	N/A
Renishaw	RenAM 500Q	250 × 250 × 350	N/A	Metal	Titanium, Ti6Al4V, Aluminium, AlSi10Mg alloy, Cobalt chromium, CoCr, Stainless steel, 316L, Nickel alloys	Up to 150 cm^3/h
RepRap	Cartesio	N/A	N/A	Metal	N/A	N/A
Sciaky	The EBAM® 300 System	5791 × 1219 × 1219	N/A	Metal	N/A	7–20 lbs/h

SLM Solutions	SLM® 500	500 × 280 × 365	20–75 μm	Metal	Al-Alloys, Ni-Alloys, Ti-Alloys, Co-Alloys, Tool and Stainless Steel, Cy-Alloys,	Up to 171 cm^3/h
Solidscape	S500	N/A	N/A	Wax	N/A	N/A
Stratasys	F900	914.4 × 609.6 × 914.4	0.508 mm	Plastic	Thermoplastics	N/A
Stratasys	OBJET1000 PLUS	1000 × 800 × 500	16 microns	Plastic (multi)	Can allow as many as 14 materials	N/A
Tiertime	X5	180 × 230 × 200	0.05–0.4 mm	Plastic	UP Fila ABS, ABS +, PLA, TPU and more	N/A
Voxeljet	VX4000	4000 × 2000 × 1000	N/A	Sand	N/A	123 l/h
Voxeljet	VX1000	2800 × 2400 × 2300	150/300 μm	Plastic	Plastic and sand	N/A
Wuhan Binhu Mechanical & Electrical Co., Ltd	HRPS-V	1000 × 1000 × 600	0.08–0.3 mm	Plastic	Polystyrene, coated sand	N/A
Wuhan Binhu Mechanical & Electrical Co., Ltd	HRPM-II	250 × 250 × 250	0.02–0.2 mm	Metal	Stainless steel, Ti / Ni alloys (10-45um)	N/A
Wuhan Binhu Mechanical & Electrical Co., Ltd	HRPL-III	600 × 600 × 500	0.05–0.3 mm	Plastic	Photosensitive resin	N/A