Research-Technology Management

ISSN: (Print) (Online) Journal homepage: www.tandfonline.com/journals/urtm20

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To cite this article: Bardia Naghshineh, Miguel Fragoso & Helena Carvalho (2023) Rethinking Additive Manufacturing for Spare Parts Supply Chain Management, Research-Technology Management, 66:4, 38-47, DOI: 10.1080/08956308.2023.2207970

To link to this article: https://doi.org/10.1080/08956308.2023.2207970

Published online: 26 Jun 2023.

Rethinking Additive Manufacturing for Spare Parts Supply Chain Management

Manufacturers and customers in the spare parts supply chain can use the questions developed in this study to assess the advantages and barriers of additive manufacturing.

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OVERVIEW: Given the ongoing advancements in additive manufacturing (3D printing), many companies are considering using this digital technology for the supply of spare parts. This study identifies the advantages and barriers of additive manufacturing in the context of spare parts supply chain management. The case study examines the perspectives of a manufacturer and a customer of a spare parts supply chain. We present several questions that practitioners can use to (re)consider additive manufacturing for their companies.

KEYWORDS: Additive manufacturing technology, 3D printing, Spare parts, Supply chain management

Additive manufacturing, more commonly known as three-dimensional (3D) printing, is an emerging digital technology being used in different industrial sectors at a growing rate (Wohlers 2021) (see "Additive Manufacturing Technology" on page 39). In recent years, researchers and practitioners have focused on additive manufacturing due to its potential in redefining industries and supply chains as we know them (Naghshineh and Carvalho 2022a). This digital technology differs considerably from the conventional methods of production: it offers innovative solutions to mitigate the risks and costs related to stockouts, obsolescence, and maintenance throughout the supply chain (Aversa et al. 2021; Oettmeier and Hofmann 2017), mainly due to its ability to manufacture the necessary parts on demand close to the point of use (Zanoni et al. 2019).

Additive manufacturing, combined with good supply chain management, can offer companies in different industries a competitive advantage (Belhadi et al. 2022; Naghshineh et al. 2021). The spare parts supply chain is one of the most promising areas for additive manufacturing. The lack of spare parts, when they are needed, can disrupt the supply chain operations (Sirichakwal and Conner 2016). Additive manufacturing can help mitigate such disruptions compared to conventional methods of production such as machining (Khajavi, Partanen, and Holmström 2014).

Spare parts are generally defined as parts that are used to maintain the operating conditions of equipment, and they can have diverse characteristics (Sirichakwal and Conner 2016). Companies use different strategies to find the right trade-off between the on-time availability of spare parts and their burdensome holding costs. Additive manufacturing is

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DOI: 10.1080/08956308.2023.2207970

Additive Manufacturing Technology

Additive manufacturing, also known as 3D printing, uses raw materials and 3D computer-aided design (CAD) software to create objects directly. Contrary to conventional methods of production, in which parts are normally created by removing the material, additive manufacturing deposits incremental layers of material on the build platform until the desired geometry is shaped (ASTM.org 2021). With additive manufacturing technology, it is possible to use various types of material, which generally come in different forms—for example, filament, powder, and resin. Additive manufacturing encompasses several processes, each of which has different advantages and limitations and is better suited for certain applications—for example, prototyping, rapid tooling, parts production, etc. Depending on the additive manufacturing process used, there will be variations in accuracy, surface finish, post-processing, etc. New and different additive manufacturing processes yield considerable advantages. The medical, energy, construction, automotive, and aerospace industries are closely following the ongoing advancements in additive manufacturing technology and its different applications (Wohlers 2021).

one strategy that has proved to be quite advantageous (Li et al. 2017; Akmal et al. 2022). In this article, we explore using additive manufacturing for companies with different roles and positions in the supply chain. We aim to answer the following research question:

What are the advantages and barriers of using additive manufacturing technology for the supply of spare parts?

A company's efforts to gain competitive market advantage stems from the dynamic capability view, which is an extension of the resource-based view whereby management attempts to use different resources such as technology to foster a competitive edge (Teece, Pisano, and Shuen 1997). Contrary to the resource-based view, however, the dynamic capability view motivates managers to strategically appraise whether investing in such resources can help the company gain a sustainable competitive advantage and grow over time in today's dynamic supply chains that are constantly under resource pressures (Kalaitzi et al. 2019). We draw on the dynamic capability view to explore the potential competitive advantages and barriers that additive manufacturing technology can prompt for different companies (Petrick and Simpson 2013), particularly in the context of spare parts supply chain management.

Literature Review

Over the last decade, several studies have explored the use of additive manufacturing technology for spare parts supply chain management. Khajavi et al. (2014) used scenario modelling to evaluate how additive manufacturing would affect the configuration of the spare parts supply chain in the aeronautics industry. They appraised the cost trade-offs of using additive manufacturing for the supply of spare parts. They found that additive manufacturing enabled the distributed production of spare parts in different locations but that this configuration would be viable only if the cost of equipment and the production cycle times were reduced. They also showed that distributed manufacturing via additive manufacturing reduces costs related to logistics activities, especially transportation.

Sirichakwal and Conner (2016) devised an inventory cost model, which showed how additive manufacturing can reduce the production lead time and holding costs of spare parts. They found that additive manufacturing is particularly useful in production systems where the risk of stockouts and parts obsolescence is high. Li et al. (2017) used a system dynamics simulation approach to examine the advantages of using additive manufacturing for the supply of spare parts under different scenarios. Using the total cost of production and carbon emission as key performance indicators, they posited that additive manufacturing leads to reduced carbon emissions in most cases, mainly due to less transportation, thus reducing the environmental impacts of the spare parts supply chain. They found that the high cost of equipment diminishes the cost benefits of using additive manufacturing. They predicted that over time, however, the advancement of raw materials and equipment would make additive manufacturing both environmentally and economically more sustainable.

Muir and Haddud (2018) examined the effects of additive manufacturing on the firm's inventory performance and customer satisfaction while considering the role of delivery lead time, cost, and supply risk. They reported increased demand for 3D-printed spare parts as well as improved customer satisfaction, but noted that there is a trade-off between reducing the delivery lead time of spare parts and their cost. Overall, they found that additive manufacturing improves inventory performance by enabling the adopting firm to reduce its safety stock levels when dealing with supply risks.

Chekurov et al. (2018) explored the benefits and obstacles of using additive manufacturing for the supply of spare parts. Their findings suggest additive manufacturing would yield several opportunities—namely, reduced repair time and maintenance costs, reduced emissions and material waste, and reduced delivery lead time and inventory levels. They also identified multiple obstacles: limited part size, inadequate part quality, excessive need for post-processing, lack of uniform standards, material supplier quality issues, and ICT inadequacies like software problems that reduce the effectiveness of additive manufacturing in providing spare parts. Heinen and Hoberg (2019) found that a switchover to additive manufacturing is useful in cases of high-cost spare parts with low demand that would require minimum order quantities when manufactured via conventional production methods. By contrast, additive manufacturing would allow flexible replenishment options like small batch production for such spare parts. Heinen and Hoberg (2019) also reported challenges such as the lack of technical knowledge and limited expertise that hinder the effective use of additive manufacturing.

Knofius, van der Heijden, and Zijm (2019) analyzed the potential benefits and downsides of consolidating spare parts with additive manufacturing, whereby multiple subcomponents are integrated into one spare part. The reduced number of subcomponents in the supply chain using highly customized consolidated spare parts would lead to fewer assembly steps, reduced material usage, less dependency on material suppliers, and less supply chain complexity, all of which result in performance improvements. Spare part consolidation with additive manufacturing may lead to higher total costs, however. When a consolidated spare part fails, it usually has to be replaced entirely, whereas by only replacing the defective subcomponent(s) in a conventional assembled spare part, this issue may no longer persist. Companies should consider such cost trade-offs when applying design changes aimed at consolidating spare parts via additive manufacturing (Knofius, van der Heijden, and Zijm 2019).

Boer, Lambrechts, and Krikke (2020) evaluated the effects of additive manufacturing on the supply of fully customized, high-tech, and mission-critical spare parts for the armed forces. Additive manufacturing offered several advantages: reduced inventory levels, reduced waste, and reduced delivery lead times, which improved the efficiency, sustainability, and responsiveness of the armed forces' spare parts supply chain. They also identified several barriers such as the high energy consumption and high cost of additive manufacturing, which would be outweighed by the criticality of these spare parts. Additive manufacturing would enable the armed forces to quickly develop and optimize new spare parts that fit the immediate needs of their missions.

Akmal et al. (2022) explored the after-sales operations of a case company to develop a procedure for selecting problematic spare parts (in terms of economies of scale) for switchover to additive manufacturing. These spare parts followed no predictable demand pattern and at the same time required on-demand availability to minimize the risk of stockouts. The authors studied different scenarios under which it would make sense to use additive manufacturing for the supply of these spare parts. They noted trade-offs between the lead time and supply cost of these spare parts that required careful consideration before switching over to additive manufacturing.

While these studies highlight different advantages and barriers of using additive manufacturing in the context of spare parts supply chain, they do not collectively consider them in one study to provide holistic insights. By contrast, we aim to comprehensively explore the advantages and barriers of using additive manufacturing technology for the supply of spare parts by studying a manufacturer and a customer that have different roles in a spare parts supply chain.

Case Study

We conducted a case study of two companies in a spare parts supply chain in Portugal between September and November 2021. FAN3D manufactures spare parts using additive manufacturing technology, while Metropolitano de Lisboa purchases additively manufactured spare parts (see "Case Companies: FAN3D and Metropolitano de Lisboa" on page

Case Companies: FAN3D and Metropolitano de Lisboa

FAN3D

Based in Lisbon, Portugal, FAN3D had 10 employees when we conducted this case study. The company provides services related to additive manufacturing, including selling equipment and materials. In addition to 3D-printing services, it also offers consulting services, training, and technical support. As the manufacturer, FAN3D possesses the necessary additive manufacturing tools and know-how and offers solutions to different industrial sectors. Since its inception, FAN3D has specialized in using material extrusion and vat photopolymerization processes. Its predominant additive manufacturing materials are acrylic resins, polylactic acid (PLA) and polyethylene terephthalate glycol (PETG) filaments, transparent polypropylene (PPF), nylons, and carbon fibers. FAN3D's ability to include antibacterial material in the production of spare parts presented an added value during the COVID-19 pandemic. The company's production strategy was "print-to-order," which is synonymous with the make-to-order production policy in supply chain management (Torres et al. 2020), representing more than 80 percent of its sales volume. FAN3D manufactured the handles via material extrusion, making the use of this additive manufacturing process suitable mainly due to the type of material (PLA) and the geometry of the intended parts. The company produced the handles in small batches. For the grips, material extrusion was only used during the product development and validation phase (prototyping). Once the prototypes were finalized, injection molding was used to produce large numbers. The application of additive manufacturing for parts production depended on the requested volume and order lead time while considering the cost-effectiveness of using the technology.

Metropolitano de Lisboa

Metropolitano de Lisboa is based in Lisbon, Portugal, and has between 1,000–2,000 employees. The company provides public passenger transport services throughout the Lisbon Metropolitan Area. As the only company to run the first metro network in Portugal, Metropolitano de Lisboa needs to carry out periodic, preventive, and corrective maintenance of its stations and carriages. As part of its expansion plan, Metropolitano de Lisboa had invested in 42 new carriages along with their maintenance, which required various spare parts to be available in a timely manner. The company was considering the use of additive manufacturing technology for the on-demand acquisition of spare parts. It initiated a "collaborative research and technological development" project with FAN3D, where additive manufacturing was used to manufacture two parts present in the carriages—that is, carriage handle and carriage grip (Figure 1). Metropolitano de Lisboa considered this initiative a first step towards appraising additive manufacturing's potential for the supply of spare parts. Metropolitano de Lisboa agreed to demonstrate the use of these 3D-printed parts, which were originally intended for maintenance purposes. Their on-time availability was important to the company. The inclusion of antibacterial material was an added value for Metropolitano de Lisboa during the COVID-19 pandemic. These parts suited our study objective to investigate the advantages and barriers of additive manufacturing technology for the supply of spare parts.

40. Since each company has a different role and position in the supply chain, we were able to explore the research question from two different supply chain angles.

We examined two spare parts in this study—a carriage handle (“handle”) and a carriage grip (“grip”) (Figure 1). The handles are for operating the carriages, and the grips are used by passengers during the journey. The added value of these parts compared to the parts that Metropolitano de Lisboa already possessed was the antibacterial material used in their production. Metropolitano de Lisboa wanted to use these materials to mitigate the spread of the coronavirus. Spare parts can have diverse characteristics, which can influence the case study findings, leading to distinctive results (Naghshineh and Carvalho 2022b). In this case study, the main differences between the two parts are their demand rate, batch size, and production time (Table 1). These differences are mainly due to the number of grips used per carriage (100), compared to the number of handles used per carriage (2). The demand rate was much higher for the grips, which led to larger production batches and longer production lead times.

Methodology

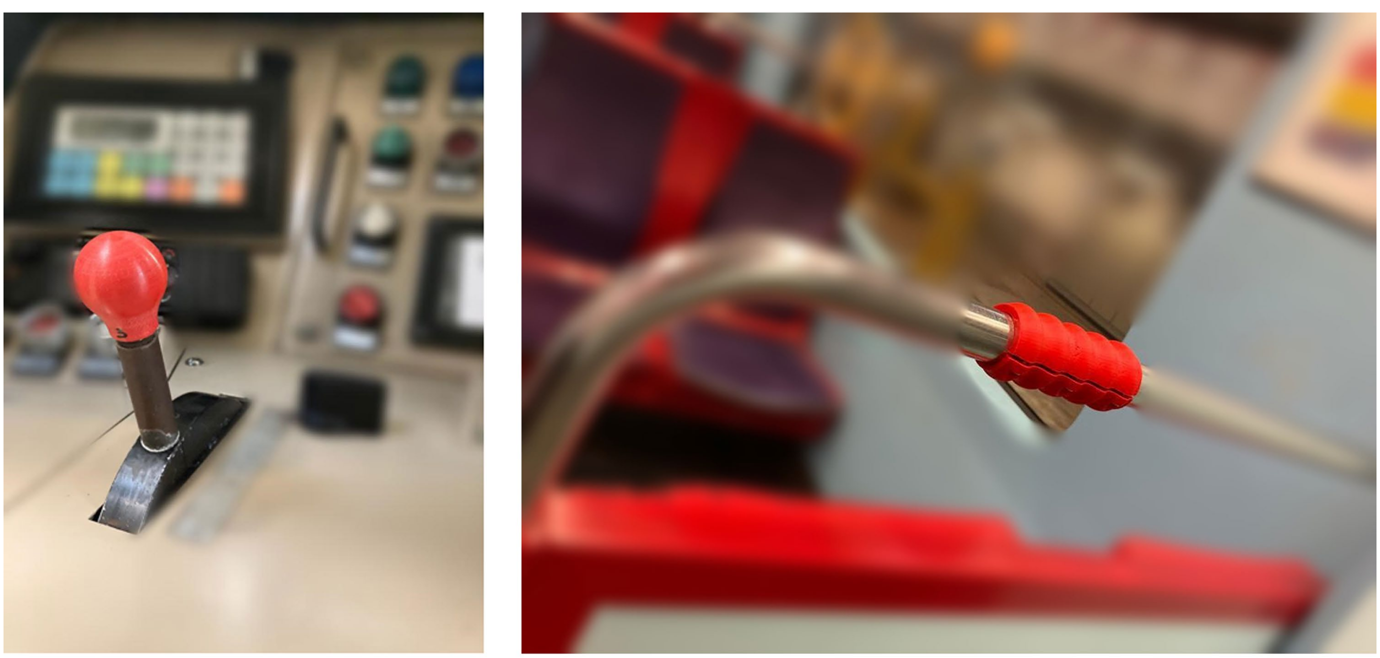
This study included in-depth interviews, follow-up interviews, site visits, and the use of secondary materials.

We conducted in-depth, semi-structured interviews (approximately one hour) with one participant from each company who, according to their companies, had the most knowledge about the research topic (Guion, Diehl, and McDonald 2011). We used a five-point Likert scale protocol to capture the interviewees’ perceptions regarding the advantages and barriers of using additive manufacturing technology for the supply of spare parts (Durach, Kurpjuweit, and Wagner 2017; Ukobitz and Faullant 2021). We also conducted one follow-up unstructured interview (approximately two hours) with each participant to seek further explanation and clarity regarding their perceptions (Kahkonen 2014). We took notes because we did not have permission to record the interviews.

The main differences between the two parts we studied are their demand rate, batch size, and production time.

We interviewed FAN3D’s project manager, who has an academic background in mechanical engineering and oversaw the project with Metropolitano de Lisboa. We interviewed Metropolitano de Lisboa’s head of maintenance, who also has an academic degree in mechanical engineering and worked for the company since 1989.

We also conducted three site visits to learn about the use of additive manufacturing technology and the characteristics of the spare parts under study. To complement the primary data we collected, we gathered secondary data from the companies’ official websites and internal sources, such as part designs or information on carriage maintenance processes. Overall, the data collection and validation phase took almost three months to complete.



(a) Handle (b) Grip

FIGURE 1. FAN3D’s additively manufactured handle (a) and grip (b) used by Metropolitano de Lisboa

TABLE 1. Spare parts' characteristics

Characteristics	Handle	Grip
Demand rate	Low	High
Batch size	Small	Large
Production time	Short (few units needed)	Long (many units needed)
Production cost	Low	Low
Design complexity	Low	Low
Size	Small	Small
Weight	Light	Light
Post-processing	Required	Required
Multi/single material	Single material (polylactic acid)	Single material (polylactic acid)

We took necessary measures to improve the case study's quality and rigor (Seuring 2008). To ensure construct validity and reliability, we used multiple data sources (interviews, site visits, secondary data), accomplishing data triangulation (Stuart et al. 2002). We input the collected data into a database to establish chain of evidence. We also asked the participants to review the interview findings (Riege 2003). In forming the Likert scale protocol, we used the existing literature at the intersection of additive manufacturing technology and spare parts supply chain management, including the common advantages and barriers of using additive manufacturing, thereby further improving the construct validity and reliability of our study (Stuart et al. 2002). We ensured internal validity by asking the participants to explain their responses to the Likert scale questions, thereby establishing causal relationships (Yin 2018) and increasing the credibility of the findings through explanation building (Riege 2003). We also cross-analyzed the results from each company to ensure external validity and relevance (Yin 2018).

Results

We describe the identified advantages and barriers of additive manufacturing for the supply of spare parts for each company (Tables 2 and 3).

Manufacturer Advantages

Using additive manufacturing to develop new parts was highly advantageous for FAN3D as it allowed the company to swiftly prototype and test the customized parts. The possibility of reducing the number of subassemblies per part (part consolidation) via additive manufacturing was not significant to FAN3D because the parts under study did not have

TABLE 2. Additive manufacturing advantages and their perceived influence by the case companies

Company	Advantages	Very low influence	Low influence	Moderate influence	High influence	Very high influence
FAN3D	New product development					X
	Part consolidation			X		
	Reduced material waste				X	
	Reduced environmental impacts			X		
	Small batch production					X
	Reduced production lead time					X
	Flexibility in production planning					X
	Improved customer experience					X
	Increased demand for 3D-printed parts					X
Metropolitano de Lisboa	Reduced maintenance costs				O	
	Reduced delivery lead time				O	
	Reduced logistics costs				O	
	Improved health and safety			O		
FAN3D & Metropolitano de Lisboa	Part customization	O				X
	Part optimization	O				X
	Reduced parts obsolescence	O				X
	Supply chain simplification				O	X
	Reduced stock levels				O	X

Note: X = FAN3D answers; O = Metropolitano de Lisboa answers

TABLE 3. Additive manufacturing barriers and their perceived influence by the case companies

Company	Barriers	Very low influence	Low influence	Moderate influence	High influence	Very high influence
FAN3D	High cost of equipment				X	
	High cost of materials		X			
	Dependence on material suppliers		X			
	Additive manufacturing training requirements				X	
	Difficulty in recruiting personnel with additive manufacturing knowledge				X	
	Unavailability of software			X		
	Post-processing				X	
Metropolitano de Lisboa	Stock replacement					O
FAN3D & Metropolitano de Lisboa	Limited part size					X O
	Reduced part quality	X				O
	Absence of uniform quality standards				X O	

Note: X = FAN3D answers; O = Metropolitano de Lisboa answers

complex designs. Reducing material waste via additive manufacturing was significant; however, FAN3D still had to go through post-processing steps (trim, sand, and polish) to obtain the desired part geometries/properties (smooth surface finish), which resulted in some material waste. The project manager mentioned that additive manufacturing processes normally consume a high rate of energy and generate CO_2 emissions, which would decrease the environmental sustainability of the production process. FAN3D considered the possibility of producing one-off or small batches of parts cost efficiently as well as reducing the production lead time highly advantageous: it would give the company flexibility in production planning and enable it to fulfill customer orders on short notice without having to worry about unpredictability in demand. FAN3D used additive manufacturing to send prototypes to the customer and make the necessary adjustments based on customer feedback, which improved the customer's experience. This capability, in turn, led to a noticeable increase in demand for additively manufactured parts.

Customer Advantages

Given the importance of spare parts to maintain the working condition of equipment, Metropolitano de Lisboa considered additive manufacturing important for reducing maintenance costs. Specifically, additive manufacturing would allow the company to acquire and replace quickly the spare parts it needed to mitigate equipment breakdown and downtime. The head of maintenance noted that the reduced delivery lead time of 3D-printed parts was an advantage. The company also reduced its logistics costs related to warehousing and storage of inventory as it could order parts on demand in different batch sizes. Given the ongoing COVID-19 pandemic, it was an advantage to be able to acquire manufactured parts with antibacterial properties that prevented the spread of coronavirus. However, for health and safety purposes, Metropolitano de Lisboa required the parts to be flame retardant, which limited somewhat the use of additive manufacturing for the manufacture of parts. Some materials used in additive manufacturing are flame retardant, while others are not.

Manufacturer and Customer Advantages

Using additive manufacturing to develop fully customized parts proved to be advantageous for FAN3D but not for Metropolitano de Lisboa. FAN3D could easily prototype and test the parts in the customization process, whereas Metropolitano de Lisboa did not necessarily need new customized parts to improve its system as it was functioning properly with standardized parts. Also, FAND3D considered the possibility of using additive manufacturing to optimize the parts according to the customer's specific needs very important. This benefit was also inconsequential to Metropolitano de

Using additive manufacturing to develop new parts was highly advantageous for FAN3D as it allowed the company to swiftly prototype and test the customized parts.

The on-demand acquisition of spare parts enabled Metropolitano de Lisboa to reduce its supplier base and lower its stock levels to nearly zero.

Lisboa because it did not need to optimize the standardized parts given that its system was already working effectively.

FAN3D also benefited significantly from reducing the obsolescence rate of parts. The on-demand manufacture of parts enabled by a print-to-order production strategy using additive manufacturing helped the company to lower its stock levels. Obsolescence risk was not an issue for Metropolitano de Lisboa because it used standardized parts that did not require change or improvements over time. Simplifying the supply chain by employing a print-to-order production strategy considerably decreased FAN3D's work-in-progress and relieved the company from having to store the manufactured parts as finished goods inventory. Simplifying its supply chain using additive manufacturing was also advantageous for Metropolitano de Lisboa: the on-demand acquisition of spare parts enabled the company to reduce its supplier base and lower its stock levels to nearly zero.

Being able to include antibacterial material in the parts was beneficial for FAN3D as the manufacturer and for Metropolitano de Lisboa as the consumer.

Manufacturer Barriers

FAN3D emphasized the expensive cost of equipment and consumables. For instance, the high cost of equipment for metal additive manufacturing forced FAN3D to delay purchasing such equipment multiple times. However, purchasing additive manufacturing materials was not an issue for FAN3D due to the growing number of material suppliers in the market for the material extrusion and vat photopolymerization processes. FAN3D was able to reduce its sourcing costs and look for more suitable suppliers.

FAN3D considered additive manufacturing training very important since its employees needed to keep their additive manufacturing knowledge and skills up to date. A key barrier for FAN3D was difficulty in recruiting personnel with adequate additive manufacturing knowledge. This barrier highlights the need for professionals with hands-on experience in operating additive manufacturing equipment and software. By contrast, limitations regarding software availability and functionality were not a big issue as FAN3D had access to different software. The need for post-processing to finish the printed parts forced FAN3D to allocate labor to this task, resulting in higher operational costs.

Customer Barriers

The main barrier for Metropolitano de Lisboa was replacing the parts that were still operational. The company had multiple units of the spare parts in stock and those in use were still functional, which meant there was no immediate need for replacing them with additively manufactured parts.

Manufacturer and Customer Barriers

Both companies considered limited part size a significant barrier. There were many instances where FAN3D rejected orders as its additive manufacturing equipment did not meet the part size requirements. Similarly, Metropolitano de Lisboa noted that size restriction considerably limits its use of 3D-printed parts. Moreover, Metropolitano de Lisboa considered the quality of these parts—especially in terms of mechanical properties like durability—to be less than parts produced via conventional methods.

For FAN3D, the ability to produce lightweight parts and the possibility to go through multiple iterations (prototyping) before producing the final part were key benefits of additive manufacturing that helped the company to greatly increase the quality of the parts. The potential increase in the number of defective parts had almost no influence on FAN3D's decision to use additive manufacturing. Based on the company's experience, by choosing the right equipment, calibrating the equipment correctly, taking their limitations into careful consideration, and performing the post-processing tasks correctly, often there would be no defective parts. By contrast, for Metropolitano de Lisboa, the likelihood of defective parts was discouraging, especially in the absence of uniform quality standards for additive manufacturing. FAN3D also considered the lack of uniform standards an important barrier, and therefore, took the measures necessary to ensure the quality of the additively manufactured parts before dispatching them.

Rethinking Additive Manufacturing

We examined additive manufacturing based on a dyadic relationship in a spare parts supply chain between a manufacturer (FAN3D) who used the material extrusion process to produce two types of spare parts with specific characteristics, and its customer (Metropolitano de Lisboa) who used these parts for maintenance purposes. We identified specific advantages and barriers for each company as well as some commonalities between the two. FAN3D could better meet its customers' needs by using additive manufacturing to develop new parts based on customer requirements, prototype and customize the parts, and optimize the parts frequently. Metropolitano de Lisboa used 3D-printed spare parts to reduce the delivery lead time and logistics costs, simplify its supply chain, and take advantage of the antibacterial quality in the materials.

Overall, the identified barriers did not prevent FAN3D from using additive manufacturing technology for spare parts production. By contrast, for Metropolitano de Lisboa, barriers such as limitations in the size and durability of parts were

TABLE 4. Questions for manufacturers to (re)consider the use of additive manufacturing for spare parts supply

Category	Advantages	Questions
Performance	New product development	• Are innovation and developing new products core to the company's business model?
	Part consolidation	• Is the number of subassemblies per part too high? • Is there a need to reduce the complexity of the production processes?
	Reduced environmental impacts	• Are the company's key performance indicators for environmental sustainability yielding unsatisfactory results?
	Improved customer experience	• Are there many customer complaints concerning the usability/functionality of the conventionally manufactured parts? • Is the company willing to include customer feedback in its processes?
	Increased demand for 3D-printed parts	• Is the market in which the company participates moving towards additively manufactured parts?
Cost + Performance	Reduced material waste	• Is the production system generating excessive material waste?
	Flexibility in production planning	• Are customer orders erratic and hard to forecast? • Is the company frequently struggling with stockouts, lost orders, and/or unsold inventory?
Performance + Delivery	Small batch production (vs. economies of scale)	• Do customer orders normally come in small numbers?
	Reduced production lead time	• Do the customers require the requested parts on short notice?
Category	**Barriers**	**Questions**
Cost	High cost of equipment	• Can the company afford the acquisition cost of additive manufacturing equipment and its consumables? • Does the projected rate of return justify investing in additive manufacturing equipment?
	High cost of materials	• Can the parts be manufactured using alternative additive manufacturing materials at lower prices?
	Additive manufacturing training requirements	• Does the company have the necessary resources to invest in additive manufacturing training?
	Difficulty in recruiting personnel with additive manufacturing knowledge	• Are there professionals in the job market with adequate additive manufacturing knowledge and experience available for hire (at an affordable cost)?
	Post-processing	• Can the company afford the necessary resources and expertise for additive manufacturing's post-processing requirements?
Performance	Unavailability of software	• Is the necessary additive manufacturing software available? • Are the selected additive manufacturing machines/3D printers compatible with different types of software (open-source systems)?
Delivery	Dependence on material suppliers	• Are there different suppliers in the market offering the same type of additive manufacturing materials? • Is there a range of material options available for the selected additive manufacturing process(es)? • Can the selected additive manufacturing machines/3D printers work with different types of materials?

TABLE 5. Questions for customers to (re)consider the use of additive manufacturing for spare parts supply

Category	Advantages	Questions
Cost	Reduced maintenance costs	• Are there frequent production halts and prolonged equipment downtimes due to spare parts shortages? • Do the spare parts need to be replaced frequently?
	Reduced logistics costs	• Are the logistics costs (warehousing and storage of inventory) of the parts unreasonably high?
Performance	Improved health and safety	• Do additively manufactured parts present an opportunity to improve health and safety conditions? • Do the additively manufactured parts comply with the established health and safety protocols?
Performance + Delivery	Reduced delivery lead time	• Do long lead times and delays in the delivery of spare parts affect the performance of the company considerably?
Category	**Barriers**	**Questions**
Cost + Performance	Stock replacement	• Can the company replace its existing stock with additively manufactured parts?

TABLE 6. Questions for manufacturers or customers to (re)consider the use of additive manufacturing for spare parts supply

Category	Advantages	Questions
Performance	Part customization	• Does the company need to frequently customize the parts?
	Part optimization	• Does the company need to frequently optimize the parts for enhancing functionality and performance?
Cost + Performance	Reduced stock levels	• Are the stock levels excessively high? • Can the on-demand manufacture and supply of parts help reduce safety stock?
	Reduced parts obsolescence	• Is the existing stock/inventory vulnerable to obsolescence? • Do the part designs need to change frequently?
Cost + Performance + Delivery	Supply chain simplification	• Is the system struggling with too much work-in-progress and finished goods inventory? • Does contracting multiple suppliers incur excessive costs and difficulties in managing the deliveries?
Category	**Barriers**	**Questions**
Performance	Limited part size	• Are the required part sizes/dimensions suitable for production via additive manufacturing?
	Reduced part quality	• Can the parts be produced by the selected additive manufacturing process(es) while meeting the required quality criteria? • Can prototyping help improve the quality of parts?
	Absence of uniform quality standards	• Can the company internally measure and control the quality of the additive manufacturing processes and parts (in-house Quality Assurance/Quality Control standards)?

discouraging, causing the company to reconsider the use of additively manufactured spare parts.

Based on the advantages and barriers we identified in this study, we present a set of questions that managers and decision makers can use to (re)consider the use of additive manufacturing technology in the context of spare parts supply chain management (Tables 4, 5, and 6). We categorize these questions according to three main criteria: cost, performance, and delivery. This categorization can facilitate the appraisal of potential trade-offs between the additive manufacturing's advantages and barriers that we identified. For instance, while some additively manufactured spare parts may not perform as well as conventionally manufactured spare parts in terms of quality, or may be limited in size, they tend to be delivered faster while reducing the logistics costs. Practitioners can discuss these types of trade-offs prior to becoming manufacturers or customers of additively manufactured spare parts. Practitioners may wish to categorize some of the identified advantages and barriers and their respective questions under different criteria. For instance, practitioners can appraise "Reduced material waste" in terms of cost and performance improvements. Overall, if practitioners have more "Yes" than "No" answers to these questions, it may be time for them to (re)consider using additive manufacturing for the supply of spare parts.

Conclusion

Based on our study of two companies, we identified several key benefits and barriers of using additive manufacturing in the spare parts supply chain. While the advantages and barriers of additive manufacturing technology are not universal, they serve as an important guide for companies exploring additive manufacturing. Notably, companies will inevitably encounter different advantages and barriers depending on the additive manufacturing process, targeted application, part characteristics, and their position in the supply chain. Practitioners can use the questions we developed based on our findings to assess whether or not their company would benefit from additive manufacturing technology for the supply of spare parts. We encourage companies to use these questions to conduct a thorough analysis prior to investing in additive manufacturing technology.

The first author acknowledges Fundação para a Ciência e a Tecnologia (FCT–MCTES) for its financial support via the MIT-Portugal Program (PRT/BD/152828/2021) and the last author via project UNIDEMI (UIDB/00667/2020).

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