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Review

Additive Manufacturing Technology for Spare Parts Application: A Systematic Review on Supply Chain Management

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Abstract: Additive manufacturing (AM) is gaining interest among researchers and practitioners in the field of manufacturing. One major potential area of AM application is the manufacturing of spare parts, which affects the availability of the operation and supply chain. The data show that the application and adoption of AM has contributed to a reduction in lead times and inventory, which also contributes to a reduction in holding costs. This paper provides a review of recent work on the application of AM technology specifically for spare parts. The review shows that there are supply chain opportunities and challenges to the adoption of AM in spare parts within various application sectors. Our research reviews both the quantitative and qualitative models used for analysis to meet the emerging needs of the industry. The review also shows that the development of technology and its application is still emerging; therefore, there will be further opportunities to develop better spare parts supply chains to support AM applications. This paper concludes with future research directions.

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

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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. A study 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 reviews were previously conducted in the areas of SC and AM. For example, Kunovjanek et al. [8] conducted a systematic review 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 our knowledge, this is the first review that discusses the recent work 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. This paper provides a holistic view of the current modeling of AM.

The potential of AM in spare parts logistics is discussed within various contexts such as resource allocation, logistics, manufacturing, decision making, etc., which will be explored in detail in Section 3. Difficulties and hurdles in terms of AM adaptation and spare parts handling are also discussed. This study aims to answer the following research questions:

RQ1: What opportunities exist for AM in spare parts SC?
RQ2: What models are available to analyze AM in SC?
RQ3: What challenges make AM more difficult to adopt?
RQ4: What difficulties are faced in spare parts management?

The main contribution of this study is to provide a broader understanding of the status in the analysis, adoption, challenges, and research of SCs that can support spare parts management by utilizing AM. This paper uses a systematic review process and content analysis to review the literature on additive manufacturing-based spare parts SC. As AM is generally a recent phenomenon, this study focuses on the literature published in the last 10 years. The remainder of this paper is organized as follows. Section 2 presents the results of this review process. Section 3 discusses the SC potential for AM based on the results obtained in Section 2. Section 4 summarizes the main findings and proposes future research directions. This paper follows a systematic literature review method to extract the content of the literature. The literature used in the review was extracted from the following databases: Scopus, Web of Science, IEEE, and ScienceDirect. The search was conducted using a combination of the following keywords: "Additive Manufacturing", "3D Printing", "Supply Chain", and "Spare Parts" within the title, abstract, and keywords of the publications. The search range date was limited to the last 10 years, from 2010 to April 2021. The inclusion criterion considered articles which concentrate mainly and contribute at least one of the three core subject areas: AM, SC, and spare parts management. After the systematic method, the content analysis was applied to extract and analyze the literature content. Table 1 illustrate the references along with the areas where they contribute. In total, 152 articles were retrieved, of which 60 were eligible for the study according to the established criteria as shown in Figure 1.

Table 1. References along with their dealt topics.

Authors	Subject Areas
[3,5,6,9–12,15–40]	✓ Additive Manufacturing ✓ Spare Parts Management ✓ Supply Chain
[8,41–48]	✓ Additive Manufacturing ✓ Supply Chain
[4,7,49–58]	✓ Additive Manufacturing ✓ Spare Parts Management
[14,59–62]	✓ Additive Manufacturing

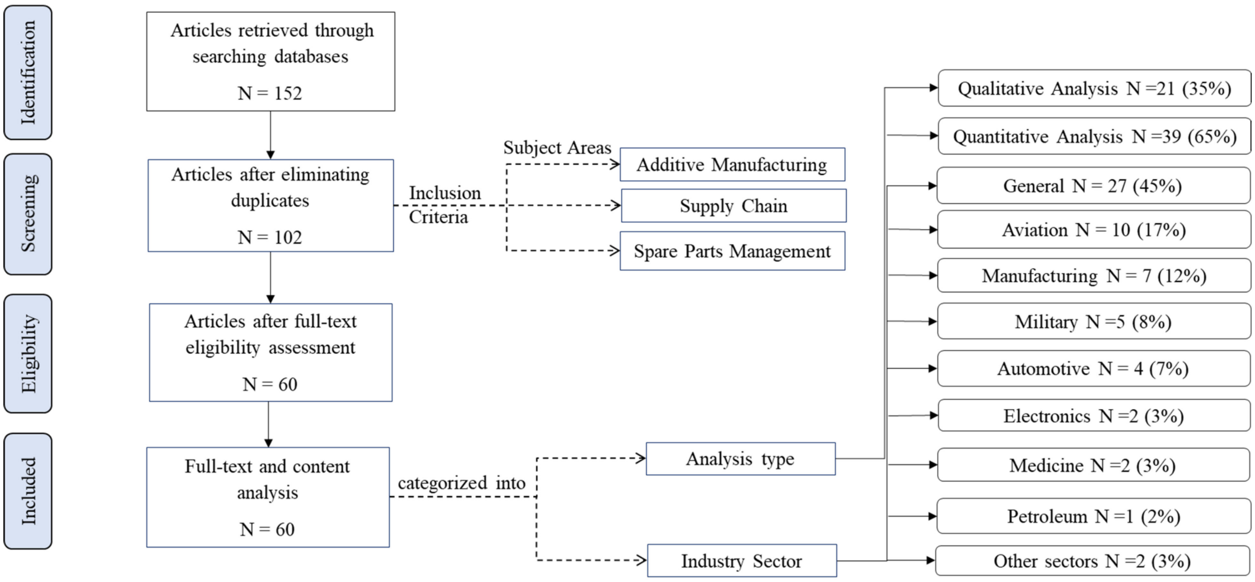

Figure 1. Review process flowchart.

2. Results of Literature Analysis

The literature analysis was divided into several segments. The first part discusses the systematic process of reviewing the literature. This is followed by a content analysis of the literature. Section 3 of the review paper summarizes these findings and discusses them.

2.1. Systematic Process

The literature search showed AM applications in various industries that include aviation [17,24,27,34,35,54,56,57,59], manufacturing and logistics [5,9,18,20,28,38,63], automotive [15,25,32,39], military [7,11,22,37,55], medicine [16,52], electronics [31,64] and petroleum [41]. However, most of the literature provides research which is not related or specified to any particular industry sector [3,6,10,14,19,23,26,29,33,36,40,42,43,45,46,48–51,53,58,60–62,65,66]. The review shows that AM has significant impact and growth in SC networks, largely in the aerospace industry. Quantitative analysis refers to research articles involving various types of quantitative and analytical studies. Qualitative analysis refers to literature reviews, scenario analysis, empirical studies, surveys, and case studies related to AM and SCs. Scenario analysis can be considered using a quantitative model. The review shows that the majority of the literature focuses on the quantitative analysis of SC in AM. The classification of the analysis method is given in Table 2. Empirical studies focus on examining the impact of the AM on the inventory performance and technical feasibility of digital spare parts, whereas scenario analysis aims to compare different SC configurations and models adopting AM. Quantitative analyses are mainly conducted in the contexts of resource allocation, inventory management, and dual sourcing.

Table 2. References of literature for different approaches.

Study Type	Authors
Empirical Study	[23,28]
Case Study	[39,40,44]
Scenario Analysis	[17,20,22,26,27,29,31,32,34,35,37,43,49,63]
Quantitative Modeling	[1,3–6,11,17,18,25,38,50,52–58,62,64]
Other approaches	[9,10,15,16,24,30,36,41,51,59–61]

2.2. Content Analysis

To extract the insights provided in the selected literature, the BLOC-ICE systems conceptual framework developed by Pokharel [67] was used. Based on the BLOC-ICE framework (Figure 2), the content of the literature was divided into four parts: (i) inputs for initiating AM-based SC; (ii) the SC processes such as resource allocation, manufacturing, inventory, and logistics, and decision-making to facilitate the AM; (iii) constraints that limit the functioning of the processes; and (iv) the outputs. The contents mentioned in Figure 2 are discussed below. The inputs consider material availability, demand for spare parts, uncertainty factors, supply potential, and digital files, which transmit the required information in order to manufacture the 3D printed parts using the system process. The raw and input materials are demanded and scheduled to be replenished from a particular supplier with a certain quantity at a certain period. The demand for spare parts is usually uncertain, which explains the uncertainty factors in the input stage. The supply potential is related to the supplier capacity. Initially, the raw material should be available to move to the processing stage. Then, the material is processed in the AM-based SC system to undergo different processes, including decision-making. In the processing stage, the material and other resources are allocated, and parts are manufactured, stored, and transported. Resources such as spare parts, 3D printers, and raw materials must be optimally allocated to minimize the cost and increase the efficiency of the production system to meet the demand.

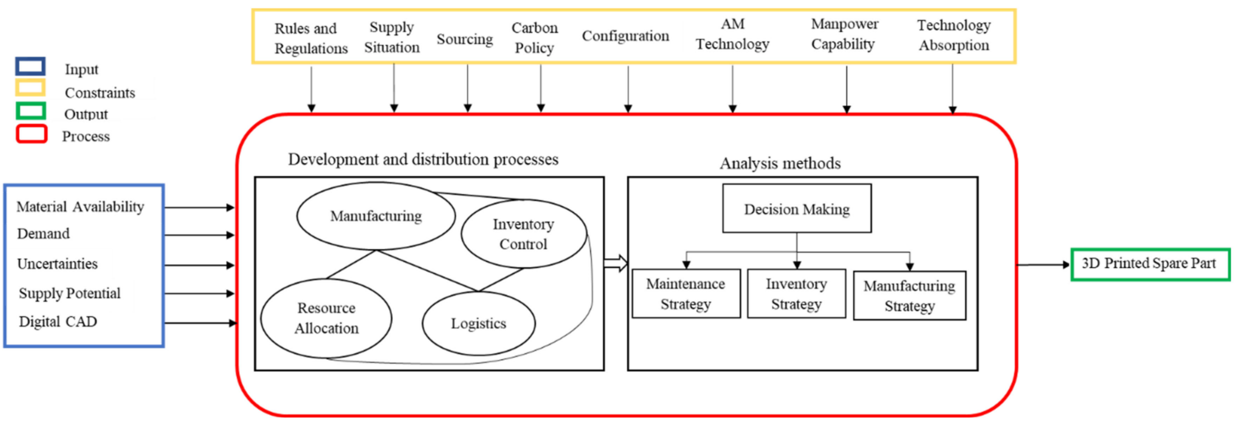

Figure 2. Supply chain process adopting additive manufacturing in spare parts management.

The control of inventory is dependent on the available storage space, quantity of raw materials, demand for spares, manufacturing capability, and logistics capability of packaging and transportation. Parts can be transported either through agents (such as third-party logistics providers or freight forwarders) or directly by the company to the service location. The management of the AM-based SC is supported by decision-making in which inventory, manufacturing, and maintenance strategies of the company are considered. The optimal manufacturing strategy could be to partially focused on conventional methods instead of the total dependence on the additive methods. Maintenance strategies can be implemented in different types, including corrective maintenance, preventive maintenance, condition-based maintenance, and predictive maintenance. The company decides on the maintenance approach which suits the business and assets the most. Therefore, the spare parts production system also focuses on the type of maintenance strategies used by the company. A mixture of maintenance strategies can be adopted by organizations [68]. Inventory strategy also becomes important to balance the production and storage, lead time to meet the demand through internal production or purchase of spare parts, service efficiency, and cost of handling and operation. Therefore, the decision to produce spare parts requires multi-level analysis.

The output of the process is 3D printed spare parts. Note that all parts are developed by strictly adhering to the 3D digital computer-aided design (CAD) input file. The AM and SC processes that are shown in Figure 2 also show the constraints. There are various constraints or limitations which govern the conversion of inputs to the intended outputs. Multiple constraints were identified in the literature. Policies, rules and regulations, and other factors, including the type of AM technology adopted in the industry, the impact of the adoption, and the use of AM in the company. The SC process is controlled by the rules and policies of various parties, including suppliers, original equipment manufacturers (OEMs), distributors, and customers. The supply potential and sourcing strategy of the components and the adopted SC configuration also control the process. Other requirements which are essential to driving the system are the level of technology absorption of the company and the capability to utilize and maintain a certain type of AM technology. Carbon policy through carbon tax can also facilitate the SC process for AM. With a carbon taxation policy, the carbon footprint of the AM process is low compared to other manufacturing processes. It is expected to be reduced more when the buy-to-fly ratio is taken into consideration. AM can have values of nearly close to one concerning the buy-to-fly ratio, whereas traditional manufacturing method ratios vary from 5 to 20. Therefore, waste can be avoided due to the almost optimal buy-to-fly ratio of additive manufacturing technology [69,70].

2.2.1. 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 the work of Knofius et al. [11], such that the spare parts management system becomes profitable with AM. Li et al. [29] demonstrated the utility of a system dynamics-based model to compare the costs and emissions between AM and conventional manufacturing. The authors mention that spare parts supply adopting AM is superior to conventional manufacturing in terms of both costs and carbon emissions.

Liu et al. [35] 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. The author 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.

A study on the spare part demand characteristics with AM was provided by Zhang [53]. The author 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 [19] integrated the demand factor and arrival rate for cost and SC comparisons. The author 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. The author 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. The author 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. [15] 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] studied five scenarios in spare parts SC by considering a digital distributor. The author mentioned that when digital files of the production system are used, the role of the logistics service provider will be reduced. The authors 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 [23] evaluated the current economic and technical feasibility of digital spare parts. The author 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]. The author presented a manufacturing methodology that can support the design and manufacture of spare parts through AM. The author 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 [40]. The author 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.

2.2.2. Process

Based on the content in the literature, research on the SC process for AM can be divided into two main groups: (i) industry-based processes and (ii) decision-making processes, as shown in Figure 2. The discussion of each sub-process is provided below.

Development and Distribution Processes

- *Manufacturing*

An analysis of AM application in COVID-19-related healthcare is provided by Salmi et al. [52]. The authors 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. [53] 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. The authors observed that the AM operation is dependent on the size of the spare part, and in some cases, 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. [71] analyzed different dimensions of automotive SC integration, performance, and firm performance from the perspective of additive manufacturing adoption. The authors found that the adoption of AM improves SC and firm performance. However, the authors 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 [23] mentioned the opportunities for digital spare parts production by considering three aspects: demand production, speed of production compared to CM, and digital storage. The author 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. A review of the paper shows 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. [53] 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 was studied by Westerweel [55] by considering the cost and inventory for introducing AM for spare parts production in remote locations. The author 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 [28]. The author mentioned that the adoption of AM has the potential to reduce supply risk and result in better inventory performance and management. The review shows 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 studies 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] studied an integrated job and vehicle scheduling problem using best-fit heuristics to minimize the makespan in an AM SC. The author found that the best-fit capacity utilization-based selection (BFCUBS) algorithm is superior to other methods in improving the make span. Similarly, He [50] studied the integration of additive manufacturing with JIT delivery systems with the aim of minimizing delivery times and transportation costs. The authors 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. The author 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. The author 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 studied by Caldas et al. al [5]. The authors 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 studies investigated 3D printer allocation in sites and facilities in the context of AM [5,25]. To quantify the cost and classification of spare parts, Ott [58] 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. The author 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 [38] studied 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 case study with nine production centres, each with a 3D printer. The study mentioned that this type of optimal analysis would help companies manage challenges at different locations where AM is adopted.

Bonnín et al. [17] 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. The authors applied the proposed methodology to an aviation case study and found that the decentralized configuration was only suitable for low-volume products. Darwish et al. [16] 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. The authors found that the utilization of 3D printers was improved, and the workload between them was balanced. The study 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

The research on different strategies of analysis methods in decision making for AM is reviewed in the section below, according to Figure 2. 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. [54] investigated the reduction of the overall system lead time through the addition of different percentages of AM spares into the inventory mix. The authors 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. [35] 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. The authors 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. The authors 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. [72] assessed the switch from conventional manufacturing of slow-moving spare parts to additive manufacturing based on models and concepts of inventory management. The authors 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%. The authors 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 in their study 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. The authors mention that AM has the capability of highly customized manufacturing, but it may be good for manufacturing batches with a lower volume. The authors developed a simulation model to study 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. The authors indicate 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 [62] compared the manufacturing of components with conventional manufacturing and AM using a lifecycle cost model. The author 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 authors' methodology helps to increase the effectiveness and efficiency of selecting promising facilities for after-sales service logistics. Similarly, Marek et al. [51] 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 [59] 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 [60]. Each of the processes, machines, parts, material, environment, and logistics objectives and constraints were identified and used in decision support. The review shows 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 study the viability of AM in maintenance activities. The developed model and costing approaches included three stages: design, manufacturing, and warehouse management. The author highlighted the importance of the potential of AM in reducing maintenance costs and extending machine lifetimes.

Cardeal [56] applied a sustainable procedure model for aircraft maintenance. The authors studied the impact of shifting from traditional maintenance, repair, and overhaul activities to AM. The authors 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. [37] 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. [54] 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. The review shows 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.

- *Analysis Methods*

The following section presents the analysis methods and available quantitative models for analyzing AM in SC. Many approaches were applied to adopt AM in spare parts SC. Most existing studies rely on qualitative, analytical, and optimization analyses [19]. The research focuses on empirical studies, case studies, and scenario analyses to study the implementation of AM in spare parts logistics. However, the review shows that the most utilized approach is the quantitative modeling method. As quantitative modeling and computer-based tools are becoming important for decision making in companies, their utility is also widely spreading for AM-based SC decisions [73]. Based on the content of these methods, the two main categories considered for quantitative models are optimization and simulation modeling.

Optimization models can be used for many purposes, including supporting decisions for resource allocation, making span minimization in scheduling problems, and studying the effect of resupply time on inventory performance. Mixed-integer linear programming

(MILP) and the Markov decision process (MDP) are other approaches utilized among optimization models. MILP is used because of its robustness [38]. Table 3 provide an overview of the optimization model structure in terms of the approaches and tools utilized in the optimization process, the objective of the model, parameters, number of stages, and nature of the planning horizon. This shows that all models deal with time and cost minimization. Table 4 also illustrate the simulation modeling in terms of the approaches and performance metrics. The models were developed for either a single time or multiple time periods. In general, only one period is considered as the planning horizon for optimization models. Westerweel [55] studied an infinite time horizon to investigate on-site additive manufacturing for the Royal Netherlands Army. The analysis showed that AM spare parts were the best solution to avoid stock-out between the two replenishment periods. However, at the end of an order cycle, whenever the conventionally manufactured parts arrived, the AM part was immediately replaced and disposed of as the reliability of AM parts was assumed to be inferior, as they are less resistant to cyclic loading.

Table 3. Approach, stage, objective, parameters, and period for optimization quantitative methods.

Author	Approach	Stage	Objective	Parameters	Period
Brito [38]	MILP	Bi stage	Cost minimization	Internal facility, Holding 3D printers, Part Production, Delivery costs	Single period
Knofius et al. [11]	SDP	Single stage	Cost minimization	Holding, discarding for parts and tools, purchasing, setup, backorder	Single period
Knofius et al. [57]	MDP	Single stage	Cost minimization	purchasing, maintenance, holding, backorder	Single period
Cestana [6]	MDP	Bi stage	Cost minimization	Holding, backorder	Single period
Westerweel [62]	MDP	Single stage	Cost minimization	Unit Ordering, Unit Printing, Inventory Holding, Backorder	Multi-period
Yilmaz [1]	Heuristics	Bi stage	Make span time minimization	Jobs completion time	Single period
He [50]	MILP	Single stage	Delivery time minimization	Transportation, Route	Single period

Table 4. Approaches and Performance metrics for simulation modeling.

Author	Approach	Performance Metrics
Ghadge [27]	SD	Inventory level and inventory cost Time horizon for the simulation
Li [29]	SD	Costs (transportation, manufacturing, administrative, and inventory) Carbon Emission Sources (raw material production, material powder production, manufacturing, material transportation, product transportation)
Zhang [53]	Discrete Event Simulation	Costs (material, energy, operator, penalty, maintenance, AM, parts) Interarrival time
Caldas [5]	Discrete Event Simulation	Average Service Level Average Lead Time. Costs (Fixed Production and supplying Inventory Stockouts)
Li [19]	Discrete Event Simulation	Sojourn time (queue, manufacturing time, and logistics time) Total costs (penalty, machine, and logistics)
Xu [37]	Discrete Event Simulation + Agent-based Simulation	Order fulfilling lead time Order fulfilling average cost Proportion of cannibalization
Togwe [54]	Monte Carlo Simulation	System average lead time
Chekurov [31]	Monte Carlo Simulation	Turnaround time
Khajavi [22,34]	Monte Carlo Simulation	Occurrence of expected spare parts demand

Discrete event simulation is widely used in the analysis of the AM environment to simulate operational and tactical decisions. These models adopt variability and uncertainty; therefore, they may represent the dynamics of the spare parts business [5]. System dynamics (SD)-based simulations are also used in the spare parts SC. They are useful for analyzing the outcomes of different scenarios by analyzing variations in parameters [64]. System dynamics are widely applicable in situations where different ranges of materials, information flows, and complex dynamic problems intersect [29]. The review shows that SD-based simulation models were only employed in the scenario analysis. Optimization and simulation modeling, cost models, business models, and theoretical models are utilized for many purposes. The purposes of the models include lifecycle costing analysis, the feasibility of 3D printer installation, and tackling the production of AM spares in remote locations. Cost models incorporate cost objectives in their analysis. The stages and parameters of the economic cost models are listed in Table 5.

Table 5. Economic models.

Author	Stage	Parameters	
		Cost	Other
Ott [58]	Multi-stage	Preparation, building the job assembly, setup, building of the part, removing the part from the machine, separating the part from the substrate plate and postprocessing.	-
Salmi [52]	Single stage	3D printer, printer's maintenance, raw material, labor, overhead, and sterilization.	-
Westerweel [62]	Single stage	Production, inventory holding, downtime and repair, investment	Performance benefit, probability loss
Cardeal [3]	Single stage	Labor, software, 3D scanner, machine, building, energy, raw material, consumable, warehouse unitary	Machine setup time, Machine clean-up time, Inspection time

2.2.3. Constraints

As mentioned above, the AM process, decision-making, and strategies are governed by the constraints imposed by the business, government, and standards. The literature 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 cases, 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 case. The authors also mentioned that in other cases, sourcing using the conventional method remains profitable.

Knofius et al. [57] studied the value of sourcing spare parts using a mix of AM and CM methods. Their study focused on the aerospace industry. The authors analyzed sourcing through the optimization model, optimal inventory policy, optimal sourcing, and maintenance strategy. Their analysis shows that dual sourcing is the best in the aerospace industry. Westerweel et al. [55], who studied 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. This review shows 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. [49,63] analyzed a decentralized manufacturing scenario for spare parts. The authors 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. The authors 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. [35]. The configurations focused on analyzing the safety inventory. The authors 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]. The authors 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. [26] proposed three SC configurations based on different locations of AM implementation and compared them based on qualitative lead time analysis. Nyamekye [43] compared SC scenarios in terms of sustainability, where CNC machining and laser additive manufacturing (LAM) were compared. The authors 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 study, it can be mentioned that the SC configuration with LAM-based production can provide better sustainable gain in terms of material efficiency.

Qualitative methods were also used for SC configurations. Li et al. [29] and Ghadge et al. [27] considered the SD approach to conducting simulations to compare different configurations. Li et al. [29] used the cost and emissions from SC configurations of spare parts. The costs included transportation, manufacturing, inventory, and administration. The authors mentioned that emissions in SCs come from raw material processing, manufacturing, distribution, and use. Carbon footprint was also associated with waste, spare parts storage, and transportation. They mentioned that in terms of cost alone, SC configurations for AM may not be a good option for the industry; however, when the efficiency of energy conversion, carbon tax, and the emissions quota is provided to the industry, AM-based supply chains can be a more attractive option. Ghadge et al. [27] analyzed spare parts management inventory policies for both AM and CM on aircraft SC and mentioned that the configuration should focus on lead time influencing inventory management. Two other studies compared different SC configurations based on performance [31], sojourn time, and cost [19]. Chekurov and Salmi [31] mention that AM is usually an option for a small number of AM-based spare parts production companies, but that would require the locations to be near the consumption centres. This will reduce the turnaround time and increase the profitability of the company. The authors mentioned that over time, SC configurations with AM are going to pay off due to the rapid advancement in technology development. However, Li et al. [19] mentioned that the distributed AM facilities are not a prescription for all spare parts, as they cannot guarantee a faster turnaround time when there is a high demand from different clients. Therefore, a mixed SC configuration could still be an option for the time being.

Khajavi et al. [22,34] compared two SC scenarios in two dimensions, namely AM technology and SC configuration, in terms of costs. The authors incorporated various costs such as those for personnel, initial investment in AM and depreciation, inventory obsolescence, initial inventory production, aircraft downtime, inventory carrying, spare parts transportation, and material. The authors mentioned that SC configurations with a hub-based production system with multiple part production capabilities could be more economical and effective. Xu et al. [37] compared SC configurations based on a hybrid simulation method and demonstrated the benefit of additive manufacturing capabilities on operational efficiency and effectiveness in maintenance based on the lead time and cannibalization cost. Babak [36] studied potential SC modifications to minimize the cost of AM-enabled decentralized production systems. The author discussed SC strategies, namely, hub manufacturing configuration, production postponement, and internet-based customization and distribution. It was found that, in general, the distributed configuration was more suitable for AM in various service locations. However, as would be found in Li et al. [19], a hybrid configuration of both centralized and decentralized systems might be profitable in some spare parts supply and demand situations. The review shows that SC configurations are very important for feasibility, economic efficiency, and environmental effectiveness. It also shows that there is no one configuration that fits all approaches for AM-based spare parts supply configurations, but it also shows that with increased technological advancement in AM technology, SCs in the future can become more energy- and cost-effective regarding emission abating options.

AM Technology

Kretzschmar et al. [23] studied the technical barriers related to AM technology, such as materials, accuracy levels, additive manufacturing chamber, 3D model, and postprocessing capabilities. The author investigated the economic barriers related to digital spare production costs, investment costs, employees' skills, and supplier contracts. Salmi et al. [52] 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 [43] mentioned the availability and use of metal powders for laser-based AM. The authors 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 [29] 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 [56] included the carbon footprint in the environmental assessment of a new business model canvas. The author obtained carbon emissions for a full lifecycle of a spare part, including production, transport, use, and end-of-life. The authors 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 studied by Isasi-Sanchez [39]. The author mentioned that AM options are more sustainable in terms of energy and emissions. The review shows 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. The authors 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.

3. Discussion

The discussion presented here focuses on the four research questions mentioned above. Three sections are used to provide the main findings and their consequences for the adoption of AM in spare parts service management.

3.1. Discussions on AM Applicability and Analysis Methods

This review aims at content analysis to address four research questions. The first research question (RQ1) concerned the 'opportunities for AM in spare parts SC'. The review shows that multiple aspects of opportunities were considered by researchers, such as materials, technology, processes, and SC configurations. This review shows that research on AM is increasing significantly. In the past five years, AM was considered a manufacturing technology rather than a prototyping tool. The review shows that research focuses mostly on the process part rather than on the analysis of inputs and constraints. Studies also focused on resource allocation and decision-making. However, no research on the details of the rules and regulations, supply situation, manpower capability, and technology absorption could be found in the AM literature. A few authors considered emissions from AM SC configurations which can support the industry in making an environmentally friendly decision by correctly locating the AM facilities in the SC. The review also shows that the sourcing of spare parts was also a point of analysis, and most studies recommend having dual sourcing or mixed sourcing rather than single sourcing based on the current technological option. While research shows more confidence in conventional manufacturing for long-term spare parts management, AM can provide a short-term supply that can be replaced immediately upon receipt of conventionally manufactured parts.

The second research question (RQ2) concerned the models available to analyze AM in SC. The review shows that such models can be, in terms of technology, analytical models, SC configurations, and carbon analysis. This review shows different SC configurations and their advantages in adopting AM. The configurations were analyzed both qualitatively and quantitatively. The literature shows that a distributed SC design may be more appropriate for spare parts management based on currently available technologies. With a distributed SC, AM hubs can be developed at different service locations to reduce lead time and transportation costs. The review also shows that AM SCs are neither totally centralized nor totally decentralized. The combination can be made to make strategic decisions on the spare parts model at a centralized location because of the availability of expertise and panning ability to assess the market situation and operational decisions at decentralized locations for faster replenishment of demand [74]. From the input perspective, only a few frameworks or models can be found in the literature. Although the availability of raw material, supply potential, capacity, and demand is crucial for AM-based systems, it seems that researchers focus more on processes and technologies rather than the inputs for driving the AM process. The raw material must be supplied at the right time in the appropriate quantities. Suppliers of AM materials are not widespread, and the raw materials used for AM are costly. Therefore, alternative materials for both short- and long-term use and the recuperation of the materials from the AM parts or the conventional parts do not seem to be in the purview of AM SC researchers.

Industry-wise, most research on AM is related to the aviation sector. This may be a point of attraction because of the high cost and stringent specifications of spare parts. Researchers mainly focus on making the total SC efficient in terms of lead time, inventory holding, and demand management. The reviewed authors used scenario comparisons and quantitative methods for analysis. Based on the review, it can be perceived that researchers may be focused on technological improvement on one side (based on the product management concept) and the strategic management of spare parts management on the other. As service SC is the focus of this study, many of the models focus on inventory minimization and service level as a way to promote AM. Research shows that other popular areas for AM-based applications are military, automotive, and medical emergency situations (COVID-19 condition).

3.2. Challenges in Terms of AM Adoption

The third research question (RQ3) adopted in this paper concerns the challenges that make AM more difficult to adopt. This review shows 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 [21], and quality testing. In some cases, 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 [40,75]. 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.

3.3. Difficulties of Spare Parts Management

The fourth question (RQ4) examined in this research relates to 'the difficulties faced in spare parts management'. The review shows that spare parts are usually faced with uncertainties in terms of demand. Sometimes, material supply capability is constrained by a specific type of AM technology; therefore, its management can be different. Spare parts demand is affected by stochastic factors such as wear behaviour, the type of maintenance adopted, and failure rates [27]. One needs to know that the parts fail not only because of their own wear and tear but also because of the problem with the integrated parts. Any part failure results in downtime, which can be costly for the industry. Therefore, safety stocks are still maintained, albeit at a lower level, so that the service level can be increased. As studies showed, AM-based spare parts are usually for a short-term gap, and the trade-off between the spares and raw materials also needs to be assessed. It should be noted that some spare parts can take months or even a year, especially if it is a rare component or requires a special raw material for production [9]. Some spares can even be very costly, and some others can be so large in size that they require specific AM technology. However, in high-value businesses, the cost of spares can be a secondary issue, as the loss due to downtime could be much larger [9]. SC management challenges are faced in aircraft spare parts owing to the variability of aircraft locations. This provides challenges in terms of locating AM facilities and investing in SC management [27].

4. Conclusions and Future Research

This paper provides a review of recent literature covering three main areas: additive manufacturing, SC, and spare parts. The review, which followed a systematic review methodology and content analysis, shows that most research on AM and SC for spare parts is recent, and AM is increasingly being considered in SC configurations. The review shows that although the adoption of AM is growing, it is not considered a replacement for conventional spare parts supply and conventional SCs. It is considered a complementary measure to support spare parts management. Considering the service level, the capability of AM technology, the turnaround time, and the quality of spare parts with AM, the development of technology and the utilization of AM for smaller and low-value parts with higher demand variability can be an option to increase SC efficiency. There are also challenges related to investments. As investments need to be made for a specific type of technology using a specific type of material, and as it is difficult to convert manufacturing processes to digital processes, it seems that it takes a bit of time for the industry to adopt AM. Nevertheless, opportunities exist, methods are being developed, quality aspects are being sorted out, and analysis is becoming stronger to support the decision-making process. It should be noted that AM has added value to various stages and echelons of SCs. The review shows that there are opportunities for AM in terms of technical and economic feasibility.

4.1. Limitations

The review process was conducted with high-quality standards; uncertainty and bias still exist which are related to the evaluation of studies from different perspectives. The studies were analyzed based on the inherent content that suits the focus of the study. Therefore, the limitations mentioned in those studies and discussions on other non-related areas in some of those studies may not have been considered. The study included literature published between 2010 and April 2021. Therefore, some recent studies may have been missed in this review. As the collection of literature focused on the databases available at the university, some industry literature covering the scope of this review might have been omitted.

4.2. Future Directions

A few considerations are mentioned below for possible future research on additive manufacturing potential in the spare parts SC. As mentioned in the SC process mentioned in Figure 2 and the content extracted in the review, the following are proposed for future directions. These parts are shown in Figure 3.

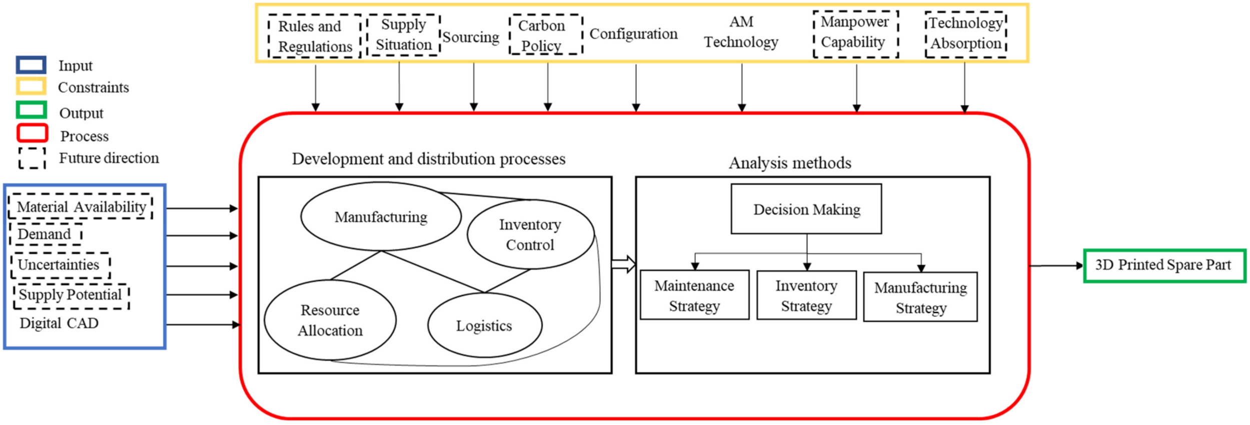

Figure 3. Proposed areas of research directions are indicated in dashed lines.

- Quantitative models lack complexity in terms of SC design instances to produce optimal solutions [38]. In addition, some parameters and factors are simplified for the modeling process. Modeling can be more representative if the impact of lead time on uncertainties related to post-processing is also considered [3]. Because of the complexity of SC for the adoption of hybrid manufacturing, focus can be turned towards developing a heuristics approach so that large larger demand scenarios can be analyzed [18,38]. The availability of real data and practical numerical examples from real-world cases would enhance the reliability of the results and model solutions [29].
- Regarding the transition from a traditional SC to a digital SC configuration, intellectual property rights (IPR) could represent an obstacle because of the ownership rights of the spares CAD files. Therefore, further research in the area of the certification process and data management handling could help the industry to be assured of data exchange and facilitate the AM process [4,20,40,52].
- Most AM research is focused on the aerospace industry, possibly due to high-value components and continuity of the spare parts needs. There are other industries, such as oil and gas, where heavy investments are made for capital assets and operational expenditures. Petroleum asset operations require heavy investment in spare parts acquisition and assessment, as high fulfilment rates and reliability levels have to be achieved [41]. Although the petroleum industry is also highly value-added and sensitive to quality, some AM capabilities may already be available for use in the petroleum industry. Future research could focus on specific spares, demand uncertainty, technology capability, and the development of optimal SC configurations for the petroleum industry.
- Based on the content of the AM process shown in Figure 3, there are only a few studies discussing the inputs. The review shows that material availability and supply potential, demand, and the analysis of uncertainties are important, and they can vary from one industry to another. The availability of raw materials can avoid inventory and promote just-in-type AM, which will reduce the impact of demand changes and uncertainties related to other aspects. Therefore, input analysis for operating the AM process and its impact on AM SC processes could be considered in future research. The modeling process might require integration of the development and distribution processes and decision-making processes.
- Researchers have recognized the value of AM in reducing emissions. The impact of the carbon cap, carbon tax policy, and carbon cap and trade policy can alter SC configurations. As SCs in AM can extend beyond a country, such research can help develop a greener and socially responsible AM process.

- The review could not obtain literature that focuses on the rules and regulations, manpower capability, and technology absorption. A higher level of technology absorption leads to adaption, innovation, and risk-taking in improving current technology. Technology absorption can also be increased through education and exposure [76], which can help in the adoption of new technologies [75,76], such as additive manufacturing [77] in different application areas. These are management-related constraints, and therefore, they can be considered highly by the industry aiming to adopt AM. In addition, the concept of hybrid manufacturing as an upcoming technology] in the AM domain should also be studied for spare parts management, as this is a new area within AM.

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Abbreviations

The following abbreviations are used in this manuscript:

SC	Supply Chain
AM	Additive Manufacturing
MILP	Mixed Integer Linear Programming
SD	System Dynamics
MDP	Markov Decision Process
SDP	Stochastic Dynamic Programming
IPR	Intellectual Property Rights
PPE	Personal Protective Equipment
LAM	Laser Additive Manufacturing
CAD	Computer Aided Design
OEM	Original Equipment Manufacturer
MRO	Maintenance, Repair, and Operations

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