Additive Manufacturing Technology for Spare Parts Application

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Spare parts management is an important part of many capital-intensive businesses, which have a direct impact on the availability of high-value capital assets. Lifecycles of advanced capital goods usually last many years, and more than 60% of their costs are related to management. Spare parts management of such goods is important because the downtime of the equipment for the lack of spare parts can cause a significant loss to the company.

Keywords: additive manufacturing ; 3D printing ; spare parts ; supply chain

1. Introduction

Additive manufacturing (AM), also known as 3D printing or rapid manufacturing, is gaining the significant attention of researchers from both industry and academia [1]. AM is defined by the American Society for Testing and Materials (ASTM) as "*the process of joining materials to make objects from 3D model data, usually layer upon layer*" [2]. The application of AM has evolved from rapid prototyping and tooling to industrial manufacturing technology to produce structural load-bearing parts [3][4]. It is a disruptive technology that competes with conventional manufacturing. AM eliminates or reduces the requirement for building the spare parts inventory and changes the way logistics and manufacturing are carried out in a supply chain (SC). AM can reduce the inventory of raw materials and its associated costs, such as order costs, transportation, and inventory cost. Instead of storing a high inventory of physical spare parts, the storage of material is considered, and it requires less space and enables the production of a wide range of products. AM technology enables the manufacturing of a variety of products with a high level of customization which leads to reduced production costs, lead times, raw material usage, and SC complexity [5]. AM is considered to have the potential to change the spare parts industry because it helps in reducing the overall cost, including inventory costs; as with AM, less raw materials and less inventory space are needed, and therefore it helps to boost SC efficiency and robustness. Thus, whenever a part is demanded, AM technology can be used to print the parts immediately, enabling the need for less physical storage space and cutting inventory holding costs across the supply chain [6]. AM enables on-demand and on-site production, shortening lead times significantly [7] and consequently reducing downtime costs. However, AM raw materials are usually expensive [8]. Therefore, a trade-off between the raw material parameters (inventory, order frequency, and demand quantity) is required to justify the adoption of AM into spare parts SC. The reduction of high levels of inventory can also be one of the motivations of many industries to adopt AM [9].

Spare parts management is an important part of many capital-intensive businesses, which have a direct impact on the availability of high-value capital assets. Lifecycles of advanced capital goods usually last many years, and more than 60% of their costs are related to management. Spare parts management of such goods is important because the downtime of the equipment for the lack of spare parts can cause a significant loss to the company [10][11]. The implementation of AM in spare parts SC can be commercially beneficial [12]. Additive manufacturing has been introduced in various industries, such as healthcare, automotive, consumer goods, and electronics. It has had a significant impact, especially in the aerospace industry. It was recently suggested that the use of AM can provide over a 60% reduction in weight compared to the original nacelle hinge bracket of the Airbus A320 [11]. Therefore, there is an opportunity to use AM in the oil and gas (O&G) industry because of the involvement of many high-value capital goods and a longer waiting time for the spares.

Many were previously conducted in the areas of SC and AM. For example, Kunovjanek et al. [8] conducted a systematic one of AM based on the supply chain operations reference (SCOR) model and highlighted the benefits and challenges of AM. Niaki et al. [13] explored AM research domains in management, industry, and economics, focusing on SC, AM technology selection, production cost models, product design, environmental aspects, strategic challenges, manufacturing systems, open-source innovation, and business models and economics. Caviggioli [14] analyzed the impact of AM on industry, business, and society. Frandsen et al. [12] also mentioned that most spare parts could be manufactured via additive manufacturing. To the best of the knowledge, this is the first one that discusses the recent progress conducted on AM, specifically in the area of spare parts logistics. As the obstacles which prevent AM from being competitive in various sectors and the strategic ways to overcome these challenges are currently at the hedge of the debate among decision makers and policy makers [14], the technology of additive manufacturing is gaining more interest among firms, industries, and academia. It was provided a holistic view of the current modeling of AM.

2. Inputs for AM Based Supply Chain

Very few researchers have focused on the input of AM-oriented SC systems. Although the SC system may be strategically designed for spare parts management, SC efficiency depends on uncertainties, demand changes, and changes in the supply potential. The type of materials required for printing can differ based on the type of spare part. Uncertainties in demand can cause problems in material availability, and this can impact the decisions to be made in the SC. Decision models based on stochastic programming may be used to analyze the impact of uncertainty in AM, such as Knofius et al. [11], such that the spare parts management system becomes profitable with AM. Li et al. [15] demonstrated the utility of a system dynamics-based model to compare the costs and emissions between AM and conventional manufacturing. It was mentioned that spare parts supply adopting AM is superior to conventional manufacturing in terms of both costs and carbon emissions.

Liu et al. [16] analyzed the performance of three SC configurations for aircraft spare parts by considering demand characteristics, manufacturing and logistics lead time, and cycle service level factors for three supply configuration scenarios: conventional, centralized, and distributed. It was obtained the demand for the spare parts, lead time, and required safety inventory for each of the regional distribution centres, service locations, and original equipment manufacturer for the three scenarios. They showed that AM has the potential to increase the efficiency of aircraft SCs.

It is on the spare part demand characteristics with AM was provided by Zhang [17]. It was examined the impact of spare parts demand on AM operations and SC performance. Demand rate effects were studied for both regular and emergency spare parts. Li [18] integrated the demand factor and arrival rate for cost and SC comparisons. It was mentioned that the demand arrival rate is a critical factor in the overall system performance of the AM-based spare parts SC. In addition, any change in the demand arrival may cause turbulence in the operating costs. It was found that a mixed supply chain configuration would outperform the centralized (where AM machines are located at centralized distribution centres) and decentralized configurations (where AM machines are deployed at each service location), especially when the demand frequency and technology development reach a certain stage. Additionally, this form of mixed configuration allows the simultaneous allocation of AM machines at regional distribution centers and service locations.

Chekurov [9] investigated the issues and industrial perceptions of adopting digital spare parts. It was provided possibilities, obstacles, networks, and requirements of digital spare parts and mentioned that long-tail products are potential candidates for digital distribution, especially long-tail spare parts, such as digitization results in the reduction of inventory and transportation costs. Bacciaglia et al. [19] introduced the photogrammetry technique which is utilized to obtain a 3D model of spare parts in the automotive industry. This technique facilitates the creation of the 3D object model, meshes and fixes its surface, and finally prints it.

Pause [20] focused on five scenarios in spare parts SC by considering a digital distributor. It was mentioned that when digital files of the production system are used, the role of the logistics service provider will be reduced. It was analyzed the scenarios by assuming that the service provider is a spare parts carrier, a digital distributor, an AM decision-maker, a selector of the manufacturer, or an AM service provider. Pause found that the individual roles of such service providers would change based on the capability of the service provider. This indicates that with AM, the service provider should also change its business model.

Kretzchmar [21] evaluated the current economic and technical feasibility of digital spare parts. It was highlighted that digital storage is more important for large enterprises, as they must store a large number of products. Digital spare parts in the defense industry were analyzed by Montero [4]. It was presented a manufacturing methodology that can support the design and manufacture of spare parts through AM. It was mentioned that in AM, the redesign requirements could become one of the barriers to creating spare parts as spare parts manufacturing uses the conventional methods.

Chekurov [9] explored the benefits of increased digitization of SC, which can help to reduce the cost related to the operator, machine, material, consumables, and energy and storage compared to conventional manufacturing. This type of benefit was also mentioned by González-Varona [22]. It was mentioned that a digital SC for spare parts can significantly benefit small- and medium-sized enterprises. This type of benefit comes from cutting the response time and reducing emissions avoided due to the elimination of spare parts transportation over a long distance and with different modes. The challenge could be to reduce the costs and emissions associated with the transportation of raw materials to be used for AM.

2.1. Process

Development and Distribution Processes

- *Manufacturing*

An analysis of AM application in COVID-19-related healthcare is provided by Salmi et al. [23]. It was analyzed the cost components for 3D printers, printer maintenance, raw material, labor, overhead, and sterilization, and mentioned that the majority of healthcare products could be produced via additive manufacturing with equipment that is available on the market. Zhang et al. [17] identified the operational details of an AM process to analyze the total costs of material, energy, operator, machine maintenance, annualized machine depreciation, and on-time delivery. It was observed that the AM operation is dependent on the size of the spare part, and in some situations, they may not be able to financially compete with the conventional method of parts supply. Cestana et al. [6] also mentioned that the performance of AM is better because of the longer set-up times required for CM. Therefore, if there are continuous requirements for the spare parts, the CM-based setup does not need to change, so in terms of setup time alone, CM may be more advantageous. However, there are other factors such as spare parts inventory requirements, the ease in obtaining and storing raw materials, and easier production of available digital files for the parts.

Delic et al. [24] analyzed different dimensions of automotive SC integration, performance, and firm performance from the perspective of additive manufacturing adoption. It was found that the adoption of AM improves SC and firm performance. However, It was mentioned that adopting AM technology alone would not create this improvement; it will also have to focus on the integration of AM with the existing SC activities. Kretzschmar [21] mentioned the opportunities for digital spare parts production by considering three aspects: demand production, speed of production compared to CM, and digital storage. It was mentioned that the limited types of 3D printers, the volume of production, integration of the IT system, and post-processing problems are some barriers to the adoption of AM in the industry. It was showed opportunities for AM, but there could be problems with the wider acceptance of AM as it requires a continuous flow of demand so that the spares can be developed on a continuous basis. If the spare parts are more durable, investments in AM may not increase cost efficiency, although it will reduce lead time requirements and increase production efficiency.

- *Inventory Control*

Zhang et al. [17] also focused on a discrete event simulation model that involves spare parts backordering, inventory replenishment, and order evaluation to assess the inventory for an AM-based manufacturing system. The model considers costs in terms of operator cost, inventory-carrying cost, fixed ordering cost, replenishment shipping cost, fixed warehouse cost, and penalty costs for late delivery. Cestana et al. [6] developed a minimization problem and mentioned that comparing the inventory performance of AM is better than that of CM because of the lower stock level with AM. As there is already a facility to produce spare parts with AM, the stock levels in AM are lower than those in the CM.

The on-site inventory level by Westerweel [25] by considering the cost and inventory for introducing AM for spare parts production in remote locations. It was suggested an optimal inventory policy that helps determine when to print a part and when to wait for its scheduled replenishment. The impact of additive manufacturing on inventory performance was also investigated by Muir [26]. It was mentioned that the adoption of AM has the potential to reduce supply risk and result in better inventory performance and management. It was showed that inventory and warehousing are crucial in managing the supply of spare parts. However, the provision of AM can create lower inventory and reduce the need to have a larger volume of space, technology, and manpower to handle such inventory, thus reducing costs.

- *Logistics*

Only a few ones deal with the logistics aspect of AM. As mentioned earlier, the adoption of AM may make some of the logistics specifically related to production management and some parts of transportation redundant. AM adoption may eliminate some parts of the SC, thus making the network shorter and with fewer players. Yilmaz [1] focused on an integrated job and vehicle scheduling problem using best-fit heuristics to minimize the makespan in an AM SC. It was found that the best-fit capacity utilization-based selection (BFCUBS) algorithm is superior to other methods in improving the make span. Similarly, He [27] focused on the integration of additive manufacturing with JIT delivery systems with the aim of minimizing delivery times and transportation costs. It was used a branch and price-based methodology for integrated machine and vehicle transportation scheduling problems. A location-dependent cost minimization SC optimization model was developed by considering the sum of production, transportation, and inventory costs. It was mentioned that the integration of production and transportation can result in cost savings for companies. Knofius et al. [10] focused on the modeling of service logistics with AM by using an analytic hierarchy process to rank the spare parts in terms of their value by focusing on attributes such as the demand rate, resupply lead time, safety stock costs, the number of supply options, and supply risks. The potential for value improvement was analyzed in terms of reduction in costs such as manufacturing, ordering, direct parts use, safe stocks, and supply disruption. It was mentioned that the development of such a rank can help the company design a better after-sales service.

The configuration of SCs for additive manufacturing in different facilities was focused by Caldas et al. al [5]. It was proposed a simulation model which simulates the installation of 3D printers in a company's internal facilities where various SC designs were changed between the model runs. They measured the performance of the SC centres with the following key performance indicators: service level, production, lead, inventory level, stock-outs, and supply costs and times. The proposed model is not only able to test the impact of additive manufacturing but can also test the impact of removing and adding internal facilities, external suppliers, and products of SC.

- *Resource Allocation*

The allocation of materials and 3D printers can be considered for resource allocation. Some investigated 3D printer allocation in sites and facilities in the context of AM [5][28]. To quantify the cost and classification of spare parts, Ott [29] proposed a multi-stage process model which serves as a decision support tool for spare parts allocation. The focus was on different spare part allocation strategies, including stockpiling, the conventional production of spares, and AM strategy. It was incorporated various cost components in the proposed cost modeling for spare allocation strategies, including the AM preprocessing and postprocessing costs, setup and preparation costs, building job assembly costs, and part building costs.

Brito [30] focused on the optimal deployment of 3D printers in different facilities for spare parts production by utilizing classical p-median, location–allocation modeling, and mixed-integer linear programming. The model was tested for the optimal scenario through an elevator maintenance with nine production centres, each with a 3D printer. It was mentioned that this type of optimal analysis would help companies manage challenges at different locations where AM is adopted.

Bonnín et al. [31] investigated the determination of the optimal location and number of manufacturing sites and trade-offs between the cost of production, transportation, and inventory through a location-dependent model followed by a cost minimization supply model. It was applied the proposed methodology to an aviation one and found that the decentralized configuration was only suitable for low-volume products. Darwish et al. [32] proposed real green time allocation and scheduling architecture for large-scale distributed additive manufacturing task allocation for healthcare spare parts and personal protective equipment (PPE). The proposed architecture was designed because of the failure of global SCs, which led to a severe shortage of PPE and spare parts. It was found that the utilization of 3D printers was improved, and the workload between them was balanced. It was mentioned that the allocation of 3D printers, raw material, and human resources should be conducted in such a way that it ensures the efficiency and effectiveness of AM.

Decision Making

Different strategies of analysis methods in decision making for AM is focused. Decision-making is focused on three main strategies: inventory, manufacturing, and maintenance. As mentioned earlier, both quantitative and qualitative analyses can be adopted for decision making on the adoption of AM for spare parts logistics.

- *Inventory Strategy*

Togwe et al. [33] investigated the reduction of the overall system lead time through the addition of different percentages of AM spares into the inventory mix. It was proved that AM provides agility and positively affects lead times associated with spare parts replenishment, resulting in less capital tied up in spare parts inventory.

Taking the example of AM for spare parts supply in the aircraft industry, Liu et al. [16] mentioned that the focus of inventory strategy with AM would be to reduce the safety stock of spare parts in the SC. Owing to the high value of products in the aircraft industry, any addition of safety stock can lead to a significant increase in the cost of SCs. It was analyzed two situations to understand their impact on inventory: producing slow moving parts in a centralized location and aggregating demand for the utilization of the AM capacity, and deployment of AM in service locations to reduce the cost of transportation and inventory. It was mentioned that if a company adopts the centralized approach, its strategy would be to build an inventory based on historical demand so that the customer service level is decreased.

Heinen et al. [34] assessed the switch from conventional manufacturing of slow-moving spare parts to additive manufacturing based on models and concepts of inventory management. It was found out through the empirical dataset which they used that the switch to AM technology would result in an overall system cost reduction of 6.4%. It was explored the opportunities for the digitization of spare parts and their implications for inventory management and after-sales services.

- *Manufacturing Strategy*

Caldas et al. [5] measured the performance of SC simulations using the following key performance indicators: service level, inventory level and cost, production time and cost, lead time, stock-outs number and costs, and supply costs. It was mentioned that AM has the capability of highly customized manufacturing, but it may be good for manufacturing batches with a lower volume. It was developed a simulation model to learn the AM for spare parts for elevators. They mentioned that the model could support choosing a manufacturing strategy in an SC based on the total cost, lead time, and service level. It was indicated that based on the demand, the manufacturing capabilities might have to be changed at different locations, and the decision makers should be open to adding or removing AM facilities in some locations. Westerweel [35] compared the manufacturing of components with conventional manufacturing and AM using a lifecycle cost model. It was found that AM is more beneficial in after-sales service logistics. Break-even characteristics allow the OEM to decide which design option to adopt in the early design process.

Knofius et al. [10] suggested a scoring methodology that identifies eligible spare parts for AM. The methodology helps to increase the effectiveness and efficiency of selecting promising facilities for after-sales service logistics. Similarly, Marek et al. [36] designed a web-based software tool to select a suitable 3D printer service provider. The tool provides an AM feasibility assessment to identify the components that can be manufactured through AM. Supporting the decision-making process in aerospace MRO activities, Deppe [37] developed a decision tool that calculates the expected cost of AM, conventional technology, and the procurement of a new part from the original equipment manufacturer. The tool can support decision-making when adopting a manufacturing strategy. The proposed multi-attribute decision analysis model considered the cost, time, and quality of the technology. Another decision support tool was proposed to assist decision makers in the selection of the right AM technology class and material in a remote manufacturing environment [38]. Each of the processes, machines, parts, material, environment, and logistics objectives and constraints were identified and used in decision support. It was showed that researchers considered analytical tools to help the industry select conventional manufacturing and AM. Additionally, for AM, decisions on capacity, allocation of AM facilities, and demand-based manufacturing strategies were also considered.

- *Maintenance Strategy*

Cardeal [3] suggested a process-based model to learn the viability of AM in maintenance activities. The developed model and costing approaches included three stages: design, manufacturing, and warehouse management. It was highlighted the importance of the potential of AM in reducing maintenance costs and extending machine lifetimes.

Cardeal [39] applied a sustainable procedure model for aircraft maintenance. It was focused on the impact of shifting from traditional maintenance, repair, and overhaul activities to AM. It was showed that from the point of view of maintenance, the adoption of distributed manufacturing of spare parts unlocks the opportunity for spare weight optimization. Moreover, it reduces the transportation of parts, raw material consumption, and fuel savings during aircraft operation.

Xu et al. [40] used a hybrid simulation model to compare SC configurations to assess the effect of additive manufacturing capabilities on improvements in operational efficiency and maintenance effectiveness. However, they did not take into consideration the resource management aspect of maintenance operations, such as maintenance equipment and maintenance technicians, which will allow more rational decision-making in manufacturing resource deployment.

Togwe et al. [33] demonstrated that the use of AM in maintenance supports both preventive maintenance and corrective maintenance strategies. The adoption of AM would provide agility and positively affect lead times associated with the replenishment of spare parts. It was showed that researchers have shown that the choice of AM can also be based on the maintenance strategy and that lead time, service effectiveness, and agility can be some of the aspects that can favor AM. However, one must remember that if the company adopts a safety-stock-based policy, lead time, service effectiveness, and agility in maintenance could be much better. Therefore, a maintenance strategy should be considered along with the total system cost of adopting AM or adopting conventional manufacturing with an inventory.

3. Constraints

As mentioned above, the AM process, decision-making, and strategies are governed by the constraints imposed by the business, government, and standards. It is discussing these limitations and constraints to drive or adopt AM is discussed here.

Sourcing

In order to run the AM, material availability is one of the most important aspects. Companies can adopt single sourcing, dual sourcing, or competitive sourcing by controlling the quantities and negotiating prices. The focus in AM is on raw materials, for which the number of suppliers may be higher. The AM industry can treat these items as leverage or non-critical items rather than strategic or bottleneck items, and sourcing strategies can change. The company must adopt a long-term collaboration with the raw material supplier (even the technology supplier) if there are only a few suppliers in the market. However, due to the uncertainty of demand and better perception of conventionally manufactured products, industries would have to judge their sourcing strategy.

In most situations, industries seem to focus on dual sourcing, one for AM and the other for CM-based spare parts development [11]. Knofius et al. [11] mentioned that sourcing with AM is better when the AM piece purchase price is high, and the demand rate and backorder costs are high. The reduced holding cost can be an advantage for the AM in this. It was also mentioned that in others, sourcing using the conventional method remains profitable.

Knofius et al. [41] focused on the value of sourcing spare parts using a mix of AM and CM methods. It was focused on the aerospace industry. It was analyzed sourcing through the optimization model, optimal inventory policy, optimal sourcing, and maintenance strategy. It was showed that dual sourcing is the best in the aerospace industry. Westerweel et al. [25], who focused on AM-based spare parts for the army, also mentioned that a dual sourcing strategy, printing urgent spare parts instead of waiting for conventional parts to arrive at scheduled replenishments, is a better option. Although they assume that printed parts are less reliable, AM parts can fill the short-term gap until the CM-based parts are replenished. This type of policy provides a strategic advantage in decreasing the army’s reliance on vulnerable supply lines and enables more efficient and effective operations on foreign missions. Currently, most firms and organizations rely on the dual sourcing option to experience the adoption of AM, as they are still hesitant about this technology. It was showed that sourcing is important in making the AM system work. If single sourcing is adopted, or if the materials are considered as leverage items rather than strategic items, then the industry may suffer from a lack of continuous supply of spare parts.

Configuration

The configuration and design of the SC structure impose a constraint on the AM-based SC. The adoption of AM into SCs can be performed in three configurations: distributed or decentralized configuration, centralized configuration, and hybrid or mixed configuration. These configurations can be based on either AM, conventional manufacturing, or both. Scenario analysis is primarily used to develop the configuration options. Durão et al. [42][43] analyzed a decentralized manufacturing scenario for spare parts. It was tested different configurations using a central factory and distributed AM sites to identify the main differences and requirements between the levels of integration in distributed manufacturing. It was used AM in various stages in the supply network and different configuration scenarios and mentioned that AM could support the creation of specialized central manufacturing (for developing product models) and flexible production systems closer to the client side. As mentioned earlier, different SC configurations for AM were also discussed by Liu et al. [16]. The configurations focused on analyzing the safety inventory. It was found that these SCs can be configured to use AM; such a configuration has the potential to reduce safety inventory and cut inventory-holding costs across the entire SC.

SC configurations with five scenarios were also discussed by Pause et al. [20]. It was mentioned that the traditional configuration might be considered redundant. As a result, the role of the logistics service provider as the AM-based SC is focused on digital distribution, platform-based decision making on production, and the selection of the manufacturer. This creates a new type of SC configuration, which service providers should carefully assess. Similarly, Shuang et al. [44] proposed three SC configurations based on different locations of AM implementation and compared them based on qualitative lead time analysis. Nyamekye [45] compared SC scenarios in terms of sustainability, where CNC machining and laser additive manufacturing (LAM) were compared. It was mentioned that factors such as material consumption, manufacturing steps, length of SC, and the swiftness of production affect the sustainability of a process. Based on this, it can be mentioned that the SC configuration with LAM-based production can provide better sustainable gain in terms of material efficiency.

AM Technology

Kretzschmar et al. [21] focused on the technical barriers related to AM technology, such as materials, accuracy levels, additive manufacturing chamber, 3D model, and postprocessing capabilities. It was investigated the economic barriers related to digital spare production costs, investment costs, employees' skills, and supplier contracts. Salmi et al. [23] utilized three different AM technologies, namely vat photopolymerization (VP), material extrusion (ME), and powder bed fusion (PBF), to produce medical spare parts. These spares included face shields, facemasks, nasal swabs, and venturi valves, which were in high demand, especially during the COVID-19 pandemic. Vat photopolymerization (VP) is used the most in the medical field as it supports biocompatible materials. However, additive manufacturing technologies are being adopted in various applications and industries; however, some limitations still exist, such as the printing time, raw material cost, and the need for post-processing. Nyamekye [45] mentioned the availability and use of metal powders for laser-based AM. It was mentioned that with this type of technology, owing to the optimized geometry of the parts for manufacturing, the cost of production and the management of SC could be cheaper. Technology is advancing in AM; however, the main factors in spare parts manufacturing could be the suitability of the technology, material supply, and efficiency in terms of costs and emissions. As AM technology is considered a constraint, decision makers need to analyze the available technology and match it with the demand pattern, lifecycle costs of operation, and the quality of spare parts produced. Once the investment is made, changes to be made in manufacturing and SC configurations can be very costly.

Carbon Tax

One important aspect of AM is the potential to reduce emissions. However, such options are usually only possible when there is a strong carbon policy with the allocation of the maximum emissions cap and taxing the carbon above that particular cap. This type of policy, called the carbon cap policy, can be a factor for the adoption of AM as it reduces spare parts transportation, improves parts production through digitation, and promotes decentralized parts production. Therefore, the existence of a carbon tax is an important constraint for the promotion of AM. Analysis can be performed to assess emissions scenarios with different SC configurations and material use. Li [15] developed carbon emission models for three different SC scenarios. Although AM raw materials generate more carbon emissions than conventional materials, emissions are higher for the conventional process, as each CM product consumes more raw material than the AM product. Cardeal [39] included the carbon footprint in the environmental assessment of a new business model canvas. It was obtained carbon emissions for a full lifecycle of a spare part, including production, transport, use, and end-of-life. It was mentioned that AM has a significant advantage in terms of reduced emissions on a year-on-year basis compared to conventional manufacturing. Therefore, if carbon tax regulations are effective, the industry can adopt AM. Similarly, carbon analysis and energy savings were also focused on by Isasi-Sanchez [46]. It was mentioned that AM options are more sustainable in terms of energy and emissions. It was showed that with the advancement of AM technology, increased quality of AM parts, reduced costs of technology, and reduced emissions in the overall SC configuration, AM can be an option for spare parts service management. It was also analyzed emissions as one of the important outputs of AM. If there are justifiable carbon tax or carbon cap policies implemented in various parts of the SC, the industry can aim to adopt AM as a way to become more environmentally friendly and sustainable.

4. Difficulties of Spare Parts Management

It was showed that there are several challenges in AM adoption. One of the greatest challenges seems to be the perception of the inferior quality of AM-based spare parts. Most researchers still show AM as a stop-gap for a short-term supply of spare parts until the availability of conventionally manufactured parts. This could be because conventional manufacturing produces parts based on established processes, with established machines, and with the required quality assurance and control. Homogeneity in terms of material and the performance of the produced parts can be considered implicitly by the researchers as the benefits of conventional manufacturing. It is assumed that postprocessing may be needed to meet the accepted standards of quality parts [4], and this could add processing and quality control costs. Postprocessing could include heat treatment, surface treatment, secondary machining, assembly [47], and quality testing. In some situations, the integration of AM parts with other parts can also pose a challenge. Therefore, added costs and the limited number of material suppliers make it a challenge to adopt AM [22][48]. There seems to be no challenge in terms of configuring or reconfiguring SCs. Another challenge is the constraints owing to the cost of the technology. Because of investment costs, the purchase of multiple machines may not be economical, and therefore, one way to counter this is to develop hub-based manufacturing for spoke-based demand centres. Another technical limitation is the design of the spare parts. When spare parts are designed for conventional manufacturing, the digitation of manufacturing can become difficult owing to the limitations of AM technology. [4]. Another challenge is the intellectual property rights (IPR) of these parts. Security and certification requirements exist in terms of handling digital data and producing spares.

References

1. Jiménez, A.; Bidare, P.; Hassanin, H.; Tarlochan, F.; Dimov, S.; Essa, K. Powder-Based Laser Hybrid Additive Manufacturing ofMetals: A Review.Int. J. Adv. Manuf. Technol.2021,114, 63–96.
2. Vendra, L.; Achanta, A. Metal Additive Manufacturing in the Oil and Gas Industry. In2018 International Solid Freeform FabricationSymposium; University of Texas at Austin: Austin, TX, USA, 2020; pp. 454–460.
3. Cardeal, G.; Sequeira, D.; Mendonça, J.; Leite, M.; Ribeiro, I. Additive Manufacturing in the Process Industry: A Process-BasedCost Model to Study Life Cycle Cost and the Viability of Additive Manufacturing Spare Parts.Procedia CIRP2021,98, 211–216.
4. Montero, J.; Weber, S.; Bleckmann, M.; Paetzold, K. A Methodology for the Decentralised Design and Production of AdditiveManufactured Spare Parts.Prod. Manuf. Res.2020,8, 313–334.
5. Caldas, N.; de Sousa, J.P.; Alcalá, S.G.S.; Frazzon, E.; Moniz, S. A Simulation Approach for Spare Parts Supply Chain Management.In Proceedings of the International Conference on Industrial Engineering and Operations Management, Pilsen, Czech Republic,23–26 July 2019; pp. 1072–1081.
6. Cestana, A.; Pastore, E.; Alfieri, A.; Matta, A. Reducing Resupply Time with Additive Manufacturing in Spare Part Supply Chain.IFAC-PapersOnLine2019,52, 577–582.
7. Boer, J.D.; Lambrechts, W.; Krikke, H. Additive Manufacturing in Military and Humanitarian Missions: Advantages andChallenges in the Spare Parts Supply Chain.J. Clean. Prod.2020,257, 120301.
8. Thomas, D.S.; Gilbert, S.W.Costs and Cost Effectiveness of Additive Manufacturing: A Literature Review and Discussion AppliedEconomics Office; Engineering Laboratory, National Institute of Standards and Technology: Gaithersburg, MD, USA, 2014.
9. Chekurov, S.; Metsä-Kortelainen, S.; Salmi, M.; Roda, I.; Jussila, A. The Perceived Value of Additively Manufactured Digital SpareParts in Industry: An Empirical Investigation.Int. J. Prod. Econ.2018,205, 87–97.
10. Knofius, N.; Van Der Heijden, M.C.; Zijm, W.H.M. Selecting Parts for Additive Manufacturing in Service Logistics.J. Manuf.Technol. Manag.2016,27, 915–931.
11. Knofius, N.; van der Heijden, M.C.; Zijm, W.H.M. Moving to Additive Manufacturing for Spare Parts Supply.Comput. Ind.2019,113, 103134.
12. Frandsen, C.S.; Nielsen, M.M.; Chaudhuri, A.; Jayaram, J.; Govindan, K.; Selmer Frandsen, C. In Search for Classification andSelection of Spare Parts Suitable for Additive Manufacturing: A Literature Review.Int. J. Prod. Res.2020,58, 970–996.
13. Khorram Niaki, M.; Nonino, F. Additive Manufacturing Management: A Review and Future Research Agenda.Int. J. Prod. Res.2017,55, 1419–1439.
14. Caviggioli, F.; Ughetto, E. A Bibliometric Analysis of the Research Dealing with the Impact of Additive Manufacturing onIndustry, Business and Society.Int. J. Prod. Econ.2018,208, 254–268.
15. Bacciaglia, A.; Ceruti, A.; Liverani, A. Photogrammetry and Additive Manufacturing Based Methodology for DecentralizedSpare Part Production in Automotive Industry. InInternational Conference on Intelligent Human Systems Integration; AISC; Springer:Cham, Switzerland, 2020; Volume 1131.
16. Darwish, L.R.; Farag, M.M.; El-Wakad, M.T. Towards Reinforcing Healthcare 4.0: A Green Real-Time IIoT Scheduling and NestingArchitecture for COVID-19 Large-Scale 3D Printing Tasks.IEEE Access2020,8, 213916–213927.
17. Bonnín Roca, J.; Vaishnav, P.; Laureijs, R.E.; Mendonça, J.; Fuchs, E.R.H. Technology Cost Drivers for a Potential Transition toDecentralized Manufacturing.Addit. Manuf.2019,28, 136–151.
18. De Brito, F.M.; Da Cruz Junior, G.; Frazzon, E.M.; Basto, J.P.; Alcala, S.G.S. An Optimization Model for the Design of AdditiveManufacturing Supply Chains. In Proceedings of the 2019 IEEE 17th International Conference on Industrial Informatics (INDIN),Helsinki, Finland, 22–25 July 2019; pp. 881–885.
19. Li, Y.; Cheng, Y.; Hu, Q.; Zhou, S.; Ma, L.; Lim, M.K. The Influence of Additive Manufacturing on the Configuration ofMake-to-Order Spare Parts Supply Chain under Heterogeneous Demand.Int. J. Prod. Res.2019,57, 3622–3641.
20. Pause, D.; Marek, S. Supply Chain Scenarios for Logistics Service Providers in the Context of Additive Spare Parts Manufacturing.InIFIP International Conference on Advances in Production Management Systems; Springer: Cham, Switzerland, 2019; Volume 567.
21. Knofius, N.; van der Heijden, M.C.; Zijm, W.H.M. Consolidating spare parts for asset maintenance with additive manufacturing.Int. J. Prod. Econ.2019,208, 269–280.

22. Khajavi, S.H.; Holmström, J.; Partanen, J. Additive Manufacturing in the Spare Parts Supply Chain: Hub Configuration andTechnology Maturity.Rapid Prototyp. J.2018,24, 1178–1192.
23. Kretzschmar, N.; Chekurov, S.; Salmi, M.; Tuomi, J. Evaluating the Readiness Level of Additively Manufactured Digital SpareParts: An Industrial Perspective.Appl. Sci.2018,8, 1837.
24. Togwe, T.; Tanju, B.; Eveleigh, T.J. Using a Systems Engineering Framework for Additive Manufacturing.Syst. Eng.2018,21,466–475.
25. Ivan, S.; Yin, Y. Additive Manufacturing Impact for Supply Chain—Two Cases. In Proceedings of the 2017 IEEE InternationalConference on Industrial Engineering and Engineering Management (IEEM), Singapore, 10–13 December 2017; pp. 450–454.
26. Ma, S.; Tan, M.K.J.; Chen, S. Supply chain perspective on additive manufacturing. In Proceedings of the 3rd InternationalConference on Progress in Additive Manufacturing (Pro-AM 2018), Singapore, 14–17 May 2018; pp. 353–357.
27. Ghadge, A.; Karantoni, G.; Chaudhuri, A.; Srinivasan, A. Impact of Additive Manufacturing on Aircraft Supply Chain Perfor-mance: A System Dynamics Approach.J. Manuf. Technol. Manag.2018,29, 846–865.
28. Muir, M.; Haddud, A. Additive Manufacturing in the Mechanical Engineering and Medical Industries Spare Parts Supply Chain.J. Manuf. Technol. Manag.2018,29, 372–397.
29. Li, Y.; Jia, G.; Cheng, Y.; Hu, Y. Additive Manufacturing Technology in Spare Parts Supply Chain: A Comparative Study.Int. J.Prod. Res.2017,55, 1498–1515.
30. Kostidi, E.; Nikitakos, N. Exploring the Potential of 3D Printing of the Spare Parts Supply Chain in the Maritime Industry. InSafetyof Sea Transportation, Proceedings of the International Conference on Marine Navigation and Safety of Sea Transportation, TRANSNAV2017, Gdynia, Poland, 21–23 June 2017; pp. 171–178.
31. Chekurov, S.; Salmi, M. Additive Manufacturing in Offsite Repair of Consumer Electronics.Phys. Procedia2017,89, 23–30.
32. Savastano, M.; Amendola, C.; Massaroni, E. 3-D Printing in the Spare Parts Supply Chain: An Explorative Study in the AutomotiveIndustry. InDigitally Supported Innovation; Springer: Cham, Switzerland, 2016; pp. 273–284.
33. Loy, J.; Tatham, P. Redesigning Production Systems. InHandbook of Sustainability in Additive Manufacturing; Springer:Singapore, 2016.
34. Khajavi, S.H.; Partanen, J.; Holmström, J. Additive Manufacturing in the Spare Parts Supply Chain.Comput. Ind.2014,65, 50–63.
35. Liu, P.; Huang, S.H.; Mokasdar, A.; Zhou, H.; Hou, L. The Impact of Additive Manufacturing in the Aircraft Spare Parts SupplyChain: Supply Chain Operation Reference (Scor) Model Based Analysis.Prod. Plan. Control2014,25, 1169–1181.
36. Mohajeri, B.; Khajavi, S.H.; Nyberg, T.; Khajavi, S.H. Supply Chain Modifications to Improve Additive Manufacturing Cost-BenefitBalance. In2014 International Solid Freeform Fabrication Symposium; University of Texas at Austin: Austin, TX, USA, 2014.
37. Xu, X.; Rodgers, M.D.; Guo, W. Hybrid Simulation Models for Spare Parts Supply Chain Considering 3D Printing Capabilities.J.Manuf. Syst.2021,59, 272–282.
38. Marinho De Brito, F.; Junior, G.D.C.; Frazzon, E.M.; Basto, J.P.T.V.; Alcala, S.G.S. Design Approach for Additive Manufacturing inSpare Part Supply Chains.IEEE Trans. Ind. Inform.2021,17, 757–765.
39. Isasi-Sanchez, L.; Morcillo-Bellido, J.; Ortiz-Gonzalez, J.I.; Duran-Heras, A. Synergic Sustainability Implications of AdditiveManufacturing in Automotive Spare Parts: A Case Analysis.Sustainability2020,12, 8461.
40. González-Varona, J.M.; Poza, D.; Acebes, F.; Villafáñez, F.; Pajares, J.; López-Paredes, A. New Business Models for SustainableSpare Parts Logistics: A Case Study.Sustainability2020,12, 3071.
41. Chandima Ratnayake, R.M. Enabling RDM in Challenging Environments via Additive Layer Manufacturing: Enhancing OffshorePetroleum Asset Operations.Prod. Plan. Control2019,30, 522–539.
42. Manco, P.; MacChiaroli, R.; Maresca, P.; Fera, M. The Additive Manufacturing Operations Management Maturity: A Closed or anOpen Issue?Procedia Manuf.2019,41, 98–105.
43. Nyamekye, P.; Leino, M.; Piili, H.; Salminen, A. Overview of Sustainability Studies of CNC Machining and LAM of Stainless Steel.Phys. Procedia2015,78, 367–376.
44. Corsini, L.; Aranda-Jan, C.B.; Moultrie, J. The Impact of 3D Printing on the Humanitarian Supply Chain.Prod. Plan. Control2020,33, 1–13.

45. Franco, D.; Miller Devós Ganga, G.; de Santa-Eulalia, L.A.; Godinho Filho, M. Consolidated and Inconclusive Effects of AdditiveManufacturing Adoption: A Systematic Literature Review.Comput. Ind. Eng.2020,148, 106713.
46. Da Silva, M.; Da Silva, L.C.A.; Brambilla, F.R. Implications of additive manufacturing on supply chain and logistics.Indep. J.Manag. Prod.2020,11, 1323.
47. Yilmaz, Ö.F. Examining Additive Manufacturing in Supply Chain Context through an Optimization Model.Comput. Ind. Eng.2020,142, 106335. [
48. Verboeket, V.; Krikke, H. The Disruptive Impact of Additive Manufacturing on Supply Chains: A Literature Study, ConceptualFramework and Research Agenda.Comput. Ind.2019,111, 91–107.