Chekurov, Sergei; Metsä-Kortelainen, Sini; Salmi, Mika; Roda, Irene; Jussila, Ari

The perceived value of additively manufactured digital spare parts in industry

Published in:
International Journal of Production Economics

DOI:
10.1016/j.ijpe.2018.09.008

Published: 01/11/2018

Document Version
Publisher's PDF, also known as Version of record

International Journal of Production Economics 205 (2018) 87–97

Contents lists available at ScienceDirect

International Journal of Production Economics

journal homepage: www.elsevier.com/locate/ijpe

The perceived value of additively manufactured digital spare parts in industry: An empirical investigation

Sergei Chekurov[a,*], Sini Metsä-Kortelainen[b], Mika Salmi[a], Irene Roda[c], Ari Jussila[b]

[a] Aalto University, School of Engineering, Department of Mechanical Engineering, Production Technology, Otakaari 1, 02150, Espoo, Finland
[b] VTT Technical Research Centre of Finland Ltd., P.O. Box 1000, FI-02044, VTT, Finland
[c] Politecnico di Milano, Department of Management, Economics and Industrial Engineering, Via Lambruschini 4/b, 20156, Milano, Italy

ARTICLE INFO

Keywords:
Spare parts
Digital manufacturing
Additive manufacturing
Supply network management
Distributed manufacturing
3D printing

ABSTRACT

The purpose of this paper is to verify the conceptual benefits of the implementation of additive manufacturing (AM) in spare part supply chains from the point of view of industry. Focus group interviews consisting of five sessions and 46 experts in manufacturing were conducted for this study. The focus group interviews served to identify the issues in the adoption of digital spare parts (DSP) and to expand on the available literature. The benefits found in the reviewed literature were partially verified by the participants but certain limitations, such as the excessive need of post processing, supplier quality parity, and ICT inadequacies, were presented that were absent or not highlighted in literature. The information gathered from the participants made it possible to create a realistic model of a digital spare part distribution network. According to the focus group interviews, digital spare parts could be deployed immediately for a specific type of product in the long tails of company spare part catalogues. However, improvements in AM, company ICT infrastructure, and 3D model file formats need to be achieved for a larger deployment of DSP.

1. Introduction

Additive manufacturing (AM) has certain advantages over traditional manufacturing in that it allows for viable lot-one-size production because no tooling and minimal set-up time are needed (Mellor et al., 2014). Therefore, the additional costs of part complexity and variability are significantly lower than in traditional manufacturing and the total delivery time for AM is typically shorter (Simhambhatla and Karunakaran, 2015; Weller et al., 2015). Another major benefit of AM is that, compared to subtractive manufacturing, the expertise needed to operate AM machinery is more easily transferable between product types. (Jonsson and Holmström, 2016).

While AM was originally used to produce prototypes, it is now used increasingly for industrial end-use applications (Kellens et al., 2017). The increase in end-use applications is also observed in the annual AM global report produced by Wohlers Associates, in which they report that, in 2012, 28.1% of all additively manufactured objects were functional parts, while in 2016 the respective percentage was 33.8% (Wohlers, 2013, 2017). In addition to the growth of the relative percentage, the absolute number of produced end-use parts has grown greatly, because the worldwide revenue of AM products and services grew from $2.25 billion in 2012 to $6.05 billion in 2016 (Wohlers, 2017). However, Schniederjans (2017) reported that only 10% of the companies they interviewed use AM to produce end-use parts. Since the percentage given by Wohlers is calculated from the total amount of additively manufactured parts, it follows that although few companies use AM for end-use production, they use it to produce parts in large quantities.

With the fact that end-use components can now be created with AM in mind, several researchers have presented that spare parts could be digitized and additively manufactured. This article aims to validate the results of the researchers by analysing the results of focus groups and to define the concept of AM of spare parts.

1.1. Advantages of additive manufacturing in the supply chain

It has long been hypothesized that implementing AM in supply chains would lead to significant benefits, to the point that AM has been likened to the internet in its ability to cause a paradigm shift (Holmström and Partanen, 2014). Pérès and Noyes were some of the first researchers to suggest implementing AM in supply chains in order to manufacture spare parts closer to the point of need (Pérès and Noyes, 2006). They presented several avenues of research to verify the potential of the concept: research into technical features of spare parts

* Corresponding author.
E-mail address: sergei.chekurov@aalto.fi (S. Chekurov).

https://doi.org/10.1016/j.ijpe.2018.09.008
Received 3 July 2017; Received in revised form 2 September 2018; Accepted 7 September 2018
Available online 10 September 2018

(materials, tolerance, life cycle etc.), organisational features (logistics, storage, recycling etc.), and economical features (total cost of spare part). These research questions have been investigated extensively in recent literature (Mellor et al., 2014; Lindemann et al., 2015; Lyly-yrjänäinen et al., 2016; Oettmeier and Hofmann, 2016; Rylands et al., 2016).

Some of the benefits of introducing AM in a supply network include reduced changeover time (Tuck et al., 2007), decreased energy costs (Gebler et al., 2014), and increased sustainability (Kothman and Faber, 2016). Another trend in the research concerning AM in supply chains is exploring what the role of the customer could be in the process. With the emergence of AM, the customer could potentially have control over the design and production of components alone or in collaboration with the company whose product is being redesigned. This type of consumers are referred to in literature as prosumers (Fox and Li, 2012; Rayna and Striukova, 2016; Rylands et al., 2016).

Pérès and Noyes noted in 2006 that AM was too limited to produce end-use components. While there has been significant improvement in the technologies since then, as is implied also by the growth of end-use part manufacturing according to Wohlers associates, there are still severe limitations. For example, the viable maximum part size in AM is smaller than is desirable when manufacturing precise components (Gausemeier et al., 2012), the price of material for AM is higher than in conventional manufacturing (Scott and Harrison, 2015), the cost of AM systems is high (Thomas, 2016), and the material selection in AM is quite limited when taking into account the needs of companies from different sectors (Singh et al., 2017). Additionally, materials must be approved for certain applications, which must be done to every single material (Gray et al., 2017). For the strictest applications, each manufactured material batch requires verification of quality (Portolés et al., 2016). A thorough list of barriers to progression of AM for end-use products as perceived by industry has been collected and published by Thomas-Seale et al. (2018).

Although there are still clear limitations, AM technology has advanced enough to be a viable manufacturing method for end-use components in certain applications (Lindemann et al., 2015). With the notion that components could be moved digitally and produced locally, the question of piracy has been brought up by Lindemann et al. (2015) and Appleyard (2015), who present two opposing views. While Lindemann et al. present that protecting the 3D designs to deter their copying is the right approach Appleyard argues that companies might need to change their approach to spare part distribution to be more open.

1.2. Potential of AM in spare part management

Spare part management is a vital part of many capital-intensive businesses having direct impact on the availability of high-value capital assets, essential to the operational processes (Driessen et al., 2015; Behfard et al., 2018). In fact, unavailability of a spare part item when needed may lead to long unproductive downtimes affecting the operating company's profit (Sarker and Haque, 2000). Given the general function of spare parts to support maintenance activities, the policies that govern the spare parts inventories are different from those that govern other types of inventory such as raw material, work-in-process and finished goods inventories (Kennedy et al., 2002; Molenaers et al., 2012; Roda et al., 2014). Specifically, two of the main critical issues when managing spare parts are the high uncertainty about when a part is required and about the quantity of its requirement that derives from the unpredictability of failures occurrence. These are also the reasons explaining why the level of spare parts inventory kept by companies is usually very high in order to try to avoid risk of unavailability, leading to high inventory holding cost (Ledwoch et al., 2018). Moreover, sourcing of spare parts is often limited to one or a few suppliers, causing constraints for the procurement lead time and the costs; or in the opposite case of multiple sourcing, the related risk of the variations of the quality of supplied materials can incur. Obsolescence may also be a problem; indeed, it is difficult to determine how many units of a spare part item to stock for an obsolescent machine (Kennedy et al., 2002; Roda et al., 2014; Driessen et al., 2015). All these challenges opened the path in the scientific literature to the investigation on spare parts integrated inventory management (Kennedy et al., 2002; Cavalieri et al., 2008) and on spare parts supply chain management (Huiskonen, 2001; Kennedy et al., 2002; Martin et al., 2010; Driessen et al., 2015; Zanjani et al., 2014; Driessen et al., 2015, 2015). Moreover, the relevance of studying the AM technology's impact on these topics is evident because the key challenge in spare part management is to maintain high spare part availability with low cost. AM can be of aid in this issue as producing spare parts by AM can lower inventory stock while maintaining a good level of stock out avoidance (Khajavi et al., 2014). Sasson and Johnson (2016) reported that AM can be beneficial in the production of spare parts belonging to the long tail, which Anderson (2006) describes as the majority part of a company's inventory that consists of items with a low demand. Such spare parts include, for example, products that are in a purely after sales stage of their life cycle such as discontinued consumer products, retired machinery, and antique elevators (Liu et al., 2014).

2. Development of the digital spare parts concept

Several studies have specifically paid attention to the potentialities of AM technology in the context of spare parts supply chain to reduce the size of central and local storages, eliminate the need to locate uncommon spare parts in the distribution network, and diminish the duration and cost of logistics (Walter et al., 2004). The concept of spare part production using AM has been investigated by numerous researchers. The main studies specifically focusing on AM and spare part management along with their key findings and identified obstacles of DSP deployment are collected in Table 1.

The studies on AM in supply chain and the digital spare part (DSP) concept shown in Table 1 present an increased value to practitioners in industries that produce or use spare parts. However, although the findings in the body of research of spare part production by AM are generally positive, in reality very few companies implement digital spare parts in their supply chain operations. There is an evident research gap between why the results of the research are so positive and why it is yet to achieve a notable status in the field of maintenance management.

This study attempts to investigate how industrial practitioners perceive the value of DSP proposed by the researchers and to verify whether the results of the body of research are realistic or attractive to the companies that would benefit from the application of this technology. To reach the research objective, the interest of companies needed to be gauged together with understanding if there are relevant limitations for AM of spare parts diffusion in industry. The research was guided by the following research questions:

RQ1: How do industrial practitioners perceive the value of the DSP concept?

RQ2: What are the main advantages and criticalities of the DSP implementation in the perception of industrial partners?

To this end, focus group interviews were conducted with the representatives of industry to verify if their opinions line up with the implementation of AM in spare part supply chains brought up in the literature in sections 1.1 and 1.2.

Another goal of this study, in addition to answering the research questions, was to refine the concept of DSP. From a methodological point of view, the focal concept was created according to Podaskoff's (Podsakoff et al., 2016) stages for developing good conceptual definitions. According to the first stage of the methodology, potential attributes have to be identified by collecting a representative set of definitions. Therefore, relevant literature was surveyed for what other researchers consider critical to the definition of DSP. The potential attributes of other researchers' works have been collected in Table 2 in

Table 1
Description of studies connecting AM and spare part management and their findings and identified obstacles of DSP deployment.

Authors	Description of study	Key findings	Obstacles of DSP deployment
(Walter et al., 2004)	Introduced the concepts of distributed manufacturing of spare parts through AM	Concept of distributed manufacturing	The general cost of AM is high
(Pérès and Noyes, 2006)	Described on a conceptual level the use of AM in delivering spare parts to isolated locations	Concept of delivering spare parts to isolated locations digitally	AM is not suitable for end-use applications because of technical limitations
(Holmström et al., 2010)	Compares on a conceptual level centralized and distributed AM spare part manufacturing	Centralized AM more likely to be used than distributed at the beginning	Quality of parts cannot be guaranteed
(Liu et al., 2014)	Simulated supply chains with and without AM for six different aircraft parts	Lower safety inventory	The general cost of AM is high
(Khajavi et al., 2014)	An aircraft spare part scenario analysis study that demonstrated that introducing AM in the supply chain reduced transportation costs, inventory costs, and part obsolescence costs	Reduced transportation costs Reduced inventory costs Reduced part obsolescence cost	Level of automation of AM is low; cost of AM machinery is high; AM machinery is slow
(Knofius et al., 2016)	Developed a methodology to identify which spare parts would benefit from being additively manufactured	Identified more than 1000 positive business cases of AM in service logistics	Quality and availability of spare parts product data varies
(Li et al., 2016)	Theoretical comparison between simulated AM-based and conventional supply chains	Reduced transportation costs	The cost of AM equipment is high
(Sasson and Johnson, 2016)	Explores a rollout scenario of AM in a supply chain and qualitatively evaluates supply chain reconfigurations	Increased costs of AM spare parts can be justified by downtime reduction	AM material costs are high
(Sirichakwal and Conner, 2016)	Analysed inventory-related benefits with a simulation.	Reduced lead time Reduced holding cost Reduced stock-out risk	Qualification and certification is needed for spare part production
(Chekurov and Salmi, 2017)	Conducted a case study by simulating inserting AM in a consumer electronics warranty repair network	Reduced total repair time	AM machinery is slow

the manner demonstrated by Maynes and Podsakoff (2014). To explore further the concept of DSP, the attributes of Table 2 were also subjected to a focus group study, as suggested by the first stage of the Podsakoff methodology (Podsakoff et al., 2016).

In the second stage of the methodology, the attributes need to be condensed into a reduced list and the sufficiency and necessity of the attributes needs to be established. The necessity of an attribute for a concept in this case means that the attribute is necessary to define the concept, and the sufficiency means that a combination of attributes is sufficient to distinguish a concept from another. The key attributes of DSP from the literature were compared to the ones discovered in the focus groups to get the overlapping attributes. The remaining attributes were given a designation and evaluated for necessity and sufficiency for DSP, traditionally produced spare parts, and additively manufactured parts.

3. Methodology

A focus group is a form of qualitative research in which groups of individuals composed of selected backgrounds are interviewed simultaneously. A focus group approach was chosen to conduct this research because it allows to probe deeper than quantitative methods and allows for the pursuit of new and emerging ideas (Morgan, 1988).

Conducting focus group interviews is an accepted tool in management research to gauge the interest of company leaders in future possibilities (Flynn, 1990). As focus group interviews are designed to challenge assumptions, they are a good instrument in determining the perceived value of research concepts in real life applications (Greenbaum, 1998; Fern, 2001; Puchta and Potter, 2005; Barbour, 2007).

A series of semi-structured focus group interviews were organized in Espoo, Finland in April 2016, in which 46 individuals from 34 companies and institutions participated. The recruitment of the participants was carried out by public invitation on the websites of the hosting organizations and national industrial mailing lists. Heterogeneity in the length of work experience, company types and sectors was sought and therefore no restrictions were set on who could participate, as long as they were professionals working in the field related to manufacturing. The participants were not compensated for their participation.

3.1. Demographic information about participants

The participants of the focus group interviews were experts in the field of manufacturing and familiar with the principles of AM. The companies involved were original equipment manufacturers (OEMs), manufacturing subcontractors (MSCs), AM service providers (AMSPs) and software developers (AMSDs), and national institutes (NIs). The number of participants ranged between 8 and 11 in each focus group.

Table 2
Summary of attributes of digital spare parts in literature.

Study	Conceptualization of digital spare parts	Key Attributes
Pérès and Noyes (2006)	• "In order to shorten the time of immobilisation of a system having to be repaired, it is essential to have whatever the place and at any time the part needed to replace the one, which has failed."	• Delivered to replace a defective component
	• "… to be able to create, on demand and in situ, the part required to proceed to the maintenance intervention."	• Manufactured on site
	• "… a distant preparation of the digital files built from the CAD data for the optimisation of the part positioning …"	• Parts built from CAD data
	• "… a transfer of digital data through adapted networks …"	• Production data transferred by network
Holmström et al. (2010)	• "… on demand and centralized production of spare parts is proposed as the most likely approach to succeed."	• Can use centralized manufacturing
	• "… if RM [Rapid Manufacturing] technology develops into a general purpose technology the distributed approach becomes more feasible."	• Can use distributed manufacturing

Table 3
Focus group participant characteristics.

	AM service provider (n = 7)	AM software developer (n = 2)	Manufacturing subcontractor (n = 9)	National institute (n = 3)	OEM (n = 22)	Other (n = 3)	Total (n = 46)
Work experience in years							
< 5	1	0	1	1	4	1	**8**
5–10	2	0	2	0	5	0	**9**
10–15	2	2	1	1	4	0	**10**
15–20	0	0	3	0	4	2	**9**
20–25	0	0	2	0	3	0	**5**
> 25	2	0	0	1	2	0	**5**
Position in company							
Specialist	0	0	2	2	9	1	**14**
First-line management	0	0	3	1	4	0	**8**
Middle management	1	1	0	0	6	1	**9**
Top management	6	1	4	0	3	1	**15**

Table 4
Semi-structured questioning routine used in the focus group interviews.

Theme	Question	Relevant literature
Theme 1: Current status of spare parts management	1. What are the biggest problems with spare part production and logistics?	(Kennedy et al., 2002; Driessen et al., 2015)
Theme 2: Digitization of spare parts, new possibilities	2. What type of products will benefit from being additively manufactured?	(Knofius et al., 2016)
	3. What percentage of spare parts can be additively manufactured?	(Knofius et al., 2016)
	4. What do you think of the possibilities of digitizing existing spare parts?	(Khajavi et al., 2014)
	5. What are the obstacles in digitizing spare parts?	(Knofius et al., 2016)
	6. What kind of changes will digital spare parts bring to the service functions of a company?	(Liu et al., 2014; Li et al., 2016)
	7. Should spare part production become more open or should it stay locked to the OEM?	(Appleyard, 2015; Lindemann et al., 2015)
Theme 3: Digital spare part network and its requirements	8. What type of actors and skills are needed?	(Holmström et al., 2010)
	9. What could be the position of your company in the new paradigm?	(Holmström et al., 2010)
	10. What action is required from the companies and governmental institutions?	(Holmström et al., 2010)
	11. Is it realistic to create a DSP network?	(Holmström et al., 2010)
	12. What kind of data issues might arise?	(Appleyard, 2015; Lindemann et al., 2015)

The work experience and position in company of participants is shown in Table 3 and the complete demographic information is given in the appendix.

All AM service providers that participated in the focus groups have B2B and B2C approaches and the AM software developers support the interaction between OEMs and AM service providers. The manufacturing subcontractors were traditional engineering companies mostly specializing in metal components. The participating national institutes were the national standardization agency and the national innovation agency. Due to the prevalent sectors in the Finnish industry, the present OEMs were mostly manufacturers of large industrial machinery. These OEMs are perfectly positioned to leverage the benefits of DSP because they not only manufacture equipment but also have extensive service operations for the maintenance of their own and their competitors' products.

> *"We divide our business in two – do we need them (spare parts) ourselves or do we sell them to our customers – these are two very different business models."* (G5, OEM)

The distribution of the participants' years of experience is wide and the median is 15 years. The distribution is shown in five-year increments in experience in Table 3. The average work experience did not differ significantly between the types of company. There was a much bigger discrepancy in positions within the company when comparing the different company types. The participants from AM service providers and software developers were mostly from high in the company hierarchy, while the participants from national institutes were specialists or first-line managers. The participants from the other company types were quite evenly distributed. The reason why AM companies had an uneven distribution in the company positions is that they are limited in size, and therefore the top management tends to the operational side of business.

3.2. Organization of the focus groups

In a manner suggested by the focus group interviews of Angell and Klassen (1999), the participants were collectively given a short introduction to the general concept of DSP before being divided into groups. The participants were divided into five groups with the consideration that no group should have two individuals from the same company. Two researchers with extensive knowledge of the topic moderated a session of each group. In total, ten researchers participated in the focus group moderation. One of the researchers in each group was chosen to be the facilitator, while the second researcher was left in charge of taking continuous notes. The sessions included extensive written tasks that could not be recorded via audio and therefore the second researcher was strictly relegated as a secretary.

Each group received the same pre-defined questioning routine to facilitate the direction of discussions and to make the results of different group interviews comparable with one another. The questions were based on literature and composed jointly during a meeting of the ten moderators. The semi-structured question routine along with references that inspired each question can be seen in Table 4.

The data were collected through a four-step process. The participants were first given a task (e.g. "Write down the problems with digitization of spare parts from the point of view of your company."), which they were to complete on their own and for which they were allocated a specific amount of time. In the second step, time was given to compare the notes internally in small groups that were created spontaneously. The third step consisted of synthesizing the acquired data in smaller groups. Finally, in the fourth step, the groups presented their views, which were then open to discussion. These views were then recorded without critical evaluation. The focus group sessions were conducted simultaneously and the duration of each session was 2 h.

3.3. Data parsing

The data collected from the focus groups consisted of notes written down by the secretaries and the written material produced by the participants. The moderator and secretary made a summary of the interviews shortly after their end to ensure that the text were representative of the actual views and opinions of the participants. The content was codified by one of the moderators using what Campbell et al. (2013) call the "free coding approach" according to the codes that emerged inductively when analysing the collected data. The final codes were:

- Problems in spare parts management
- New possibilities of digitization of spare parts
- Obstacles in digitization of spare parts
- Description of required properties of digital spare parts
- Description of a digital spare parts network
- Factors that facilitate the development of a digital spare parts network

Because the participants were professionals discussing the subject of their work, and because the subject field was narrow, the codes were limited and clearly identifiable. To synthesize, the results were cross-referenced and summarized as one. The summaries of the interviews were compared and analysed by all ten moderators together.

4. Results

In this section, the data collected from the focus group interviews are introduced systematically. The points of view of the participants are presented according to the codes and accompanied by particularly relevant quotations.

4.1. Problems in spare parts management

During the interviews, three aspects of spare parts management were mentioned most often. First, the participants felt that the availability of spare parts is a crucial problem because getting a replacement can take long in unexpected cases and rare components have long delivery times.

"In the worst case getting components can take months. Just getting the raw material for the component can take up to twelve months if it is a special material." (G1, OEM)

"Certain sizes of bearings are only manufactured once per year. If the batch is sold out, you have to wait a year." (G1, OEM)

Second, the participants emphasized that they would be ready to pay a lot of money for a spare part to avoid unexpected and lengthy process inactivity caused by part failure. In addition to the loss of productivity due to stock-outs, the risk of downtime causes large spare parts inventories, high storage expenditure and idleness of assets and the most critical parts are kept in smaller inventories around the world.

"The cost is secondary because the downtime of a process is the worst case scenario. We need large warehouses, which makes our assets idle. The customers have their own storages for critical components and would be willing to pay to eliminate them." (G1, OEM)

Third, the propensity of employees to commit costly mistakes when hurrying while attempting to fix machinery was mentioned often. Employees try to compensate for long delivery times by hurrying, which leads to mistakes or to ordering entire new products instead of spare parts.

"Rushing and scrambling inevitably leads to mistakes." (G3, OEM)

Other often-mentioned issues included that the inventories are especially big when considering long tail products and that minimum order quantities are too big when only one part is needed.

4.2. New possibilities of digitization of spare parts

Data from the focus groups suggest that there has been enough previous interest among the participants concerning the concept of digitization of spare parts to generate their own ideas of new delivery models and sum them up concisely.

"Someone presses a button here, the printer starts over there and then the data disappears from there." (G3, OEM)

The concept of customers participating in the creation and manufacturing of spare parts was brought up often in groups 2 and 4 but not in the others. The participants in these groups theorized that industrial design could benefit from becoming open source to leverage the community of designers. The digitization of spare parts also raised questions about how the laws and rules of the physical world will apply for example regarding customs clearance.

"You will be able to *make a lot of money by 3D modelling from home."* (G5, AMSP)

"If a customer *has a 3D scanner and a printer he does not need a spare part supply chain."* (G2, AMSP)

"How will the customs work in the future? If we send a digital spare part to Russia will we need to declare it?" (G2, OEM)

The participants listed possibilities of digitizing spare part manufacturing and their enablers and implications were brought up during the discussion. The enablers of the possibilities are the reasoning of the participants behind the possibilities and the implications are the continuations of those ideas. The possibilities along with their enablers and implications are collected in Table 5.

4.3. Obstacles in digitization of spare parts

The participants were asked to list the obstacles regarding digitization of spare parts, which were then discussed. The causes of the obstacles and the real-world implications for maintenance operations were discovered during these discussions. Intellectual property rights (IPR) issues of spare parts was clearly an issue about which most participants were concerned and wanted means of protection to be developed.

"With 3D printing you can create IDs for the spare parts, with which you could see if the spare part is licensed or not." (G2, AMSP)

The obstacles along with their causes and implications are presented in Table 6.

4.4. Descriptions of required properties of digital spare parts

In the discussions regarding the ideal properties of DSP components, the participants made it clear that a part has to be technically and economically viable to be considered for DSP distribution. This means that although a part could technically be manufactured with AM, it should only be used if the distribution advantages outweigh the increased costs of AM. Because standard parts are easily manufactured with conventional manufacturing methods, there is no need to involve DSP.

"If the part is simple*, a handy machinist will create it in the same time it*

Table 5
The views of the focus group participants on new possibilities and their enablers and implications of digitization of spare parts for maintenance operations.

Possibilities of digitization of spare parts	Enabler of possibilities	Implications for maintenance operations
Reduction of delivery time	Spare parts can be printed anywhere where the machinery is available	Lower delivery time and costs Improved OEM service speed and flexibility
Spare parts do not have to pass through customs	Parts can be produced directly from digital files	Spare parts can be delivered at a lower cost
Data can travel where physical parts cannot	Parts do not require specific know-how to be printed in different locations	Improved possibility to deliver spare parts in hard to reach locations
Positive environmental impact	AM uses only the material needed to produce components.	Lower emissions for the supply network
Upgraded spare parts	AM requires little set-up	Components can be improved based on field maintenance data each time they have to be replaced
Emergency spare parts		Temporary spare parts can be installed quickly until the actual spare parts are delivered

would take another to 3D model it." (G1, MSC)

The OEM participants were asked to write down the estimated percentage of parts in their companies' spare parts libraries that can be acceptably manufactured with AM. The estimation varied between 2% and 75% by the participants, but most answers stayed between 5% and 10%.

The participants were asked to write down the properties of spare parts that could affect their applicability in the DSP concept. Afterwards, the reasons behind why the participants chose the properties were discussed. The essential technological and control properties along with the causes for the preference for DSP from the perspective of the participants are presented in Table 7 along with their preferences and their causes.

4.5. DSP network and its requirements

To investigate what the DSP network should be composed of, the participants were asked to list the necessary actors and expertise that should be found in a DSP network. The participants were tasked with writing down the actors of a digital spare part distribution network and placing them in their respective places in the network. The actors that the participants proposed were:

- Network administrator
- AM service provider
- Digitization department of the service provider
- OEM
- Spare part ordering personnel of OEM
- OEM's model database
- AM plant
- Maintenance site
- Material supplier
- Software developers

The participants had a strong preference for an international service bureau network so that spare parts could be manufactured close to the customer but the 3D file of the part could be stored in one location. In particular, the OEMs would prefer to order their DSPs from one place that handles the entire spare part production and delivery process.

> *"We need a* joint *enterprise where the 3D machinery is centralized for better quality control, IPR safety and no profit margin of external service providers … big companies have the readiness to invest in this within five years. Big companies can then sell machine time to smaller companies later on."* (G3, OEM)

The role of service bureaus was emphasized because they need to be reliable and supply a choice of different service contracts.

> *"We need a platform with which we can deliver them (3D files of components) safely … and an actual manufacturer close to the customer."* (G5, OEM)

The model of a DSP network generated by the authors based on the answers by the participants is presented in Fig. 1. The network administrator of the DSP network model is a service centre jointly owned by the OEMs. The 3D models and drawings are stored in each OEM's model database, as the participants showed strong preference to host the files on their own servers.

> *"It is better and safer if the 3D model is acquired from the company every time it is printed. We must know when a spare part is produced."* (G2, OEM)

Table 6
The answers collected from the participants of the focus groups relating to the obstacles and their causes and implications of digitization of spare parts for maintenance operations.

Obstacle in digitization of spare parts	Cause of obstacle	Implication for maintenance operations
High cost of AM	High cost of AM machine hour price and materials	Increased price of producing components
Limited size of possible components	Limited build envelopes of AM machinery	Limited choice of components can be produced with AM
Inadequate quality of spare parts	AM accuracy limitations	
Variable quality between AM machines	Lacking control of process parameters in AM	Only parts that fit in the quality variability can be produced with AM
Variable quality between shipments of AM materials	Lack of standardization of AM material production processes	
Piracy	Data leaks in the supply network and reverse engineering of components	Loss of sales
File version management	Poor ICT	Lack of conviction in correct spare parts
3D model unavailability	Component manufactured based on 2D drawings or design subcontracted	More work in 3D modelling and increased labour cost
Difficulty in making 3D models from obsolete components	Imprecision of 3D scanning	
Parts are not ready after 3D printing	Parts need to be post processed and 3D scanning does not provide this information	

Table 7
The main properties of spare parts affecting the viability of digitization according to the participants.

Property of spare parts	Property type	Preference for DSP	Cause for preference
Complexity	Technological	High	The preference for high complexity comes from the fact that AM can manufacture complex products as easily as parts with simpler features.
Size	Technological	Low	The preference for smaller size comes from AM technology's current limitation of being able to produce parts only up to a certain size.
Criticality	Control	High	Highly critical spare parts cause costly periods of downtime if they are not immediately available. Therefore, the decreased lead-time enabled by distributed manufacturing of DSPs is a major advantage.
Demand pattern	Control	High variation Low volume	DSP is a benefit for items with high demand variation because additive manufacturing can meet demand very flexibly. Moreover, the preference for low volume comes from the fact that while AM is beneficial for lower volumes; at higher volumes, it usually becomes more expensive than manufacturing components by conventional means.
Value	Control	High	High value makes stocking an unattractive solution. With the use of AM, as there is no need to maintain physical inventories and the inventories are stored on a server, the cost of inventory is reduced dramatically. The small cost that remains is that of server hosting.
Delivery time predictability	Control	Low	Low delivery time predictability is also a benefit to DSPs because the delivery time predictability for AM is very reliable.
Specificity	Control	High	The lower the number of suppliers the better the part is suited for DSP. Because additive manufacturing requires no moulds and few instructions, parts can be manufactured without extensive expertise. Therefore, the number of suppliers for DSPs can be much higher than that of traditional suppliers.
Life cycle stage	Control	Very early or late	At the beginning of the life cycle, the spare parts can be created in case the main production is not ramped up yet. At the end of the life cycle, DSP can be beneficial because the tools or the supplier might be gone.
Update rate	Control	Frequent	Parts that become obsolete (through either upgrades or deterioration) have to be disposed of. If they are produced only when necessary, the stocking and disposal costs can be avoided.

In the process flow of the model, an OEM sends a request to the AM service centre to manufacture the spare part along with its 3D models or drawings. The digitization department of the service centre transforms into files fit for manufacturing and sends them onwards to the AM facilities close to the maintenance site. Once the spare part is manufactured, it is transported to the maintenance site to be installed.

The network model features the material supplier and software developers as the two external parties. The software developers offer software support to the OEM and the service provider and receive input on how they should develop their software to suit their needs better. The material supplier identifies potential materials from the OEM model database and supplies the AM plants with materials that suit the needs of the OEMs.

4.6. Facilitating factors in the development of a digital spare parts network

The company representatives shared their opinion on factors that can affect the creation of DSP networks. The factors were divided into ICT and issues that could be influenced by the government. Many of the OEMs mentioned that their infrastructure does not conform to the requirements to start up such operations without significant investments. The primary issue was that ICT is simply not present at most company warehouses, which would be necessary in order to implement the DSP concept.

"Our spare part warehouses are far from automated robotic storages. They are closer to dark attics." (G1, OEM)

Structural ICT factors in building a DSP network:

- Capacity for file transfers must be sufficient
- Storage of files must be reliable
- File transfer costs must be low
- Transfer speeds must be sufficiently fast
- Internet network conditions must be stable and fast
- Data formats must be standardized

Government factors in building a DSP network:

- Existing workforce and upcoming engineers need to be educated in AM and DSP
- Design for AM and software development for manufacturing needs to be taught more extensively in higher education institutions
- Upper-level management needs to be educated in the concepts of strategic DSP implementation
- Legal services need to become involved in the DSP concept to investigate the possibly emerging IPR issues
- Investment support for AM infrastructure development should be offered

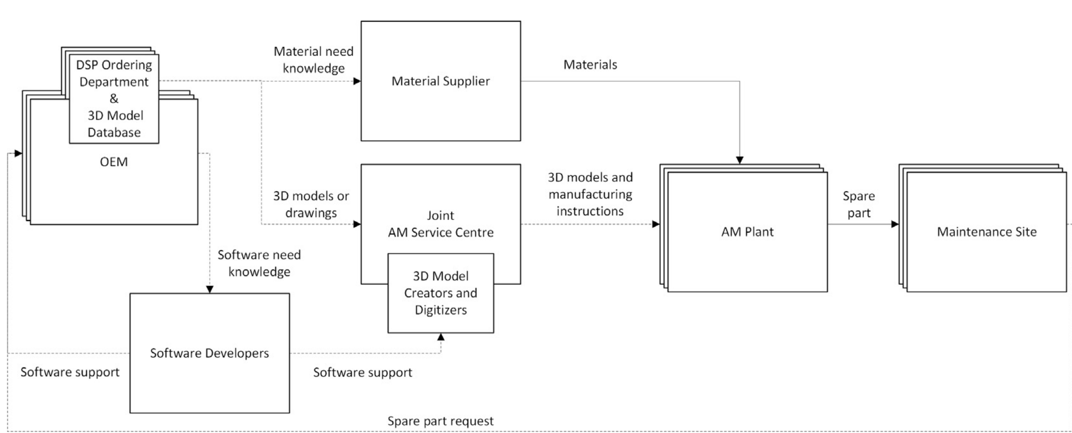

Fig. 1. A model of the optimal digital spare part network according to the participants. In this model, the AM service centre is the network administrator. Solid arrows signify the transfer of objects and dotted arrows signify the transfer of information.

5. Discussion of focus group results

The focus group interviews verified that companies find implementing AM in spare part supply chains a valuable concept for spare part management and provided information to form a more comprehensive picture of the possibilities of the digital spare part concept.

The problems with spare part management that are listed in section 3.1 are very similar to those found in the work of Sarker and Haque (2000) and Kennedy et al. (2002). The only exception is for the problem of rushing of maintenance operators for compensating long delivery times, which was clearly represented in the focus groups more than in the literature.

All the possibilities of digitization of spare parts listed in Table 5 were also found in the literature findings presented in Table 1 except for the high interest of the focus group participants in bypassing customs by manufacturing spare parts in the country where they are needed and the concepts of improved and emergency spare parts.

The obstacles of digitization of spare parts in Table 6 were largely similar to the ones found in the literature overview in the introduction. The high cost of AM compared to subtractive manufacturing was often cited as a large obstacle by the participants as well as by Walter et al. (2004), Liu et al. (2014), Khajavi et al. (2014), Sasson and Johnson (2016), and Li et al. (2016). The limited size of possible components due to AM restrictions was indicated as a major obstacle by the participants because many of their spare parts are too large for current AM build envelopes. Although the possible size of components was considered by Knofius et al. (2016) in identifying business cases of DSP, it has only been explicitly stated as an obstacle by Pérès and Noyes (2006). The obstacle of insufficient and varying quality of AM components was likewise brought up often by the participants but was only raised as a clear issue by Pérès and Noyes (2006) and Holmström et al. (2010). On the other hand, the relative slow speed of AM referenced as obstacles by Khajavi et al. (2014) and Chekurov and Salmi (2017), as well as the additional certification needs of AM referenced by Sirichakwal and Conner (2016) were not mentioned often by the participants. File version management and 3D model unavailability were listed by some participants as significant obstacles and similar views were presented by Knofius et al. (2016). The potential of losing revenue to piracy was mentioned often in the focus group results although they were only present in two articles in the referenced literature. In their article, Appleyard (2015) discusses the implications of piracy in AM and concludes that companies need to change their business models to fully leverage the AM paradigm or suffer financial losses due to piracy. Lindemann et al. (2015) present an opposing view by demonstrating copy protection of AM parts. From the points of view of the focus group participants, the participants would prefer to use the approach presented by Lindemann et al. when making their spare parts available as DSPs.

In addition to the issues of ICT nature, the obstacle of post processing components was more prominent in the focus groups than in the mentioned literature.

According to Table 7, the ideal parts for the DSP concept from the technical perspective are physically small and complex. These aspects are linked with the technological requirements of AM, and in this regard, the Lindemann et al. (2015) publication discusses ideal part selection for AM. All of the control properties in Table 7 are traditional properties of spare part classification (Roda et al., 2014).

The description of the ideal DSP in Table 7 is very close to that of a part belonging to the long tail of a company's product catalogue. This is in line with previous findings of Holmström et al. (2014) and Sasson and Johnson (2016) who noted that long tail products are good candidates for AM.

A traditional spare part supply network in the companies that were interviewed can take on a multitude of configurations, but they all have in common the fact that spare parts are sourced from a handful of suppliers, stored in central and secondary warehouses, and transported to the repair site when the need arises. In a scenario in which a company implements DSP, the transportation of data becomes more important than physical part movement. To mirror this, the role of the material supplier and the software developers is significantly larger in the DSP network especially in the early stages. Other differences between the traditional and DSP network models are the replacement of a central storage with the model database, removal of regional storage spaces, and the introduction of distributed manufacturing. These changes make it possible for spare parts to be delivered to the location much faster than in the traditional model. The DSP network model acquired by the means of this study shares notable aspects with the models developed by Holmström et al. (2010) and Khajavi et al. (2014) whose models demonstrate the concept of distributed manufacturing and the possibility of multiple OEMs sharing the supply network. The model constructed based on the priorities of this focus group study also includes these aspects but in addition emphasizes the roles of software developers and material suppliers.

6. Further definition of the digital spare parts concept

The second stage of the Podsakoff methodology consists of condensing the list of identified attributes of the concept to a smaller list and evaluating if they are indeed necessary to the concept and if they can be used to sufficiently describe the concept without being confused with another (Podsakoff et al., 2016). In this study, the condensation of the attribute list is done by comparing the key attributes found in the literature with the ones acquired from the focus group study. The overlapping attributes that emerge from both sources are then compared with the concepts of “Traditionally produced spare part” and “Additively manufactured part” and their sufficiency is evaluated. In comparison with Table 2, the missing attributes are “manufactured on site” and “can use centralized manufacturing” because the participants favoured the distributed manufacturing model. The attributes present in both the literature and the focus group reviews are presented in Table 8.

In the third stage of the Podsakoff methodology, the preliminary definition of the concept is developed. This is done by describing the necessary and sufficient attributes of the concept compared to related concepts, specifying the entity, general property, dimensionality and stability of the concept and by identifying the consequences of the concept (Podsakoff et al., 2016). The entity of the DSP concept is a component and its general property is the means of its delivery. At this level of abstraction, the concept of DSP is unidimensional, as all of the attributes exist in the same conceptual domain of system operations. Although the technical and economic performance of components in the DSP concept varies, all conceivable components share the key

Table 8
Identifying necessary and sufficient attributes of the concept of a “digital spare part”.

Attributes	Digital spare part	Traditionally produced spare part	Additively manufactured part	Conclusions
A1: Delivered to replace a defective component	Present	Present	Absent	Necessary but not sufficient
A2: Parts built from 3D model data	Present	Absent	Present	Necessary but not sufficient
A3: Production documents transferred by network	Present	Absent	Present	Necessary but not sufficient
A4: Can use distributed manufacturing	Present	Absent	Present	Necessary but not sufficient

attributes. The concept is therefore stable among all variations of the entity.

The concept of DSP has multiple necessary attributes that sufficiently define it. The combination of A1 + A2 + A3 + A4 is necessary and jointly sufficient to define a DSP. While digital spare parts and traditionally produced spare parts have one attribute, their main function, in common, the rest of the attributes apply only to digital spare parts, as traditionally produced spare parts cannot be digitally distributed. Similarly, DSP and additively manufactured parts have the possibility of digital distribution (A2-A4) in common but do not share the main function A1.

The consequences that were found both in literature and in the focus group interviews were the reduction of repair time, delivery time and costs, emissions and material waste, and inventory.

By combining the defining attributes in Table 8 and the overlapping consequences, the DSP concept could be described as "A concept in which defective components are replaced by manufacturing spare parts close to the location of need from 3D model data that are transferred by network with the main consequences of reducing repair time, delivery time and costs, emissions, and inventory".

7. Conclusions

The perceived value of implementing AM in supply networks of digital spare parts was measured and the concept of DSP was expanded by focus group interviews with manufacturing professionals. The interviews were conducted to investigate the possible benefits of DSPs and their importance to industrial companies. The interest in producing spare parts digitally was very high among the participants, but there are several issues to overcome before large-scale implementation can take place. It was noted that neither the AM technology, nor the ICT infrastructure of the companies that would make DSP distribution possible are robust enough for the digital distribution method to be deployed fully in the interviewed companies. However, the DSP distribution method could already be applied to specific types of components. Through the participants' description of the ideal DSP, it was found that long tail products make excellent candidates for digital distribution. It is therefore likely that the first implementations of DSP networks will be based on such products.

The cost of AM was not seen as a prohibitive issue for long tail products by the participants. Indeed, it was well understood that even though AM parts are generally more expensive to produce, the cost savings come from other areas of implementation. In the case of long tail spare parts; these could be related to lower warehousing and transportation costs as well as faster lead times and delivery times.

Another potential DSP subgroup is the improved spare parts that have better qualities than the original ones. This can mean, for instance, better design by topology optimisation or reduced number of joints to decrease the risk of failure. In order for DSP to become a more viable approach, AM technology has to be developed to correspond with more spare parts in companies' catalogues. This could be achieved, for example, by faster machines that produce parts that require less post treatment, or by expanding the limited material library of AM. In addition, old designs have to first be digitized for production with AM. To improve the possibility of manufacturing future spare parts digitally, any new designs have to be recorded systematically according to the attributes described by the participants.

While it will take some time for AM technology development to catch up with company needs, there are already steps that companies can take towards its implementation. The companies that view digital spare parts as advantageous and plan to utilize the concept in the future should start the preparation related to part documentation and ICT system capabilities, developing required competences and finding the right partners. Ultimately, the actual structure of the DSP network will depend on decisions of the current operators of the spare parts supply chain as well as on the actions of the new network members.

8. Limitations and future work

The study was conducted in Finland and as such, the views presented in the focus groups represent the bias of the Finnish industry. Further focus group research aimed at different sectors in different countries could expand on the results. In addition, a quantitative study regarding the readiness levels of the DSP concept and a more in-depth interview with single individuals from companies that already use AM in their supply chains using the same question routine as in this study could yield data that are more detailed. Such a study could be focused on developing mathematical models for DPS enabled supply chains that takes the findings of this study into account. Furthermore, this study can be used for initial implementation of DSP in companies.

The coding strategy in parsing the data of the focus group interviews was developed inductively. While this open-ended approach to coding yielded wide-ranging results, further studies on the same topic should use predefined coding strategies to collect more accurate data on more specific topics.

Regarding the concept definition of DSP, this study works in the domain of the first three stages and ends the process by providing an initial definition of the concept. The concept of DSP needs to be developed further by following the fourth stage of Podsakoff's concept definition, in which the conceptual definition of the concept is further refined by reducing the complexity of the language and by soliciting the feedback from peers. (Podsakoff et al., 2016).

Acknowledgements

The research on which this paper is based was conducted as a part of the Digital Spare Parts (DIVA) project and funded by a consortium of companies and Tekes - the Finnish Funding Agency for Innovation.

Appendix

Table A1
Complete demographic information of the focus group participants

Group	Company type	Position in company	Years of experience
1	AM service provider	Top management	10–15
1	AM service provider	Top management	> 25
1	Manufacturing subcontractor	Top management	20–25
1	Manufacturing subcontractor	Top management	15–20
1	Manufacturing subcontractor	Top management	15–20
1	OEM	Middle management	10–15
1	OEM	Middle management	15–20
1	OEM	Middle management	10–15

(*continued on next page*)

Table A1 (*continued*)

Group	Company type	Position in company	Years of experience
2	AM service provider	Top management	10–15
2	AM service provider	Top management	5–10
2	AM software developer	Middle management	10–15
2	Manufacturing subcontractor	Top management	10–15
2	National institute	Specialist	< 5
2	National institute	First-line management	> 25
2	OEM	Specialist	5–10
2	OEM	Specialist	10–15
2	OEM	Specialist	< 5
2	OEM	Middle management	> 25
2	OEM	Top management	5–10
3	Manufacturing subcontractor	First-line management	< 5
3	Manufacturing subcontractor	First-line management	15–20
3	National institute	Specialist	10–15
3	OEM	First-line management	10–15
3	OEM	Specialist	< 5
3	OEM	Specialist	15–20
3	OEM	Middle management	20–25
3	OEM	Specialist	< 5
3	Other	Specialist	< 5
4	AM service provider	Middle management	> 25
4	AM software developer	Top management	10–15
4	Manufacturing subcontractor	First-line management	5–10
4	OEM	First-line management	5–10
4	OEM	First-line management	5–10
4	OEM	Top management	> 25
4	OEM	Specialist	< 5
4	OEM	Middle management	20–25
4	OEM	Specialist	20–25
4	Other	Top management	15–20
5	AM service provider	Top management	< 5
5	AM service provider	Top management	5–10
5	Manufacturing subcontractor	Specialist	20–25
5	Manufacturing subcontractor	Specialist	5–10
5	OEM	First-line management	15–20
5	OEM	Top management	15–20
5	OEM	Specialist	5–10
5	Other	Middle management	15–20

References

Anderson, C., 2006. The Long Tail: Why the Future of Business Is Selling Less of More. Hyperion, New York, NY.
Angell, L.C., Klassen, R.D., 1999. Technical note: integrating environmental issues into the mainstream: an agenda for research in operations management. J. Oper. Manag. 17, 575–598.
Appleyard, M., 2015. Corporate responses to online music piracy: strategic lessons for the challenge of additive manufacturing. Bus. Horiz. 58, 69–76.
Barbour, R., 2007. Doing Focus Groups, First. ed. SAGE Publications, Inc., London.
Behfard, S., Al Hanbali, A., van der Heijden, M.C., Zijm, W.H.M., 2018. Last Time Buy and repair decisions for fast moving parts. Int. J. Prod. Econ. 197, 158–173.
Campbell, J.L., Quincy, C., Osserman, J., Pedersen, O.K., 2013. Coding in-depth semistructured interviews: problems of unitization and intercoder reliability and agreement. Socio. Meth. Res. 42, 294–320.
Cavalieri, S., Garetti, M., Macchi, M., Pinto, R., 2008. The Management of Operations A decision-making framework for managing maintenance spare parts. Prod. Plann. Contr. 19, 379–396.
Chekurov, S., Salmi, M., 2017. Additive manufacturing in offsite repair of consumer electronics. Phys. Procedia 89, 23–30.
Driessen, M., Arts, J., Van Houtum, G.-J., Rustenburg, J.W., Huisman, B., 2015. The Management of Operations Maintenance spare parts planning and control: a framework for control and agenda for future research. Prod. Plann. Contr. 26, 407–426.
Fern, E.F., 2001. Advanced Focus Group Research, First. ed. SAGE Publications, Inc., Thousand Oaks.
Flynn, B., 1990. Empirical research methods in operations management. J. Oper. Manag. 9, 250–284.
Fox, S., Li, L., 2012. Expanding the scope of prosumption: a framework for analysing potential contributions from advances in materials technologies. Technol. Forecast. Soc. Change 79, 721–733.
Gausemeier, J., Echterhoff, N., Kokoschka, M., Wall, M., 2012. Thinking Ahead the Future of Additive Manufacturing – Future Applications (Study Part 2). University of Paderborn, Heinz Nixdorf Institute.
Gebler, M., Schoot Uiterkamp, A.J.M., Visser, C., 2014. A global sustainability perspective on 3D printing technologies. Energy Pol. 74, 158–167.
Gray, G.T.I., Livescu, V., Rigg, P.A., Trujillo, C.P., Cady, C.M., Chen, S.R., Carpenter, J.S., Lienert, T.J., Fensin, S.J., 2017. Structure/property (constitutive and spallation response) of additively manufactured 316L stainless steel. Acta Mater. 138, 140–149.
Greenbaum, T.L., 1998. The Handbook for Focus Group Research, Second. SAGE Publications, Inc., Thousand Oaks.
Holmström, J., Partanen, J., 2014. Digital manufacturing-driven transformations of service supply chains for complex products. Supply Chain Manag. An Int. J. 19, 421–430.
Holmström, J., Partanen, J., Tuomi, J., Walter, M., 2010. Rapid manufacturing in the spare parts supply chain: alternative approaches to capacity deployment. J. Manuf. Technol. Manag. 21, 687–697.
Huiskonen, J., 2001. Maintenance spare parts logistics: special characteristics and strategic choices. Int. J. Prod. Econ. 71, 125–133.
Jonsson, P., Holmström, J., 2016. Future of supply chain planning: closing the gaps between practice and promise. Int. J. Phys. Distrib. Logist. Manag. 46, 62–81.
Kellens, K., Baumers, M., Gutowski, T.G., Flanagan, W., Lifset, R., Duflou, J.R., 2017. Environmental dimensions of additive manufacturing: mapping application domains and their environmental implications. J. Ind. Ecol. 21, S49–S68.
Kennedy, W.J., Patterson, W.J., Fredendall, L.D., 2002. An overview of recent literature on spare parts inventories. Int. J. Prod. Econ. 76, 201–215.

Khajavi, S.H., Partanen, J., Holmström, J., 2014. Additive manufacturing in the spare parts supply chain. Comput. Ind. 65, 50–63.
Knofius, N., van der Heijden, M.C., Zijm, W.H.M., 2016. Selecting parts for additive manufacturing in service logistics. J. Manuf. Technol. Manag. 27, 915–931.
Kothman, I., Faber, N., 2016. How 3D printing technology changes the rules of the game: insights from the construction sector. J. Manuf. Technol. Manag. 27, 932–943.
Ledwoch, A., Yasarcan, H., Brintrup, A., 2018. The moderating impact of supply network topology on the effectiveness of risk management. Int. J. Prod. Econ. 197, 13–26.
Li, Y., Jia, G., Cheng, Y., Hu, Y., 2016. Additive manufacturing technology in spare parts supply chain: a comparative study. Int. J. Prod. Res. 55, 1498–1515.
Lindemann, C., Reiher, T., Jahnke, U., Koch, R., 2015. Towards a sustainable and economic selection of part candidates for additive manufacturing. Rapid Prototyp. J. 21, 216–227.
Liu, P., Huang, S.H., Mokasdar, A., Zhou, H., Hou, L., 2014. The impact of additive manufacturing in the aircraft spare parts supply chain: supply chain operation reference (scor) model based analysis. Prod. Plann. Contr. 25, 1169–1181.
Lyly-yrjänäinen, J., Holmström, J., Johansson, M.I., Suomala, P., 2016. Effects of combining product-centric control and direct digital manufacturing: the case of preparing customized hose assembly kits. Comput. Ind. 82, 82–94.
Martin, H., Syntetos, A., Parodi, A., Polychronakis, Y., Pintelon, L., 2010. Integrating the spare parts supply chain: an inter-disciplinary account. J. Manuf. Technol. Manag. 21, 226–245.
Maynes, T.D., Podsakoff, P.M., 2014. Speaking more broadly: an examination of the nature, antecedents, and consequences of an expanded set of employee voice behaviors. J. Appl. Psychol. 99, 87–112.
Mellor, S., Hao, L., Zhang, D., 2014. Additive manufacturing: a framework for implementation. Int. J. Prod. Econ. 149, 194–201.
Morgan, D.L., 1988. Focus Groups as Qualitative Research, First. ed. SAGE Publications, Inc., Newbury Park.
Molenaers, A., Baets, H., Pintelon, L., Waeyenbergh, G., 2012. Criticality classification of spare parts: a case study. Int. J. Prod. Econ. 140, 570–578.
Oettmeier, K., Hofmann, E., 2016. Impact of additive manufacturing technology adoption on supply chain management processes and components. J. Manuf. Technol. Manag. 27, 944–968.
Pérès, F., Noyes, D., 2006. Envisioning e-logistics developments: making spare parts in situ and on demand. State of the art and guidelines for future developments. Comput. Ind. 57, 490–503.
Podsakoff, P.M., MacKenzie, S.B., Podsakoff, N.P., 2016. Recommendations for creating better concept definitions in the organizational, behavioral, and social sciences. Organ. Res. Meth. 19, 159–203.
Portolés, L., Jordá, O., Jordá, L., Uriondo, A., Esperon-miguez, M., 2016. A qualification procedure to manufacture and repair aerospace parts with electron beam melting. J. Manuf. Syst. 41, 65–75.
Puchta, C., Potter, J., 2005. Focus Group Practice, First. ed. SAGE Publications, Inc., London.
Rayna, T., Striukova, L., 2016. From rapid prototyping to home fabrication: how 3D printing is changing business model innovation. Technol. Forecast. Soc. Change 102, 214–224.
Roda, I., Macchi, M., Fumagalli, L., Viveros, P., 2014. A review of multi-criteria classification of spare parts. J. Manuf. Technol. Manag. 25, 528–549.
Rylands, B., Böhme, T., Gorkin, R.I., Fan, T.B., 2016. The adoption process and impact of additive manufacturing on manufacturing systems. J. Manuf. Technol. Manag. 27, 969–989.
Sarker, R., Haque, A., 2000. Optimization of maintenance and spare provisioning policy using simulation. Appl. Math. Model. 24, 751–760.
Sasson, A., Johnson, J.C., 2016. The 3D printing order: variability, supercenters and supply chain reconfigurations. Int. J. Phys. Distrib. Logist. Manag. 46, 82–94.
Schniederjans, D.G., 2017. Adoption of 3D-printing technologies in manufacturing: a survey analysis. Int. J. Prod. Econ. 183, 287–298.
Scott, A., Harrison, T., 2015. Additive manufacturing in an end-to-end supply chain setting. 3D Print. Addit. Manuf. 2, 65–77.
Simhambhatla, S., Karunakaran, K.P., 2015. Build strategies for rapid manufacturing of components of varying complexity. Rapid Prototyp. J. 21, 340–350.
Singh, S., Ramakrishna, S., Singh, R., 2017. Material issues in additive manufacturing: a review. J. Manuf. Process. 25, 185–200.
Sirichakwal, I., Conner, B., 2016. Implications of additive manufacturing for spare parts inventory. 3D Print. Addit. Manuf. 3, 56–63.
Thomas-Seale, L.E.J., Kirkman-Brown, J.C., Attallah, M.M., Espino, D.M., Shepherd, D.E.T., 2018. The barriers to the progression of additive manufacture: perspectives from UK industry. Int. J. Prod. Econ. 198, 104–118.
Thomas, D., 2016. Costs, benefits, and adoption of additive manufacturing: a supply chain perspective. Int. J. Adv. Manuf. Technol. 85, 1857–1876.
Tuck, C., Hague, R., Burns, N., 2007. Rapid manufacturing: impact on supply chain methodologies and practice. Int. J. Serv. Oper. Manag. 3, 1–22.
Walter, M., Holmström, J., Yrjölä, H., 2004. Rapid manufacturing and its impact on supply chain management. In: Proceedings of the Logistics Research Network Annual Conference. Dublin, Ireland.
Weller, C., Kleer, R., Piller, F.T., 2015. Economic implications of 3D printing: market structure models in light of additive manufacturing revisited. Int. J. Prod. Econ. 164, 43–56.
Wohlers, T., 2013. Wohlers Report 2013. Additive Manufacturing and 3D Printing State of the Industry: Annual Worldwide Progress Report. Wohlers Associates, Inc, Fort Collins, CO.
Wohlers, T., 2017. Wohlers Report 2017. Additive Manufacturing and 3D Printing State of the Industry: Annual Worldwide Progress Report. Wohlers Associates, Inc, Fort Collins, CO.
Zanjani, M.K., Nourelfath, M., 2014. Integrated spare parts logistics and operations planning for maintenance service providers. Int. J. Prod. Econ. 158, 44–53.