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Operations Management of Additive Manufacturing

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Abstract. This article reviews the growing literature on additive manufacturing (AM) operations management and sheds light on the emerging research areas in this field. As the AM use cases of final parts rapidly expand, it is essential to focus on the operations management of this technology and determine the primary current and future research streams. A literature study method is utilized to select, review, and categorize articles in the field of AM. The 108 articles selected after the initial evaluation were carefully examined and categorized. The selected papers evaluate AM from an operations management perspective. This article categorizes the body of knowledge studying the application and operations management of additive manufacturing into three categories: studies concerned with the industry's current state, forward-looking studies with a conceptual approach, and forward-looking papers with empirical grounding. Different AM processes studied are also considered. Our categorization showed that the latter category is still under-researched and presents an opportunity for future investigations. Moreover, six emerging streams of research in the third category were recognized. In addition to pointing out the areas of research that require more attention, this article aims to assist the researchers in better positioning their research.

Keywords: Additive manufacturing; operations management, 3D printing, rapid manufacturing, logistics, manufacturing, management, supply chain

1 Introduction

Additive manufacturing (AM), also known as 3D printing, is a digital technology for producing physical objects layer by layer from a three-dimensional computer-aided design (CAD) file. A simple explanation of this production process is as follows. The process begins with generating a three-dimensional CAD model of the object with its details and dimensions. Next, a computer program slices the three-dimensional CAD file into thin two-dimensional (2D) cross sections (layers). Then, the 2D layers are sent to the three-dimensional printing machine one layer at a time. The machine produces the object by building each layer on top of the previous one, utilizing different raw material solidification methods in its production chamber [41, 67]. The process may take from a few hours to a few days to produce an object, depending on its size, material and required production precision.

This technology, introduced initially as rapid prototyping (RP) and three-dimensional printing, was invented in the 1980s [29] to produce rough physical prototypes of final products. Since then, it has continued to evolve in different aspects. Currently, increasingly more parts produced with this method are reaching the suitable precision and quality necessary for final functional parts for special applications, such as air-cooling ducts for aircraft, hearing aid shells and medical prostheses [38]. The technical committee within ASTM (American Society for Testing and Materials) International recently adopted the term additive manufacturing for the technology, as it is no longer solely for prototype production. There are different AM processes available with different props and cons, but standards divide those into seven different processes. The advancements that have made AM possible are widening the machine's material range, improving precision and final quality, and reducing machine acquisition cost [67].

1.1 AM application in operations

With its swift advancements (e.g., precision, speed, affordability, and materials range) and inherent capabilities, AM technology has the potential to fundamentally revolutionize manufacturing operations and supply chains [85, 113]. What makes this production method a potentially disruptive technology for supply chain management is its characteristics. Holmström et al. [49] highlight the following benefits of AM methods over the conventional manufacturing methods:

- No need for tooling (economies of scale do not fully apply, which makes customization and design revisions possible).
- Feasibility of producing small production batches.
- Possibility for quickly changing the design.
- Product optimization for function (aka generative design).
- More economical custom product manufacturing (batch of one) plus the capability to produce complex geometries.
- The potential for simpler supply chains with shorter lead times and lower inventories.

Additionally, AM could significantly reduce material waste in the case of powder bed fusion of metals [85, 145] through design for performance (e.g., generative design), reduction of material scrap and increasing the material reuse. AM is still wasteful when it comes to polymer bed fusion [146]. These characteristics may enable the supply chain managers to manufacture any part (including customized parts) in various locations and batch sizes without the need to be concerned about massive tooling costs. Jeff DeGrange, former manager of Boeing Phantom Works' Direct Manufacturing Process, once said, "One day, we will be building parts on-demand in space, on aircraft carriers and at other points of use" [26]. Moreover, researchers [49, 101] who studied AM potential application in the spare parts supply chain, had indicated the possibility of introducing distributed production utilizing this technology.

From the beginning, the possibility to produce directly from a digital design file without tooling positioned AM as a method with radical implications on supply chains.

However, technology limitations needed to be ironed out. AM was initially utilized for prototyping to significantly accelerate the pace while reducing the price of each prototype [42, 147]. However, AM technology at that stage had several severe limitations, such as low material variety, post-processing and process deficiencies which led to inaccuracies or structural weakness. In a later period, AM was used to produce master patterns (e.g., wax patterns for investment casting), molds, and soft tooling. Currently, the range of material, process accuracy, and printed parts structural integrity allow for the direct manufacturing of functional parts. In a growing number of instances, companies are replacing traditional manufacturing with AM in their operations to achieve functional and economic benefits, and some such companies include General Electric (GE), Boeing, and Phonak.

Among the early and well-publicized examples is Boeing using plastics powder bed fusion to produce air cooling ducts for the F-18 Super Hornet fighter jets. The reason for that was to meet the complex part geometries needed for the modified design [52] and the relatively small production batch size of only around 500 airplanes. GE's utilization of metal powder bed fusion for the manufacturing of fuel injectors in the new jet engine (LEAP) design has several objectives: to consolidate the parts, which would consequently reduce the cost of welding and testing and extend the product lifespan [148]. However, further potential uses were left untapped. These uses can become the source of competitiveness and cost-saving, such as broad spare parts production, product market launch, and the use of AM to enhance materials handling in an assembly line. A recent study by Jiang et al. [55] has analyzed the scenarios for the future of additive manufacturing applications. Their research recognizes the significant themes in the future of AM, and among them are the areas of production localization, spare parts provision, product development, and resource sharing. This literature review enables the gap spotting in the body of knowledge related to the substantial field of operations management and screens the research done with a forward-looking approach.

The research questions of this study are as follows;

1. What are the main categories of research in the field of AM which have an operations management perspective? What AM processes and materials are they studying?
2. Which themes are emerging at the cutting edge of research on the operations management of AM?

The remainder of this paper is structured as follows; Research method is section 2 followed by the literature analysis on "forward-looking empirical research". Section 4 presents the discussion and section 5 is conclusions.

2 Research method

The methodology used for this research is the study and review of the relevant literature. A literature review utilizes a well-defined method to identify, analyze and interpret all available research related to a specific question, area, or phenomenon of interest, to provide a way to analyze the previous works on the topic comprehensively, without a bias and in a repeatable manner.

After planning the review and setting the research questions, the execution of the plan started when we used keywords to search for articles on Google Scholar and Scopus academic search engines for publications. In the next phase, the collected articles were analyzed and the relevant ones were selected for in-depth study. In the final phase of the literature review, we synthesized the findings and reported them.

The current body of knowledge which evaluates AM from an operations management perspective is still relatively limited but growing. A broad search with keywords, additive manufacturing in operations, rapid manufacturing in supply chain, 3D printing operations management and additive manufacturing operations improvement on the Google Scholar and the Web of Science resulted in 607 articles which then were analyzed by reviewing the abstracts and picking 108 closely relevant works for the categorization. Moreover, two recent literature reviews on the AM impact and AM management [53, 62] were utilized as complementary sources. Prevalent research themes in this field of study are classified into four categories; literature review studies, backward-looking empirical studies concerned with the feasibility of AM in operations management, forward-looking conceptual studies concerned with proposing new practices while AM is utilized for production and finally, forward-looking empirical studies concerned with improvement in AM operations while it is used for functional parts production. Similarly, AM processes and materials from the studies are listed. Based on this categorization and identifying the literature gap, all the relevant articles were reviewed and assigned to one or more categories. Results of this categorization are presented in Fig. 1.

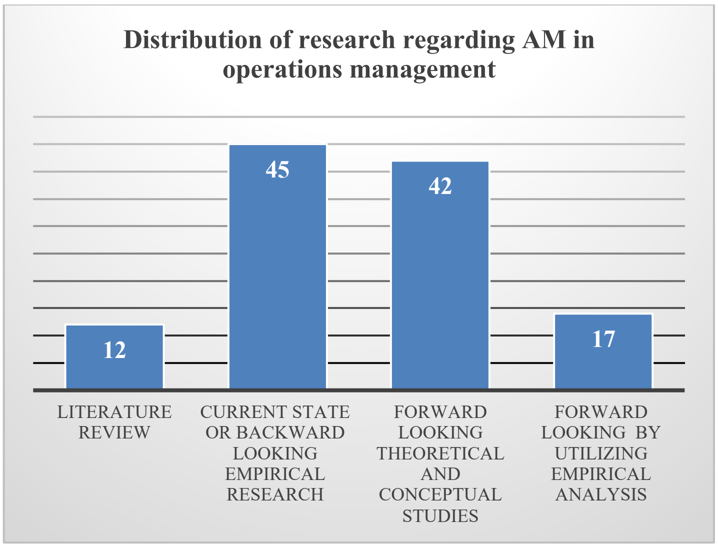

Fig. 1. Distribution of research regarding AM in operations management (more detail in Appendix)

The criteria used to classify the AM in operations management literature into the three classes of 1) Industry's current state, 2) Forward-looking studies with a conceptual approach, and 3) Forward-looking papers with empirical grounding were the following:

- Industry's Current State: Articles that study current use cases with empirical data and report the results of existing implementations are categorized under "Industry's current state."
- Forward-Looking Studies with a Conceptual Approach: Studies that do not include empirical use cases but propose future applications for AM in operations management conceptually are categorized as "Forward-looking studies with a conceptual approach."
- Forward-Looking Papers with Empirical Grounding: Articles that do not fall into the previous two classes and are not literature reviews but study a current use case and expand on that empirically through various methodologies, including simulations or scenario modeling, to empirically study the future implications of AM in operations management, are categorized as "Forward-looking papers with empirical grounding."

Articles such as Gao et al. [39], Kruth et al. [67] and Khorram Niaki, & Nonino [62], are categorized under the first column in Figure 1 as they reviewed the literature regarding the AM. Articles such as Hopkinson & Dickens [50, 51], Mansour & Hague [84], Atzeni & Salmi [5], Baumers et al. [8, 9], Mellor et al. [89], are categorized under the empirical studies in AM with a current state or backward perspectives. Articles such as Holmström & Partanen [46], Holmström et al. [48, 49], Peres & Noyes [101], Sasson & Johnson [112], Tuck & Hague [127] and Tuck et al. [128], Lehmhus et al., [75], due to their forward-looking conceptual approach towards the study of the AM, are categorized under the third column in the Figure 1.

To further clarify the forward-looking research perspective, the following example is depicted: In the spare parts supply chain, the backward-looking approach investigates the feasibility of AM utilization using the historical data to find out if the AM is feasible compared to conventional manufacturing. In contrast, the forward-looking approach goes one step further and investigates the characteristics and various operations management methods for AM implementation to achieve higher efficiency and effectiveness are. Forward-looking and empirically-based scenario research investigates a leading-edge context, considering actual supply chain settings and specific technological improvements in the short to medium term.

AM as a means for manufacturing functional parts is quite a young technology, and processes still require further improvements to make AM cost-competitive with conventional subtractive manufacturing. This consequently allows for broader applications for AM. The overall size of the AM industry in the year 2015, according to Wohlers report [139] was about $5.1 billion. Compared to the estimated $11.4 trillion total global manufacturing in the same year [124], this figure is just marginal. However, the overall size of AM industry grew to $12.8 billion in the year 2020 [140].

Moreover, the AM field is advancing, and barriers are being addressed gradually. Such barriers include material cost and range, machine costs, process reliability and repeatability, parts structural resilience and surface finish, as well as labor intensiveness of pre- and post- processes. As the barriers are addressed, the utilization increases. The annual growth rate of the AM industry over the 27 years until 2016 has been around 26% [139]. However, it had slowed to 7.5% in 2020 [140]. Still, these are considered a relatively high figure, suggesting increasing adoption of this technology.

At this point, the bulk of the body of knowledge regarding AM is focused on research concerned with technology, process, material, and design—this is evident in journals such as the Rapid Prototyping Journal and the Additive Manufacturing journal from Elsevier. Another stream of research is to compare AM and conventional manufacturing from mechanical and economic perspectives [5, 37, 110]. This emphasis is understandable, as the AM for final parts production is still in its early stages. It is still not comparable with other conventional production methods regarding the application spectrum.

However, many studies have been conducted in the context of AM applications and its enabling of new operational capabilities (such as product customization, parts consolidation, and production decentralization). These are the studies aligned with this paper's direction and provide a forward-looking perspective for operations where AM is more widely used for the production of functional parts. Research by Walter et al. [134], Tuck et al. [128] and Holmström et al., [49] were among the early works to investigate the AM impact on the manufacturing supply chain. Tuck et al. [128], discussed how AM could influence the supply chains towards leaner, more agile systems that are used to serve the customized need of the consumers.

Walter et al. [134] and Holmström et al. [49], predicted the applicability of AM to replace the inventory in aerospace spare parts supply chains. Also, Berman, [11], identified spare parts and bridge manufacturing among promising AM applications. In their book, Gibson et al. [42] refer to "electronic spare parts" as one of the main AM drivers. They also take the example of F-18 fighter jet air cooling ducts produced by AM. The concept of electronic spare parts can benefit the user not just by eliminating the need to keep the molds or stamps but also through the decentralization of production. However, these studies remained at the conceptual level.

3 Forward-looking and empirical research

Forward-looking studies that utilized empirical data to investigate AM are presented in Table 1. A detailed review is presented to pinpoint the literature gap and illustrate the areas for future research.

Table 1. Articles with forward-looking perspective using an empirical approach.

Item	Article title
1	Production planning in additive manufacturing and 3D printing [76].
2	Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030 [55].
3	Quantifying the effects of additive manufacturing on supply networks by means of a facility location-allocation model [7].
4	Implications of additive manufacturing for spare parts inventory [120].
5	Additive manufacturing of biomedical implants: A feasibility assessment via supply-chain cost analysis [35].

6	Effects of combining product-centric control and direct digital manufacturing: The case of preparing customized hose assembly kits [81].
7	E-commerce channels for additive manufacturing: an exploratory study [36].
8	Additive manufacturing in the spare parts supply chain [141].
9	The impact of additive manufacturing in the aircraft spare parts supply chain: supply chain operation reference (SCOR) model-based analysis [80].
10	Analyzing Product Lifecycle Costs for a Better Understanding of Cost Drivers in Additive Manufacturing [79].
11	Additive manufacturing for mass customization [106].
12	Rapid Manufacturing Facilitated Customization [129].
13	Cost Estimation for Rapid Manufacturing Simultaneous Production of Mixed Components Using Laser Sintering [109].
14	A Web-based Manufacturing Service System for Rapid Product Development [71].
15	Additive manufacturing as a platform for introducing cyber-physical services [59].
16	Additive Manufacturing as an Enabler of Digital Spare Parts [61].
17	Economies of collaboration in build-to-model operations [45].

3.1 Customization

Tuck et al., [129], in a case study of fighter jet pilot ejector seat customization, using stereolithography AM method, investigated the capability of rapid manufacturing for functional custom parts production. They concluded that the material used by the vat photopolymerization method was not suitable for the demanding application of the ejector seat. However, reduction in production manual operation and workforce, which is needed in traditional customized manufacturing and lack of tooling, make rapid manufacturing a new type of agile manufacturing. They also found several improvement areas in rapid manufacturing technology, such as increasing the automation of pre-production processes (e.g.: 3D scanning and design optimization) and improving AM manufacturing speed. Reeves et al., [106], in a simple case review, also studied the AM as a tool for mass customization of products by investigating cases of AM use in the production of avatars and action figures (from online and offline video games) topographic data. They have pointed out the toollessness of the AM as the profound enabler of mass customization, which lowers the cost of producing individual units. Moreover, they discussed the potential savings in packaging and transshipment costs and lower lead-time between ordering and fulfillment as the benefits of a globally distributed AM supply chain.

3.2 Decentralized production

Emelogu et al., [35] investigated the economic feasibility of AM in an in-situ production supply chain for the production of biomedical implants. They utilized a two-stage stochastic cost model to determine the number of AM facilities needed to be constructed as well as the number of implants to be ordered from AM or conventional manufacturing sites to minimize the total cost. An algorithm with an average sample approximation is used to find the solutions. Using primary data from a real-world case study, they pointed out the ratio between the unit production cost of AM and traditional manufacturing and item lead time and demand to be the key feasibility determinant parameters for AM implementation near the point of use for biomedical implant manufacturing. They recognized AM machine cost as a strong inhibitor for AM application in regional implant manufacturing at the current state of technology.

Jiang et al., [55] studied the future impact of additive manufacturing on society and the economy through scenarios based on a comprehensive Delphi survey. They conducted interviews and workshops with experts and performed a literature review to come up with 92 projections for the future of the AM in the year 2030. They narrowed down the number of projections to 18 by analyzing and combining. The 18 projections then were used in their Delphi survey. Based on their most probable scenario, in the year 2030, spare parts manufacturing of less critical parts will be done locally and by AM, while specialist conventional manufacturing hubs will produce critical parts with quality control capabilities. In the year 2030, they suggested that many AM-made parts are multi-material and/or contain embedded electronics. Also, according to their most probable scenario for the AM in the year 2030, the need to defend the intellectual property right for digital products will lead to novel practices. Moreover, they predicted that in the year 2030, critical regulatory measures would regulate AM file-sharing platforms. This study also discussed four extreme scenarios based on their Delphi survey findings.

Liu et al. [80] conducted a study investigating the AM impact on the aircraft spare parts supply chain. They utilized three scenarios to compare AM implementation in centralized and distributed settings with the current practices. They constructed the scenarios based on a case, using secondary data collected from the literature. Their findings highlighted the opportunities AM creates towards reducing spare parts safety stock in both centralized and distributed supply configurations. However, their study stopped short of providing a holistic impact projection for AM implementation in the spare parts supply chain and its feasibility.

Barz et al. [7], quantitatively compared the relationship between transportation cost and structure of a supply network for conventional subtractive manufacturing and AM. They modeled 700 two-stage capacitated facility location problem instances with seven node allocations, 25 geographical distributions, and four different buy-to-fly ratios and solved them with CPLEX mixed integer programming solver. They found that AM impact on resource efficiency through improved buy-to-fly ratios can significantly affect supply network structure while reducing raw material transportation. Moreover, they also realized AM would cause the production sites closer to the consumption locations, consequently reducing the overall transportation costs. Their study ignored all other operations costs related to machinery and material, production cycle time, and inventory.

Khajavi et al. [60], studied distributed spare parts provision as one of the three AM-enabled operations, was shown to provide additional flexibility through higher untapped production capacity compared to centralized production of spare parts. However, achieving a fully distributed implementation of AM is not feasible, even in the aerospace sector where downtime costs are exceedingly high, unless there is an increase in pre- and post-production autonomy and the ability to customize the production chamber size for the application. Additionally, AM machines need to become faster and cheaper.

3.3 Inventory replacement

Wullms [141] studied the use of AM to replace the last time buy (to support the products in the last phase of the lifecycle when the manufacturing is to stop) for a selected number of parts in the Philips healthcare product portfolio. Wullms [141] found that in all cases, AM offers cost-saving over last time buy (which requires the storage of safety stock) due to the reduction of the parts inventory. Moreover, he pointed out the sensitivity of the results to the cost of additive manufacturing compared to traditional manufacturing. AM implementation will not lead to savings if AM is 10 times more expensive than traditional manufacturing.

Khajavi et al., [61], studies the replacement of physical spare part inventories by digital ones using the data collected from two large manufacturing companies. They conclude that a small percentage of spare parts are technically and economically viable for digitalization.

3.4 Product lifecycle

In their paper, Lindemann et al. [79] proposed an analysis of AM cost drivers from a lifecycle perspective. They argued that since AM is a toolless method that enables design for performance (through complexity for free), it should be compared with conventional manufacturing methods based on product lifecycle and not just the build cost. They utilized an experimental production case by a metal AM machine to analyze the production cost breakdown. They concluded that AM machine cost is the biggest cost factor in the AM part production, followed by material cost and post-processing activities.

Khajavi et al., [59] investigated the benefits of integrating all the data required throughout a product lifecycle to the digital design of the part. They pointed out the benefits throughout the different phases of the lifecycle. In another large case study, Hedenstierna et al, [45] point out the economies of build-to-model production mode for products enabled by direct digital manufacturing.

3.5 Material handling

Ruffo and Hague [109] performed a case study and showed the economic gains in lower production costs from mixing parts (in the production chamber) for laser sintering additive manufacturing. Moreover, they introduced a method for the cost assignment to various parts in mixed production. Li et al. [76] studied the production planning and scheduling of parts on different AM machines with different specifications and distinct part geometries to minimize the average production cost per volume. They mathematically modeled the problem and solved it using CPLEX. They also developed two different heuristics for the problem. They tested against the optimum solution using a numerical example to illustrate the high quality of results provided by the heuristic methods. They also illustrated the possibility of reducing production costs by better planning the parts in the AM machines' chambers.

Lyly-Yrjänäinen et al., [81] utilized a case study of customized industrial hydraulic hose production to investigate the impact of production digitalization and product-centric control on manufacturing operation. Their findings pointed to waste reduction, simplification of production planning and better customer responsiveness. The case company utilizes a direct digital manufacturing method where the digital model of the hose plays a significant role in labor productivity and delivery performance. Digital models of customized hoses are received from the clients, including the bill of material (BOM) specifying the hose length and diameter and the required straight or 90 degrees fittings. The case company keeps the hoses and fittings used by its clients. It does not initiate production until they receive an order. When they receive an order, the manufacturing cells that are equipped with digitally controlled cutting machines cut the hoses based on the order and kit number and print the work-order information on each hose, specifying the required fitting and the kit, order and other relevant information. Through the implementation of such direct digital manufacturing (DDM) process and integration of work-order data to the product (product-centric control), the case company improved the labor productivity by threefold in comparison with conventional methods of hose making used by its competitors while simplifying control and eliminating batch production, handling of batches and inventory management. Moreover, Lyly-Yrjänäinen et al. [81] suggested their research findings could be transferable to other cases, where DDM technology is generic for the production of required products and sharing the digital product model can replace product master data.

3.6 New product development

Lan et al. [71] explored the functionality of an Internet-based manufacturing service system with embedded AM for product development. They utilized a simple case study to illustrate the benefits of such a system. Findings suggested an online AM-based new product development system can cut the costs by 50% while also shortening the go-to-market time by 75%, compared to traditional methods. Eyers & Potter [36], utilized design science methodology in conjunction with interviews and secondary data to propose a framework of four distinct e-commerce channels for AM. Tele-marketing, collaborative manufacturing, localized manufacturing, and user manufacturing are the four e-commerce models discussed in their framework.

Khajavi et al. [149], studied hybrid manufacturing for the market launch phase of new product development. In hybrid production, the model-based direct digital manufacturing (e.g.: AM or incremental sheet forming) is utilized in the beginning when the demand volume is low and then a switch over to conventional manufacturing takes place as the volumes pick up. However, the right decision on the timing of the switchover is essential to keep the production cost and the risk of losses (in the event of product launch failure) low. A heuristic method to balance the risk and cost of new product launches while utilizing hybrid manufacturing was developed to consider different launch outcomes.

3.7 AM processes considered

ISO and ASTM categorize AM process into seven different classes: Material extrusion (MEX), Powder bed fusion (PBF), VAT photopolymerization (VPP), Directed energy deposition (DED), Material jetting (MJ), Binder jetting (BJ) and Sheet lamination (SL). Figure 2 illustrates the frequency of appearance of each AM process in the papers studied and related to the operations management literature. Some studies do not specify particular AM processes, and reviews and general descriptions of AM processes were excluded. The focus was on case studies and research specially addressing individual AM processes. It is evident that the most extensively studied processes are PBF, VPP and MEX. Studies on DED, MJ, BJ and SL are also available, albeit less frequently. This closely reflects the frequency of processes used in production. None of the studies examine composite materials recently developed using continuous fibers with the MEX method.

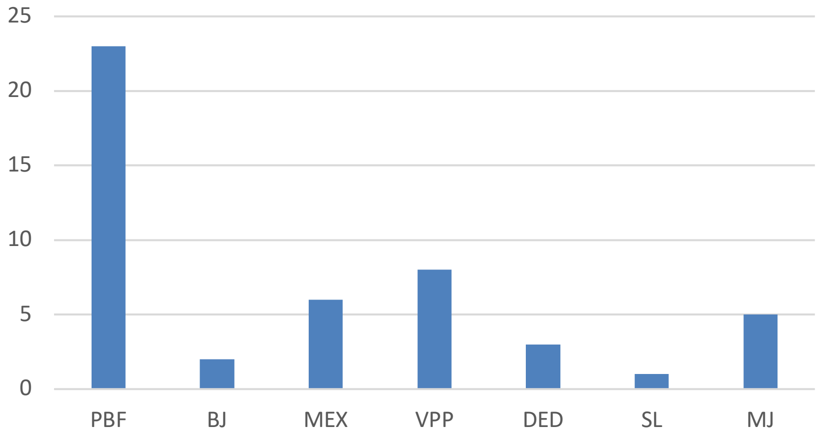

Fig. 2. Distribution of different AM processes in the operations management literature (more detail in Appendix)

4 Discussion

At this state, quite expectedly, the central part of the body of knowledge regarding AM is focused on research concerned with technology, process, material and design (Journals such as Rapid Prototyping Journal and Additive Manufacturing journal from Elsevier) as well as comparing AM and conventional manufacturing from mechanical and economic perspectives [5, 37, 110]. That is understandable, as the AM is an emerging technology and has not been yet fully established on a scale comparable to other conventional production methods. However, many studies have been conducted in the context of AM applications and their impact through enabling various capabilities (such as product customization, parts consolidation, and production decentralization). These are the studies aligned with this paper's direction and provide a forward-looking perspective for the AM while it is used for the production of functional parts.

One crucial thing in operations management research of AM is the lack of an actual AM process. AM studied as one common technique, even though there are significant differences inside same the category such as no supports required in powder bed fusion of plastics compared that metal with same processes requires heavy supports and support removal in the post-processing phase. In the future, more technology-related aspects should be taken into account and more focused case studies investigated.

5 Conclusions

This literature study contributed to the operations management of additive manufacturing by illustrating the under-researched areas. An in-depth categorization of the current AM literature related to operations management is presented.

As it stands, there are still a number of major technological challenges to be addressed in the field of AM. Such challenges include machine throughput, price, chamber size, process repeatability, reliability and standardization, material cost and requirements, intellectual property rights of digital design files, automation in the pre- and post-production processes, as well as digital model file formats. These areas need to be addressed in order to have AM prepared for wider mainstream applications [18, 150, 151]. However, this research was primarily motivated by an unfolding trend towards the utilization of AM to produce functional parts. As this utilization expands, practices aimed at enhancing AM-enabled operations are likely to become increasingly important. The aim and objective of this research are to facilitate the development of AM operations management.

Appendix

Categorization of AM literature;

Category 0: Literature review

Category 1: Current state or backward-looking empirical research (concerned with the comparison of AM with conventional manufacturing form cost or engineering perspectives)

Category 2: Forward-looking theoretical and conceptual studies

Category 3: Forward-looking (to the future when AM is used for functional parts) by utilizing empirical analysis (including the experimentation and simulations)

Table 2. The list and the classification of the reviewed articles

		Category				Additive manufacturing	
Item	**Article**	**0**	**1**	**2**	**3**	**Processes**	**Materials**
1	Achillas et al., (2015)		X				

2	Anthony et al., (2011)		X	X		PBF, BJ	steel
3	Armillotta, (2008)		X				
4	Attaran, (2017)			X			
5	Atzeni, and Salmi, (2012)		X			PBF	aluminium
6	Sherman, (2009)		X				
7	Bals et al., (2015)			X			
8	Barz, et al., (2016)				X		
9	Baumers, et al., (2013)		X			PBF	steel
10	Baumers, et al., (2016)		X			PBF	titanium, steel
11	Berman, (2012)			X			
12	Beyer, (2014)			X			
13	Bianchi, & Åhlström, (2014)			X			
14	Birtchnell, and Urry, (2013)			X		MEX	ABS, PLA
15	Bogers et al. (2016)			X			
16	Byun, & Lee, (2005)		X			PBF	steel
17	Campbell, & Ivanova, (2013)			X			
18	Campbell et al., (2011)			X			
19	Chen et al., (2015)		X				
20	Christopher, & Ryals, (2014)			X			
21	Deradjat, & Minshall, (2015)		X				
22	Despeisse et al., (2017)			X		MEX	HIPS, PET, PLA
23	Di Angelo, and Di Stefano, (2011)		X				
24	Drizo, and Pegna, (2006)	X					
25	Emelogu et al., (2016)				X	PBF	
26	Eyers, & Potter, (2015)				X		
27	Gao et al., (2015)	X					
28	Gibson, (2017)			X			
29	Hanumaiah et al., (2006)		X			PBF, VPP	Cu-Ni-Sn, photopolymer
30	Hasan et al., (2008)			X		PBF	Nylon
31	Holmström, & Partanen, (2014)			X		PBF	
32	Holmström et al., (2017)			X			

33	Holmström et al., (2010)			X			
34	Hopkinson, & Dickens, (2001)		X			VPP	
35	Hopkinson, & Dicknes, (2003)		X			VPP, MEX, PBF	Epoxy, ABS, Nylon
36	Huang et al., (2013)	X					
37	Jiang et al., (2017)			X	X		
38	Jonsson, & Holmström, (2016)			X			
39	Kellens et al., (2010)		X			PBF	Steel, PA2200
40	Kengpol, & O'Brien, (2001)		X				
41	Khorram Niaki, & Nonino, (2017)	X					
42	Khrais et al., (2011)		X				
43	Kietzmann et al., (2015)			X			
44	Kochan et al., (1999)			X			
45	Kohtala, (2015)	X					
46	Kruth et al., (1998)	X					
47	Lachmayer et al., (2017)		X			PBF	ABS
48	Lan, (2009)	X					
49	Lan et al., (2005)		X			PBF, VPP	
50	Lan et al., (2004)				X		
51	Lan et al., (2008)		X			VPP	HXJ-971
52	Laplume et al., (2016)			X			
53	Le Bourhis et al., (2013)		X			DED	
54	Lehmhus et al., (2015)			X			
55	Li et al., (2017)				X	PBF	
56	Liao et al., (2014)		X				
57	Lindemann et al., (2012)				X	PBF	steel
58	Lindemann et al., (2015)		X				
59	Liu et al., (2014)		X		X	PBF	
60	Lyly-Yrjänäinen et al., (2016)				X		
61	Mahapatra, and Panda, (2013)		X				
62	Manogharan et al., (2016)		X			PBF	titanium
63	Mansour, and Hague, (2003)		X				

64	Mashhadi et al., (2015)			X			
65	Masood, and Soo, (2002)		X				
66	Masood, and Al-Alawi, (2002)		X				
67	Mellor et al., (2014)		X				
68	Mognol et al., (2006)		X			MJ, MEX, PBF	Wax, ABS
69	Mohajeri et al., (2014)			X			
70	Mohr, & Khan, (2015a)			X			
71	Mohr, & Khan, (2015b)			X			
72	Moore et al., (2016)		X			MJ	RGD8430
73	Munguía et al., (2010)		X				
74	Nyman, & Sarlin, (2014)			X			
75	Oettmeier, & Hofmann, (2017)		X				
76	Pal et al., (2007)		X			MEX, MJ, VPP, SL	ABS, Polycarbonate, epoxy resin, wax, paper
77	Paul, and Anand, (2012)		X			PBF	
78	Pearce et al., (2010)			X			
79	Pérès, & Noyes, (2006)			X			
80	Petrick, & Simpson, (2013)			X			
81	Pour et al., (2016)	X		X			
82	Rao, and Padmanabhan, (2007)		X				
83	Reeves, (2008)			X			
84	Reeves et al., (2011)				X		
85	Rickenbacher et al., (2013)		X			PBF	
86	Roberson et al., (2013)		X			MEX, VPP, SL	ABS, PLA, PVC, photopolymer
87	Ruffo, and Hague, (2007)				X	PBF	Polyamide
88	Rylands et al., (2015)	X					
89	Sasson, & Johnson, (2016)			X			
90	Sealy, (2012)			X			
91	Sharif Ullah et al., (2013)		X			VPP	Photopolymer

92	Sirichakwal, & Conner, (2016)				X		
93	Thomas, & Gilbert, (2014)	X					
94	Thompson et al., (2016)	X					
95	Tuck, and Hague, (2006)			X			
96	Tuck et al., (2006)			X			
97	Tuck et al., (2008)				X	VPP	
98	Tuomi, Karjalainen, (2006)		X			PBF	
99	Uriondo et al., (2015)	X					
100	Waller, & Fawcett, (2014)			X			
101	Walter et al., (2004)			X			
102	Weller et al., (2015)			X			
103	Vinodh et al., (2009)		X			SL	PVC
104	Witherell et al., (2017)			X			
105	Wullms et al., (2014)				X		
106	Xu et al., (2015)		X			BJ	
107	Yoon et al., (2014)		X			PBF, MEX, VPP	
108	Zanardini et al., (2016)		X	X			

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