





Review

Impact of Additive Manufacturing on the Supply Chain of Aerospace Spare Parts Industry—A Review

Binoy Debnath ^{1,*}, Md Shihab Shakur ², Fahmida Tanjum ², M. Azizur Rahman ^{2,*} and Ziaul Haq Adnan ³

¹ Department of Industrial and Production Engineering, Bangladesh University of Engineering and Technology, Dhaka 1000, Bangladesh

² Department of Mechanical and Production Engineering, Ahsanullah University of Science and Technology, Dhaka 1208, Bangladesh; shihabshakur2016@gmail.com (M.S.S.); fahmida.tanjum.aliza@gmail.com (F.T.)

³ Department of Management, North South University, Dhaka 1229, Bangladesh; ziaul.adnan@northsouth.edu

* Correspondence: binoydebnath15@gmail.com (B.D.); aziz.mpe@aust.edu (M.A.R.)

Abstract: *Background:* Additive manufacturing (AM) applications in producing spare parts are increasing day by day. AM is bridging the digital and physical world as a 3D computer-aided manufacturing (CAM) method. The usage of AM has made the supply chain of the aviation spare parts industry simpler, more effective, and efficient. *Methods:* This paper demonstrates the impacts of AM on the supply chain of the aircraft spare parts industry following a systematic literature review. Hence, centralized and decentralized structures of AM supply chains have been evaluated. Additionally, the attention has been oriented towards the supply chain with AM technologies and industry 4.0, which can support maintenance tasks and the production of spare parts in the aerospace industry. *Results:* This review article summarizes the interconnection of the industry findings on spare parts. It evaluates the potentiality and capability of AM in conceptualizing the overall supply chain. Moreover, MROs can adopt the proposed framework technologies to assist decision-makers in deciding whether the logistics hub with AM facilities is centralized or decentralized. *Conclusions:* Finally, this review provides an overall view to make critical decisions on the supply chain design of spare parts driven by new and disruptive technologies of industry 4.0. The next-generation supply chain may replace the logistics barriers by reducing waste and improving capability and sustainability by implementing AM technologies.

Keywords: additive manufacturing; spare parts; aircraft industries; industry 4.0; supply chain; efficiency; performance; systematic literature review



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1. Introduction

Additive manufacturing (AM) is a digital technology of layered fabrication by adding material where no cutting tool is required as in the case of a subtractive manufacturing process. In the earlier time, the application of AM was confined to rapid prototyping for physical product validation in the product development process. However, AM has been turned into a form of direct manufacturing technology due to the emerging advancement of its technological capability. It is estimated that AM industry will reach 35.6 billion USD by 2024, which was 7.34 billion USD in 2017 [1]. One of the top prospects behind the scenario is the capability of AM for mass customization of the product [2], fabrication of complex parts, on-demand product fabrication, cost-minimization, and waste-reduction [3,4]. Such characteristics of AM not only permit complex shape or customization in products but also are capable of fabricating high-performance aerospace components [5] and low volume production in the aerospace industry [6,7]. Hence, AM has become a potential fabrication process for the aerospace industry [8]. However, strategic implications have been adopted to apply AM in various applications, such as automotive, aerospace, and engineering by exploiting the potential and advantages of AM [9].

In Aircraft industries, high quality, safety standards and preventive maintenance are the dominant factors. Moreover, these industries require highly valued spare parts in larger volumes due to uncertain and unpredictable demand [10]. The unprecedented demands for spare parts occur when preventive maintenance has taken place, or any components fail randomly during the part life cycle [11]. Therefore, spare parts management has become crucial; and it incurs a higher holding cost [12]. Nevertheless, high shortage costs and obsolescence risk are inevitable for the spare parts [13]. Therefore, suppliers face an unpredictable barrier in their business investments as they need to produce older spare parts for a short life cycle. High stock levels can be a solution for this issue but it can increase obsolescence cost risk, holding cost and barriers to cash flow. Furthermore, a shortage of spare parts may lead to a lack of reliability, slow responsiveness, and poor cycle service level (CSL), which finally results in poor supply chain performance [14].

The aircraft industry also consists of maintenance, repair, overhaul (MRO) and original equipment manufacturers (OEMs) with MROs and OEMs being the prime service providers. GE aviation, Airbus, Boeing, and Rolls-Royce are notable OEMs in the aircraft industry [15]. MRO organizations manage the facilities to run the aircraft company's processes and facilities smoothly [16]. Aircraft companies require MROs to deliver much-needed spare parts with high responsiveness and a higher fulfillment rate at a low cost [17]. Therefore, MRO services face significant challenges in aircraft spare parts supply chains to minimize costs [18]. Moreover, both the MROs and OEMs struggle to optimize the design and production processes to minimize the production lead times and waste by implementing lean manufacturing approaches [8]. Very few OEMs like BAE System, Raytheon, and Lockheed Martin are associated with manufacturing and designing aircraft's main component systems due to the high market entrance barriers [19]. With computer-aided designs, advanced automation in AM has improved the products and services that are currently taking center stage in this endeavor [20]. With the advancement of AM, OEMs expect the spare parts manufacturing facility to locate near service areas [13]. The benefits of AM can reduce inventory, transportation, safety stock, uncertainty, and the overall supply chain costs. Accordingly, the complex supply chain of the aerospace industry needs to be more agile and efficient through the integration of AM. Therefore, extensive analysis is required with respect to the existing work in this field. To understand the current state of the literature, contributions of related research are summarized in Table 1.

Table 1. Summary contribution of related articles.

Author name	Supply Chain	Additive Manufacturing	Industry 4.0	Spare Parts	Material Selection	Aircraft Industry
(Khajavi et al., 2014) [17]	✓	✓		✓		
(Frandsen et al., 2019) [21]		✓		✓	✓	
(Ceruti et al., 2019) [22]		✓	✓			✓
(Kalender et al., 2019) [23]		✓			✓	✓
(Li et al., 2017) [24]	✓	✓		✓		
(Caesarendra et al., 2018) [25]			✓			✓
(Zijm et al., 2019) [26]	✓	✓		✓		
(P. Liu et al., 2014) [27]	✓	✓		✓		✓
(Chekurov et al., 2021) [19]		✓		✓	✓	✓
(Mehrpooya et al., 2019) [28]		✓	✓	✓		
(Yusuf et al., 2019) [29]		✓			✓	✓
(H. Khajavi et al., 2018) [30]	✓	✓		✓		✓
(de Souza et al., 2011) [31]	✓			✓		✓
This Paper	✓	✓	✓	✓	✓	✓

Despite the increasing number of publications in this field, there are currently insufficient techniques and models that thoroughly address and organize this topic. There exists a gap in the proper extensive literature review in this field. To the best of our knowledge, there seems to be a lack of review papers in additive manufacturing of spare parts concentrating on the aviation industry, compared to many other topics in AM. Through a survey of relevant literature, the authors hope to make tangible fundamental and technical contributions. The goal is to use the findings of this research to develop new scientific methodologies and models for assessing and enhancing the supply chain of the spare parts (SP) industry through AM.

The framework of core subject areas, explained in this paper, is illustrated in Figure 1. The shared portions of the frameworks are described in this paper through a systematic literature search and literature review. Consolidation of information from various literature was induced towards bringing proper value to the research.

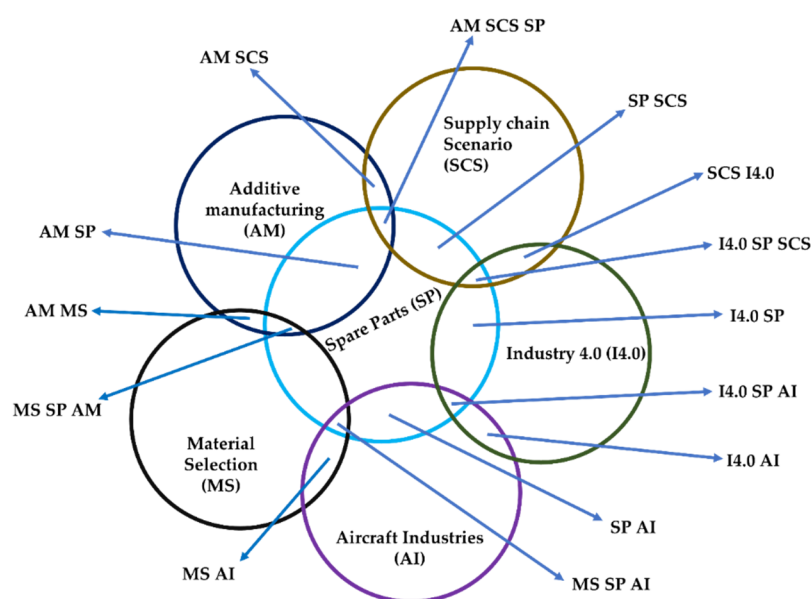


Figure 1. Framework of Core Subject Areas Mapping.

This paper is outlined in different sections. After the introduction, Section 2 presents a systematic literature review on how the study has been carried on. Section 3 identifies the impact of additive manufacturing on the aerospace spare parts industry. It also discusses the current and future trends of AM in spare parts of the aviation industry. Section 4 focuses on deriving several parameters, such as material selection criteria, part consolidation, quality, and standardization for AM spare parts. Section 5 analyzes the supply chain design and strategies for spare parts in the aircraft industry. Next, Section 6 relates AM of spare parts in the I4.0 context. Then the managerial implications are presented in Section 7. Finally, concluding remarks and future research directions are provided in Section 8.

2. Systematic Literature Review (SLR)

The framework illustrated in Figure 1 indicates the research areas covered in this study. As there remains a gap in proper data integration in these areas, this study conducts a systematic literature review (SLR) towards covering those gaps. Initially, a conceptual model was developed for SLR (Figure 2), which shows that the study was conducted in several steps toward acquiring reliable research outcomes. This SLR was developed based on the proposed methodology of [32].

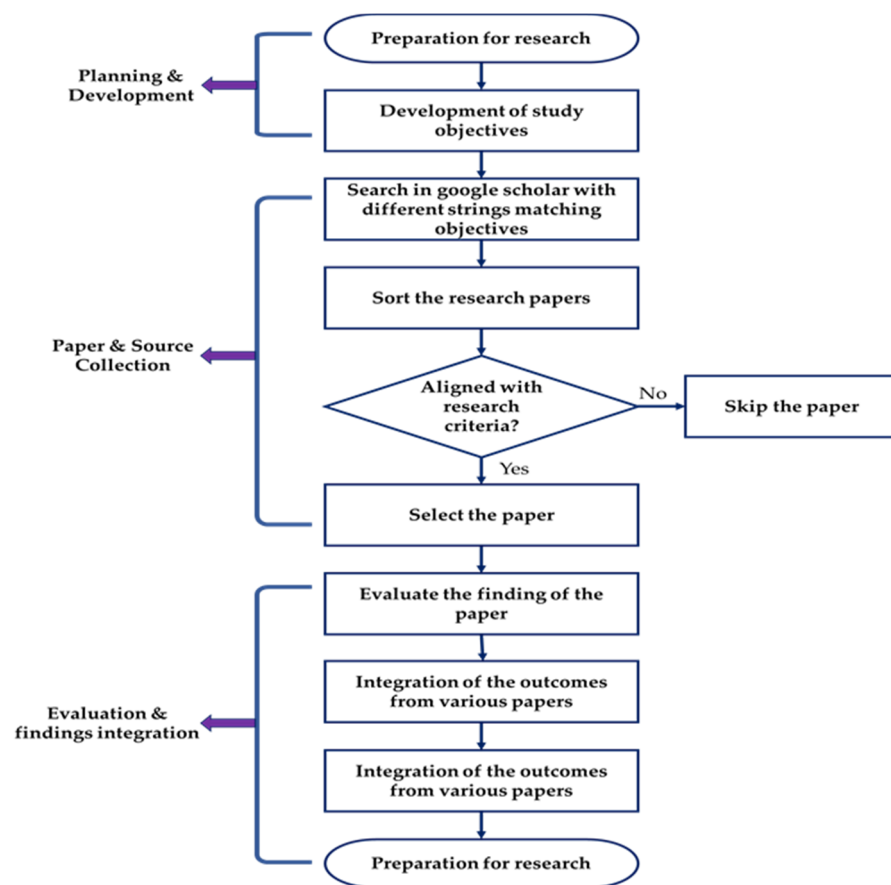


Figure 2. Steps of Systematic Literature Review.

Based on the review gaps, a set of research questions (RQs) were identified to fulfill the study. The questions are stated as follows:

RQ1: What are the states of the supply chain scenario in additive manufacturing (AM) of spare parts?

RQ2: What is the basis for selecting a particular AM supply chain strategy in Aircraft's spare parts industry?

RQ3: How does AM bring changes in spare parts of the aerospace industry?

RQ4: Which strategies are trending in the aircraft industry's spare part supply chain?

RQ5: How industry 4.0 helps different aspects of spare parts manufacturing?

RQ6: What are AM's major challenges, constraints, and considerations to use in the aerospace spare parts industry?

The planning and development phase of this research set the area of study and different questions. RQ1 and RQ2 focus on the functionality of the spare parts (SP) supply chain in the aerospace industry. It addresses how SC works and a comparison of SC scenarios in this sector. RQ3 is concerned with the impact of additive manufacturing on the SP industry on moving toward changing conventional manufacturing in every term. RQ4 focused on SP's current and future trends in the aviation industry. RQ5 deals with the effect of industry 4.0 on different aspects of the digitalization of SP industries. There remain challenges and influences of different factors. RQ6 is concerned about these factors and constraints for AM in Aircraft SP industries. Nevertheless, there remains a lack of systematic reviews that answer these questions in an organized manner.

After the planning and development phase, the researcher moved on to the source and collection. This section required critical attention to the study. A complete examination of scholarly articles in the field of AM in SP was conducted in order to address the research questions to be answered. The goal was to include a wide variety of facts in order to

minimize prejudice and assure the research's neutrality and validity. High-quality publications were identified based on the selection criteria focused on answering the research questions. Google scholar database was used to find peer-reviewed publications published in academic journals. The selection of published journals was restricted from 2005 up to 2022. Various keywords were used to select papers that helped in discovering the most relevant papers associated with AM, SP, and aviation industries. In this step, mainly the research criteria are set for the SLR. The search goal was to answer the research question and attain the research objectives. The reviewing source is peer-reviewed journals, review papers, conference proceedings, etc., Google Scholar's advanced search option has been used as Google Scholar is a free and accessible search engine with scholarly literature across all kinds of publishing formats and disciplines. During the search period, the publications in the English language were selected only. Finally, the preferable timeline for filtering scholarly articles was 2005–2022, following the changes with the advancement of the research field. The search criteria for this research are listed in Table 2.

Table 2. Search Criteria of the study.

Criteria	Description
Contribution	Importance observed in the review area
Relation to the research	Must align with research questions
Source	Journal, Review, Official Website, Proceedings
Timeline	2005–2022
Search Engine	Google Scholar
Language	English

Search strings have been identified via an unstructured literature review. The main aim of this review lies in exploring the supply chain of aerospace spare parts from AM and I4.0 perspectives. Boolean operators combined with synonyms of additive manufacturing, spare parts, aerospace industry, supply chain, industry 4.0, material selection, etc., have been used to form the word string for searching. The strings for each domain are shown in Table 3, and a relevant word-cloud is illustrated in Figure 3.

Table 3. Word Strings for publication search.

Subject Area	Word String Used
Supply chain	'Supply chains' OR 'supply chain'
Additive manufacturing	'Additive manufacturing' OR '3D printing' OR 'Three-dimensional printing' OR 'Direct manufacturing' OR 'Digital manufacturing' OR 'Rapid prototyping' OR 'Rapid manufacturing' OR 'Additive fabrication' OR 'Solid free form fabrication' OR 'Generative manufacturing'
Spare parts	'Spare part' OR 'Service part' OR 'Repair part' OR 'Replacement part'
Industry 4.0	'Industry 4.0' OR 'I4.0' or '4IR' OR 'Fourth Industrial Revolution' OR '4th Industrial Revolution'
Material Selection	'Material selection' OR 'Material application' or 'Material segmentation'
Aircraft industry	'Aircraft industry' OR 'Aerospace industry' or 'Aircraft' OR 'Aerospace application' OR 'Spacecraft' OR 'Aviation industry' OR 'Aviation'



Figure 3. Keywords for the literature search.

The resulting word string has been merged with the framework of core subject areas mapping (Figure 1) using the Boolean and Operator. Then, the search results in a total of 4788 articles. The criteria are based on the abstract, title, and keywords of the articles. The results from the selection of titles, abstracts, and keywords are shown in Table 4.

Table 4. Subject area wise publication.

Core Subject Area	Short Form of Core Subject Area	No of Papers (Abstract, Title, Keywords)
Spare parts AND Supply chain	SP SC	2050
Industry 4.0 AND Supply Chain	I4.0 SC	538
Spare parts AND Industry 4.0	SP I4.0	1
Aerospace industry AND Industry 4.0	AI I4.0	30
Aerospace Industry AND Spare parts	AI SP	1710
Material Selection AND Aerospace Industry	MS AI	34
Additive Manufacturing AND Material Selection	AM MS	13
Additive Manufacturing AND Spare parts	AM SP	103
Additive Manufacturing AND supply chain	AM SC	299
Additive Manufacturing AND Supply Chain AND Spare parts	AM SC SP	3
Industry 4.0 AND Spare parts AND supply chain	I4.0 SP SC	1
Industry 4.0 AND Spare parts AND Aerospace Industry	I4.0 SP AI	5
Material Selection AND Spare parts AND Aerospace Industry	MS SP AI	1
Material Selection AND Spare parts AND Additive Manufacturing	MS SP AM	1
Total		4789

The resulting articles achieved from the search process are either excluded or included for further assessment [33]. The exclusion or inclusion procedure has been divided into subsequent stages with specific criteria. Firstly, the 4789 papers have been identified via

the combined search strings and duplicate results have been removed. Next, the abstracts of the papers have been studied and non-relevant papers were excluded. After that, a full-read assessment was performed, and non-relevant articles were removed, resulting in about 238 articles. Finally, 136 articles qualified for the content analysis in the systematic literature review. Therefore, articles that had been identified to be related to the research of core subject areas. The inclusion and exclusion procedure have been illustrated in Figure 4.

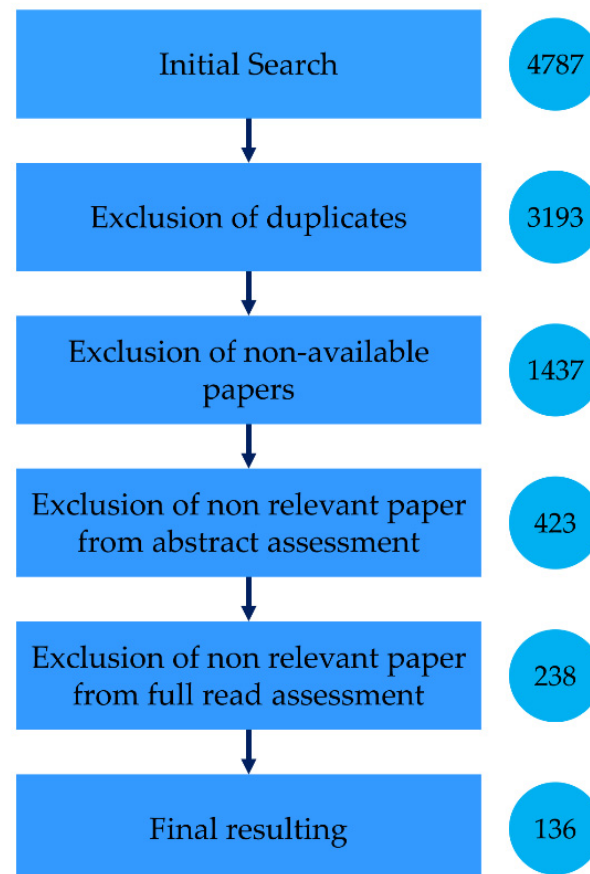


Figure 4. Screening mechanism of Paper selection.

Finally, the findings from these selected papers were evaluated, and the information was compiled for building the research paper.

3. Additive Manufacturing of Spare Parts

Additive Manufacture (AM) is the general term for the collective advanced manufacturing technologies, which construct components layer by layer. Instead of removing the material, they are made by adding material rather than by subtracting manufacturing like machining. Additive manufacturing technology has the freedom for creating complex geometry components, efficient waste minimization and highly customized products. Among other advantages, AM has a very impressive effect on the environment by increasing sustainability in the production line with respect to traditional manufacturing processes [28]. AM processes can be classified into seven categories: powder bed fusion, material jetting, material extrusion, vat photopolymerization, directed energy deposition, sheet lamination, and binder jetting [34].

The material addition or fusion is regulated by G codes directly generated from the 3D CAD models. AM has taken up the role of complex parts manufactured in small to medium sized batches in many areas of engineering and industry, with increased competition in the international economy and evolving market trends, such as increasing production rates,

increasing demand for personalized and customized goods, reduced lead time and the implementation of new business models [35,36].

The rate of AM innovation is increasing every day, and the equipment is becoming less expensive and more efficient. Parts made with new materials can match, if not exceed, the qualities of traditional production. However, it has some disadvantages as well. The advantages and disadvantages of the AM over CM are given in Table 5, respectively.

Table 5. The advantages and disadvantages of AM over CM.

	Attributes	Explanation	References
Advantages	Flexible design	AM process can overcome the limitations of not producing complex shapes in the conventional process. The parts do not need further fabrication or operator to produce complex parts.	[3,37–47]
	Low cost	Because of AM, rapid prototyping is easier based on time and monetary budgets. Compared to CM, a CNC milling setup is much cheaper with AM.	[37,47–49]
	Customized products	As AM does not have limitations over shapes, it can produce customized products massively.	[3,38,41,43,47]
	Efficient use of materials	3D printing means methodically adding materials until a part is created. Since AM starts laying down a base layer of material and then adds subsequent layers until the part is ready, the overall waste is minimal. Additionally, consolidating parts for manufacturing can save energy and manufacturing costs.	[42,44,47,48,50]
	Increased part reliability	As newer materials, such as polymers, metals, and composites become available for the AM, replacing parts with improved materials gets easier to improve the parts' performances.	[51,52]
	Reduction in on-hand inventory	Unlike the traditional manufacturing that sticks to a warehouse packed with premade parts, AM needs a virtual inventory that saves warehouse space, personnel, and obsolete parts.	[37,40,42,53]
	Small production runs often prove faster and less expensive	Almost nothing beats AM for speed and economy for a handful of products. It will be faster to print those. Gathering design files, printers, and materials are all we will need.	[44]
Disadvantages	Not preferred for mass production	The process of AM is slow, and it allows mass customization, and thus till now, it is not being able to be used for mass production.	[3,37,40,45,47,48]
	Size limitation	Industries are slow to adopt AM and consider it a niche process even in 2021, probably because 3D printing is not an efficient method of producing a considerable quantity of parts.	[42,43,53]
	Low range of material	Unlike CM, AM have fewer materials to be used.	[44,47,53]

3.1. Current Trends Additive Manufacturing in Aerospace Industry with Example

GE aviation (Ohio, United States): GE aviation has produced a leap engine fuel nozzle (Figure 5) by combining 20 parts into a single-part with cobalt-chrome materials using Laser AM that weighed 25% less than the conventional one. After getting certified by the FAA (Federal aviation administrator) in 2015 [54], GE has fulfilled a target of more than 30,000 additive fuel nozzles to be produced by 2018 [55]. Before that, GE also additively manufactured housing components of the T25 engine sensor for retrofitting GE90-94B engines.

NASA-Rocket injector (Glenn Research Center, Cleveland, United States): NASA has considered a Rapid Analysis and Manufacturing Propulsion Technology (RAMPT) to adopt AM for fabricating rocket engine parts with metal powder and lasers. The method of fabricating the powder with lasers is named 'blown powder directed energy deposition' to minimize lead time and cost for manufacturing complex engine components like combustion chambers and nozzles. The nozzle was fabricated within 30 days, whereas it would require about a year with conventional methods [56]. NASA had manufactured a metal rocket injector (Figure 6) with selective laser melting using nickel-chromium powder combining 115 parts into two parts only. The part had gone through hot fire and structural tests and was used in the J-2X engine in 2017 [57].

Boeing (Illinois, United States): Boeing, Inc., has additively manufactured more than 200 different parts for ten aircraft platforms. Boeing has also used roughly 20,000 additively manufactured parts in military and commercial aircraft, including 32 different components for its 787 Dreamliner planes. Boeing has fabricated more than 7500 tools which are additively fabricated and this is increasing [58].

Airbus (Leiden, Netherlands): Airbus has produced a Cabin bracket connector for the Airbus A350 XWB using Laser CUSING technology with Titanium powder, as shown in Figure 6. Previously, the parts were manufactured with Aluminum alloy by milling machining, which produces 95% waste. In contrast, Laser CUSING technology has a waste of about 5%. Furthermore, the component can bear a 20KN fore effect and withstand at 330 °C, without any problem. With the help of AM, Airbus can develop components in a month instead of a 6-month lead time, as projected earlier [59].

Rolls Royce (Westhampnett, United Kingdom): Rolls-Royce has manufactured a Trent XWB-97 engine part having 0.5 m and 1.5 m diameter thick front bearing housing part for holding 48 airfoils using Electron Beam melting of Titanium. By applying AM, Rolls-Royce has reduced the manufacturing time by about 30% [60].

Stratasys (Rehovot, Israel): Stratasys with Aurora flight science has Fabricated an Unmanned Aerial Vehicle (UAV) which is 80% 3D printed with a total weight of only 33 lbs and capable of gaining a speed of 150MPH. With the combination of Fused deposition Modelling and Direct metal laser sintering (DMLS), different parts have been produced by reducing design and build time by about 50% [61].

SpaceX (California, United States): SpaceX has fabricated a hypergolic propellant rocket engine named SuperDraco for passenger-carrying space capsules. It is manufactured additively with Inconel superalloy by direct metal laser sintering. The fabrication process dramatically reduces lead-time compared to the traditional process with fracture resistance, ductility, superior strength and low variability in materials properties [62,63].

3.2. Future Perspective

The future development in AM technology will tend to fabricate larger products. Larger spare parts like airplane wings are expected to be fabricated by AM technology in the future. The current establishments of AM (i.e., flexible and convenient supply chain) are being studied and investigated by Lunar Building, NASA, and 'Made in Space' towards finding the capability and potential of using this technology in zero-gravity environments [5]. With the help of Part consolidation and topology optimization, AM may create multifunctional structures that simultaneously perform several functions. Besides, 4D printing can be an emerging way that will change the part geometry with respect to humidity, heat, or radiation. Currently, repairing a damaged part through AM is time-consuming. Therefore, automation for the preparation process may reduce the time and cost of repairing the damaged part instead of producing a new product. A step has been taken by a European project named RepAIR where the geometrical deviation of the damaged part compared with the original part is identified automatically. This automation process can be extended to prepare the surface and is incorporated into producing large parts. Moreover, the automated process will be able to analyze the condition of the damaged part, whether it is repairable or needs fabrication of a new part on-demand [5,64].

4. Spare Parts with Additive Manufacturing for Aviation Industry

Additive manufacturing (AM) is established as the manufacturing process that increases the revenue of the aerospace industry with the repairing operation and supply chain [27]. AM provides new opportunities to make sustainable, topologically optimized, lightweight spare parts for aircraft. Various sophisticated components and subcomponents assemble them, and a multi-tiered manufacturing structure is required. Therefore, intensive work is needed in the inventory and supply chain to continue smooth operation in the aircraft assembly. However, continuous improvements in process are still required to ensure safety and quality in the aeronautical industry considering the below attributes.

4.1. Quality Assurance and Standardization

Some structural parts and critical components of engines are made of metals using AM, which may bring catastrophic and consequent events if they fail. These components require rigorous assessments to get certified. ISO/TC261 and ASTM F42 have been formed to establish standards on terminology, materials, processes, and test procedures for AM [65]. While SAE International primarily works on aerospace-related AM standards, both ISO and ASTM are responsible for AM standard publications [66]. Therefore, FAA and EASA have established certification and testing protocols to clear any components for service on the required application [67]. Major leading regulatory bodies like ASTM, ANSI, and SAE international have collaborated frequently with aviation regulatory bodies, such as NASA, FAA, and EASA [68,69]. This effort has accelerated the certification process and ensured continued operational safety for adopting AM in the aerospace industry [70]. However, a well-established standardization has not been conducted yet, and the process is quite costly and lengthy.

4.2. Part Consolidation

In conventional machining processes, complex shapes cannot be fabricated easily. Thereby, in CM processes, simple parts are joined together to construct or assemble complex aerospace parts which require different types of joins or fasteners like welds, braze, nut bolts, etc. However, these joining processes are less reliable and sustainable with respect to a single part [71]. Moreover, any error in tolerance, misalignment, or geometric error would complicate the assembly process [72]. Additive Manufacturing can solve this problem by fabricating a complex part combining components that enables feature integration and increases reliability, sustainability, and performance [73]. Moreover, it will reduce inventory, lead time, assembly-line footprint, and supply chain pressure by increasing components' performance [5,74]. For example, a hydraulic housing tank containing 126 parts can be reduced into a single component using AM [64]. Similarly, GE aviation has consolidated conventionally manufactured 855 components into a dozen parts using AM, resulting in a 20% improvement in fuel burn and 10% more power [75].

4.3. Materials Selection for Spare Parts in Additive Manufacturing

Spare parts forecasting is challenging as the demand pattern is intermittent [76]. A higher service level is required to avoid downtime costs, making the spare parts planning more complicated [77]. Therefore, companies need to keep high inventories of spare parts to compete with service-level requirements. AM allows producing low-volume parts away from CM processes. By removing disrupted parts with part consolidation and low volume parts from traditional fabrication methods, AM can maximize the service level for spare parts by availing time [77,78]. AM can increase responsiveness by balancing inventory levels and minimizing carbon emissions and disruptions in the supply network of spare parts [77]. AM reduces the supply risk for spare parts for low-demand parts while conventionally manufactured part is unavailable in low quantity [79]. However, a limited volume of AM, inadequate quality and post-processing requirements are the challenges for this purpose [80]. Additively manufactured spare parts can be used to repair damaged parts without replacing the whole parts, such as repairing the burner tip of a gas turbine

by Siemens [26]. Aircraft MROs require fabricating parts in minimal quantities; hence, they face a widely distributed supply chain and unpredictable demand [11]. The demand is often affected by disputable factors like failure rates, type of maintenance, and wear behaviors [81]. Many aircraft spare parts are highly valued, ordered infrequently, and require a long replenishment lead time [82]. Hence, a literature gap remains where the lead time can be simulated for varying AM spare parts percentages in the overall system and its effect on the replenishment lead time can be monitored. Sometimes, repairing tools become unavailable from OEMs [74]. AM may play a recovery role in this perspective. For example, by using AM instead of milling, the lead time and cost to repair a helicopter part have been reduced from 45 days and \$2000 to 2 days and \$412 respectively [83]. The U.S. air force has collaborated with ‘America Makes’ to supply on-demand production to reduce the lead time for maintenance and replacement components of aircraft [84]. A summary of factors to be considered for spare parts selection is given in Table 6. Appropriate supply chain and technical factors should be considered to classify spare parts with AM. Moreover, companies are not classifying spare parts with a systematic data-driven way to choose the suitable spare parts for AM, which tends to fail in searching for the potential aspects and is a time-consuming exercise. A data-driven approach and multi-criteria decision-making (MCDM) techniques may assist in prioritizing the factors [85]. Moreover, companies need to avoid evaluating a large number of spare parts covering multiple criteria as it is a time-consuming process. However, understanding the suitability of spare parts with AM is also important. By analyzing additively manufactured part characteristics, Artificial Intelligence (AI) can be a suitable technique according to regulatory bodies’ standards [86–88]. AI can ensure feature recognition characteristics for spare parts selection with AM that will not be repeated even if a new spare part is developed. As less research has been conducted in this process, identifying missing classification approaches and promising opportunities can be future research.

Table 6. A summary of factors for spare parts selection.

Spare Parts Selection Parameters	Description	Author Reference
Part size, Build volume	AM machines have limitations of build volume as well as part size which depends on the resolution of the machine.	[79,89,90]
Supplier availability, demand pattern, lead time, predictability of delivery time	Normally AM is a time-consuming process rather than the machining process depending on the process parameters and part quality. Therefore, high resolution products can take large fabrication time rather than machining process, which may result in large lead time and delivery time need to be predicted to supply the spare parts in time	[90]
Appropriate material	Different materials have different mechanical properties, and their application may vary depending on their characteristics.	[91]
Appropriate material, Dimensional accuracy	The formability of complex shapes can affect the product dimension. Hence, proper material needs to be employed depending on material properties.	[92]
Post-production shrinkage; Appropriate material, water, and temperature resistance	The AM fabrication process is conducted in an ambient temperature depending on the material. After producing the parts, it tends to have shrinkage and resulting change in the product dimensions. As accuracy and tolerance is a big factor for aviation spare parts, so the shrinkage, dimensional accuracy and temperature resistance need to be considered for the fabrication process	[3]
Stiffness to weight ratio, Appropriate material, support material, strength to weight ratio	The part mechanical properties like stiffness to weight ratio, and strength to weight ratio need to be considered for better performance under a loading environment. The mechanical properties also depend on the product material and support material to sustain under loading.	[93]

Table 6. Cont.

Spare Parts Selection Parameters	Description	Author Reference
Layer thickness, Build speed	Optimized layer thickness, and printing speed needed for better part quality and material consumption.	[94]
Supplier availability, demand pattern, lead time, responsiveness, downtime cost, maintenance type	The spare parts need to be easy to change or repair. Otherwise, it will increase downtime in the maintenance work.	[5,95]
Supplier availability, demand pattern, lead time, Annual consumption value	The annual consumption of materials and spare parts plays a vital role in the MRO's yearly revenue.	[21,96,97]

4.4. Material Criteria

Titanium, Aluminum, Nickel, stainless steel, tool steel, etc., are commonly used in AM for the aerospace industry [98]. However, the most popular materials used are Nickel and Titanium base alloys due to their remarkable properties at elevated temperature which is well suited for aerospace application [99]. Moreover, silver, gold as well as platinum can be used for selective application in the aerospace industry [53]. Furthermore, Ti6Al4V alloy has been used extensively due to its high strength and fracture toughness, low density, low thermal coefficient, etc. [100]. In addition, the titanium alloy is used widely for mass manufacturing of turbine blades for use in commercial aircraft [101,102].

Various cabin accessories in aircraft like seatbacks, entry door parts, transparent headlights, full-size panels, and functional knobs have been manufactured in a highly detailed manner with SLA clear resins [103]. Moreover, Aurora Flight science and Stratasys have fabricated the largest Unmanned Aerial vehicle (UAV) with ULTEM 9085 material with the FDM process [61]. NASA's Mars rover has used 70 Production grade thermoplastic parts in the FDM process. Mainly, plastic materials are used because they are lightweight yet durable and strong enough to withstand stringent conditions [104]. Noteworthy, in CM processes, the fabrication of a part starts with cutting down a large ingot to the desired shape. Therefore, multiple component fabrication requires more ingots and machining, resulting in high wastage of around 90%, and low material utilization, with a high 'buy-to-fly ratio' of nearly 10:1 [105]. The 'buy-to-fly ratio' is an established concept in AM for the aerospace sector that refers to the weight ratio of raw material and the component itself [106,107]. Approximately 70% weight reduction of the original weight is possible in AM process [89,108]. The main advantage of AM is to fabricate the product to near net shape with approximately 1:1 'buy-to-fly ratio' and significantly minimize material waste by nearly 10–20% [109]. Even though the material cost is higher for AM than CM, a lower 'buy-to-fly ratio', minimum wastage, mass customization, and recyclable capabilities significantly reduce the overall manufacturing cost in AM [110]. AM can be considered an economical and better option than CM with added operational, inventory, and supply chain benefits.

Recently, AM has been applied to various complex-shaped spare parts fabrication by showing significant inroads in manufacturing novel components. However, AM's drawbacks remain on maintenance requirements, standardization, part size, geometry accuracy, printing quality, limited materials, and costs for spare parts production in the Aerospace industry. Therefore, further research on design methods, consolidated part configuration, and novel materials are required to overcome the challenges and maximize the applications of AM in the aerospace spare parts industry.

5. Supply Chain Scenario

AM significantly impacts the supply chain transformation as the number of components is reduced. In the case of additive manufacturing, the functionality of different

components is integrated into one 3D printed model. This reduces the assembly of components and synchronization efforts, unlike conventional manufacturing. Digitalization of manufacturing through AM reduces inventories compared to the conventional subtraction manufacturing processes. Consider two supply chain scenarios, Centralized and Decentralized, for additive manufacturing in spare parts. Decentralizing increases customer responsiveness, and reduces lead times, transportation time, and cost. The distribution time is significantly reduced if the final product is produced near the customer [26]. In terms of cost, the current condition in additive manufacturing technology found centralized AM cost effective compared to decentralized AM but with increased automation, decentralized AM is predicted to be cost effective [111]. Decentralized manufacturing enables a production system to deal with the unpredictability of demand, including cyber-physical systems automation with improved quality [112]. A case study carried out with six different spare parts in the aircraft industry analyzes the fluctuation of safety inventory with varied standard deviations of the demand. It is seen that the safety inventory of decentralized AM is the lowest, with a standard deviation of up to 30%. Nevertheless, as the standard deviation reaches 30% or more, the safety inventory of centralized AM is lower [27]. A simulation, carried out at a service level within 65% to 95%, implied the decentralized scenario as a prominent strategy [113]. It shows that a decentralized AM reduces the lead time, holding costs, and transportation costs compared to a centralized AM at every service level point [113]. The two scenarios of centralized and decentralized AM [114] are illustrated below in Figure 5.

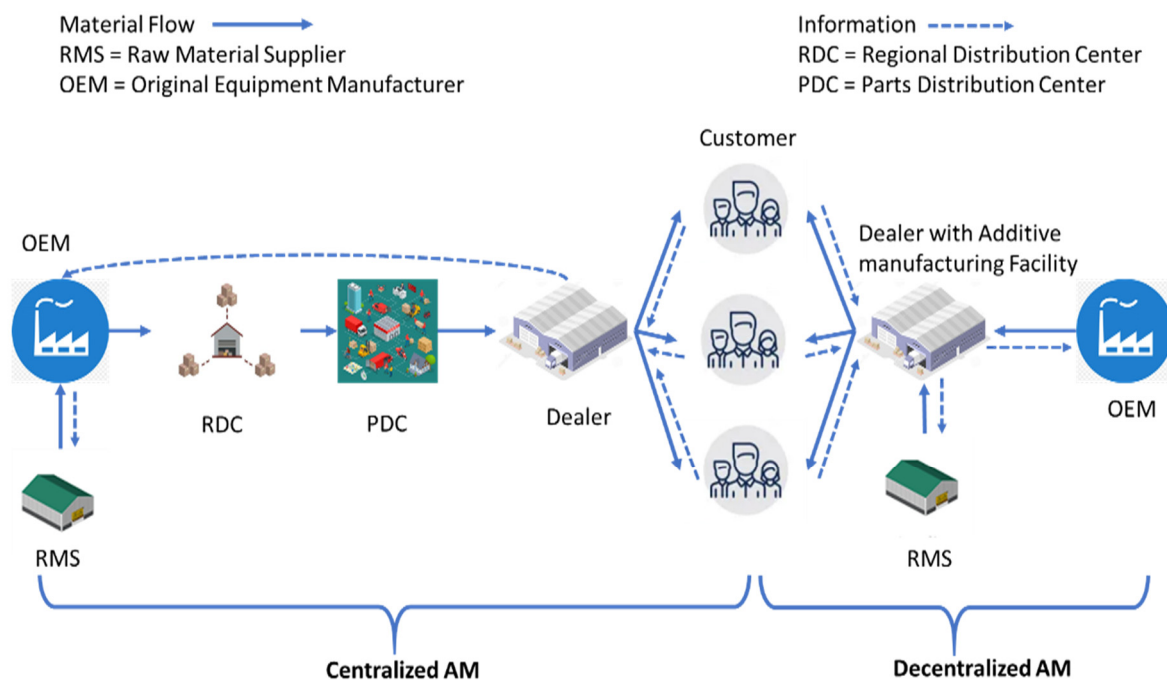


Figure 5. Illustration of Supply Chain Scenarios in Spare Parts Industry (Own illustration based on [114]).

5.1. Spare Parts Manufacturing Scenario

This sub-section discusses five spare parts manufacturing scenarios as illustrated in Figure 6. Personal, Retail, and Mobile industries are proposed to benefit from decentralized manufacturing [115]. Personal manufacturing refers to the owning of AM machines by customers and producing spare parts by themselves by purchasing the licensed model online. In retail manufacturing, an AM facility in the high street will provide an on-site manufacturing facility with access to a digital library. Mobile manufacturing is an in-transit manufacturing method that implies spare parts to be manufactured while shipping towards

reducing lead time and stock holding. In bureau manufacturing, regional centers of bureaus are provided by OEMs that reduce reliance on the central warehouse and transportation. In factory manufacturing, AM machines are incorporated with the current manufacturing system that allows mass production with customization flexibility as well [115].

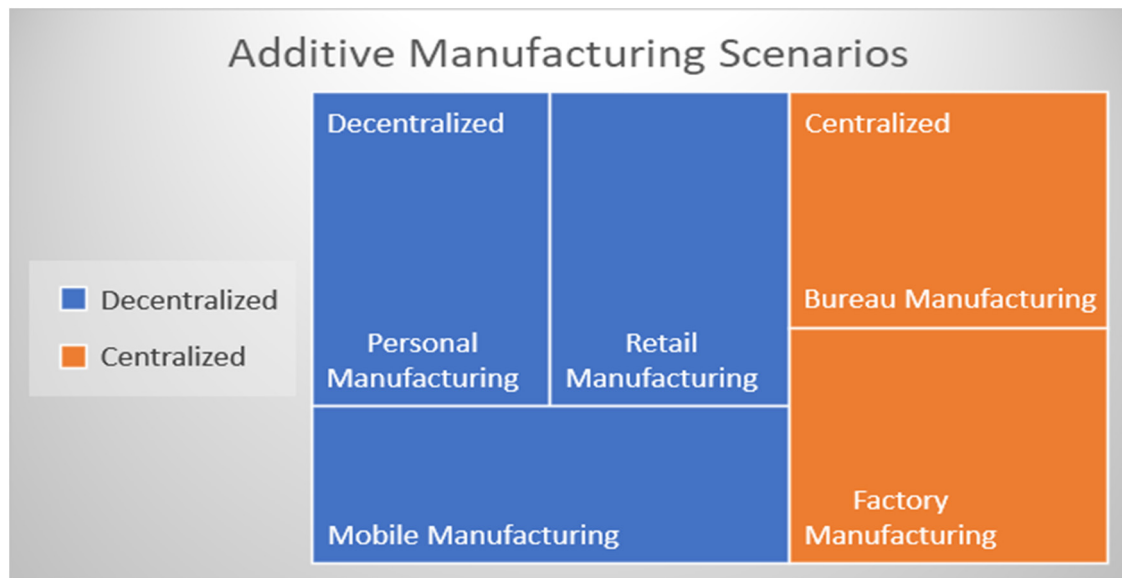


Figure 6. Different Scenarios of Centralized and Decentralized Additive Manufacturing.

5.2. Centralized vs. Decentralized Supply Chain

A comparison between centralized and decentralized supply chains of AM in the spare parts industry is discussed in Table 7.

Table 7. Cost Comparisons of Supply Chain Scenarios among AM Technologies.

Attribute	AM machine Technology							
	Current Technology				Future Technology			
	SoA-SP [30]		SoA-MP [30]		SoA-2013 [17]		ReqTecDM [17,30]	
	Centralized	Decentralized	Centralized	Decentralized	Centralized	Decentralized	Centralized	Decentralized
Material Cost	Same	Same	Same	Same	Same	Same	Same	Same
Spare parts transportation cost	High	Nil	High	Nil	High	Nil	High	Nil
Inventory carrying cost	High	Low	High	Low	High	Low	High	Low
Aircraft downtime cost	Low	High	Low	High	High	Low	High	Low
Annual cost of initial inventory production	High	Low	High	Low	High	Low	High	Low
Inventory obsolescence cost	High	Low	High	Low	High	Low	High	Low
Initial investment in AM machines, depreciation cost	Low	High	Low	High	Low	High	Low	High
Personnel cost	Low	High	Low	High	Low	High	Low	High
Total Cost	Lower	Higher	Lower	Higher	Lower	Higher	Higher	Lower

Based on the required chamber capacity, the current technology machines are classified into three sections: “state of art-2013”; “state of art- single part”; “state of art- multi part”, that are denoted as “SOA-2013”, “SOA-SP”, “SOA-MP”, respectively. Norge Ice 1 and 9 are two machines referred to as SOA-SP & SOA-MP, respectively [30]. Moreover, the future assumption of hypothetical machine technology is referred to as “Required Technology for Distributed manufacturing”, also termed as “ReqTecDM” where the machine has increased productivity and more automation. With the current technology (SoA-SP, SoA-MP, SoA-2013) of additive manufacturing, it is preferred to have centralized manufacturing rather than decentralized manufacturing. Here, the total cost for centralized is always significantly lower except for one case of future hypothetical technology (ReqTecDM) of AM where the operator to machine ratio and the procurement price of machines are reduced significantly. The future technology in AM supports the decentralized structure because the future AM machines are investigated as cheaper, smaller, and with increased automation [17,30].

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Li et al. (2017) [27] simulates the carbon emissions in two scenarios of AM and concludes that a centralized AM has a bit higher carbon emission than a decentralized AM (Figure 7). In a centralized supply chain, 63.7% of its total carbon emission is due to the production of raw materials, which is 68.31% in the case of a decentralized supply chain. For the centralized scenario, the carbon emission due to the manufacturing and transportation of the final product is 22.75% and 13.55%, respectively. In contrast, the decentralized method incurs 22.42% and 7.27%, respectively [27]. Hence, it appears that decentralized facilities reduce the carbon footprint. Nevertheless, further investigation is needed on how component design and AM’s weight savings character impacts the life cycle and carbon footprint for spare parts fabrication in the aerospace industry.

In general, OEMs perform turnaround tasks, replace aging and broken parts, inspect and identify broken parts, send out broken parts, as well as stock new spare parts of the aircraft. However, considering the details, the tasks are not as simple as it seems. There are many unique parts in Aircraft that are delivered through several distribution networks. Therefore, various managerial strategies need to be adopted to govern the system. Accordingly, these strategies face various geographical and human barriers. As Aircraft has some highly technical and critical parts, the logistics system is quite complex to make the right decisions in terms of performance, cost, and sustainability [117].

Moreover, logistical disruptions are common in the spare part supply chain when suppliers face low-volume business that is no longer economical. As a result, service providers lose interest in investing in inventories of additional spare parts to fulfill the demand. Such a high uncertainty leads to substantial costs frequently [118]. However, the low-volume production costs can be minimized by utilizing AM due to the lower tooling and setup costs [119]. For instance, AM can be used to repair worn-out spare parts, saving costs and increasing the usage period. Moreover, the total lifecycle costs are minimized as replacement intervals increase with AM.

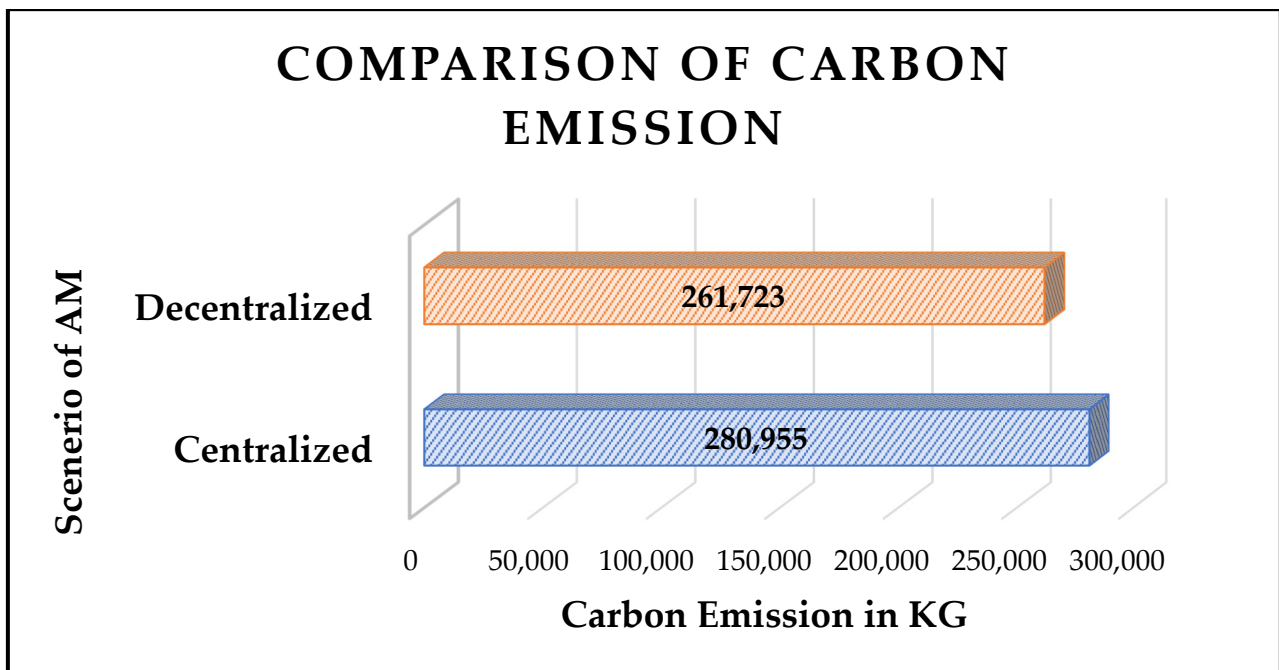


Figure 7. Comparison of Carbon Emission between Centralized and Decentralized Additive Manufacturing [27].

In addition, AM may increase the responsiveness of a supply chain [17]. For example, AM can fabricate on-demand spare parts and lower response time to avoid safety stock costs. Furthermore, order-driven production can minimize the obsolescence risk of stored spare parts. As discussed before, if spare part supply is disrupted, high costs can be incurred, especially for low-volume parts. It is possible to establish a streamlined supply chain relatively cheaply with AM technology [78]. Moreover, this practice may bring more benefits if the demand for spare parts occurs at remote locations or the customer response time needs to be short. On-demand printing of AM can be an alternative to holding high inventory and longer downtimes. This type of application is found in the military, like the US marine corps, to fabricate advanced parts at remote locations [120].

6. Industry 4.0 Context in AM of Spare Parts

The vision of Industry 4.0 (I4.0) is to construct a smart and open manufacturing platform in order to build an industrial networked information application [121]. Mostly, tracking the status and position of products, data-driven manufacturing, real-time monitoring, and control of production processes are the primary needs of I4.0 [122]. Various technologies like Cloud Manufacturing, Internet of Things (IoT), Big Data, Cyber-Physical Systems (CPS), Additive Manufacturing, Artificial Intelligence (AI), Block Chain, etc., have evolved and appeared recently for industry 4.0 [123,124]. Despite increasing research on industry 4.0, it remains stippled and fragmented [125]. For example, there may be a technical similarity, such as adopting a process perspective or decreasing failure in the manufacturing system.

A popular key concept is the Smart Factory, also called an intelligent and digital factory [126]. It consists of machines equipped with different sensors and actors, which can send, process, collect and receive data and act accordingly with the internet connection [126,127]. A smart factory illustrates the future state of a controlled manufacturing system, which operates without any human force [126]. It transfers, generates, processes, and receives the necessary data to complete required tasks to produce various types of goods [128].

Industry 4.0 gives the vision of a new industrialization concept that exploits newer technologies to fabricate spare parts for building smart factories. Smart factories are self-adaptive, making them the heart of Industry 4.0 [129]. A smart factory integrates new technologies like blockchain to improve the overall quality, performance, and transparency of the manufacturing processes. Blockchain helps to monitor printed parts with the secured exchange of data among the stakeholders, improving the process and reducing the logistic costs with the help of a flexible supply chain [130,131]. From a supply chain perspective, smart factories are self-sufficient facilities that source raw materials from local suppliers. Sustainable approaches to building smart factories need to be ensured by 4Vs volume, variety, velocity, and veracity [132]. Yet, more research is needed regarding how to adopt a smart system with the implementation of I4.0 technologies to manage spare parts production in the aerospace industry.

Big data enable process analysis and optimization by generating a large amount of data. It assists in developing an AM integrated data model [133] and benefits manufacturers, the environment, customers, and different aspects of the spare parts manufacturing phase [134]. However, a lack remains to implement big data analysis in spare parts industries to forecast the unpredictable demand, design the inventory system, and consequently minimize the overall supply chain cost.

Furthermore, Artificial intelligence (AI) explores techniques of developing intelligent programs and machinery that can solve issues creatively which has always been regarded as a human attribute. AI can minimize the required workforce to increase output and achieve greater resource efficiency. With AI, local partners and alliances can decrease lead time and inventory and simultaneously increase the customization and responsiveness of the supply chain. Research trends demonstrate that AI supported models are computer-efficient technologies that enable AM processes to achieve a high-quality standard, product consistency, optimized process, and responsiveness in the supply chain [135]. Figure 8 illustrates the AM supply chain digitalization of spare parts with industry 4.0.

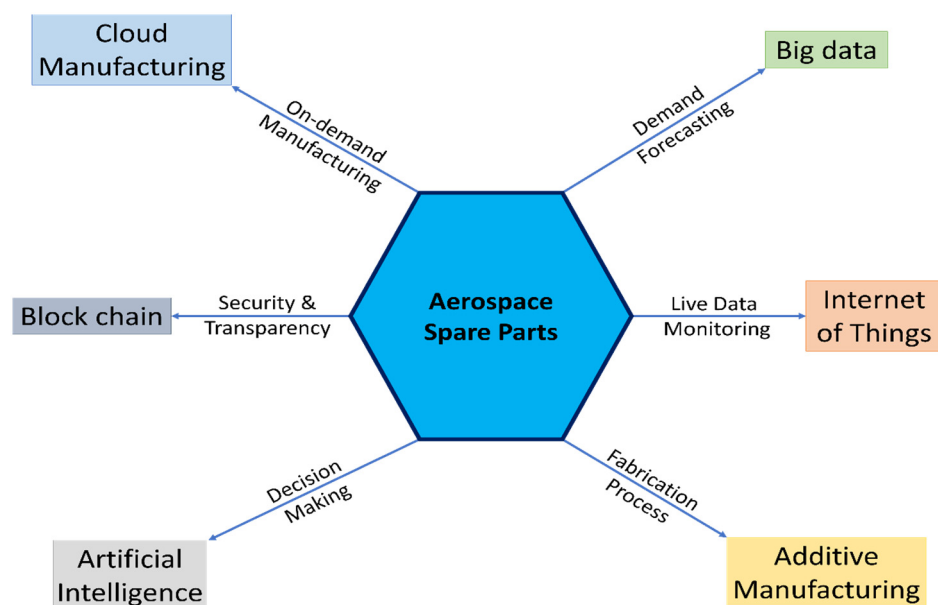


Figure 8. Digitalization of spare parts supply chain with industry 4.0.

Nowadays, additive manufacturing is becoming popular due to the capability of making parts with small sizes, complex shapes, and intricate details at a low cost. Nevertheless, this process is challenging for not determining how many parts should be produced due to inadequate exchange of information where industry 4.0 can be the solution [17,112]. Besides, industry 4.0 helps in proper inventory management. Using a cyber-physical system, more data can be acquired that can be used by sensors to determine failure time

accurately [136]. Moreover, increasing types have complicated spare parts' tracking as it moves from one place to another. The blockchain system may ease this issue [137]. Industry 4.0 connects supply chain players (e.g., supplier, manufacturer, distributor, and retailer) with the help of cyber-physical systems that initiate the growth of the 'factory of the future (FoF)' [138]. It also helps to ensure sustainability in the supply chain [139]. This system can also be used to improve flexible AM systems. Apart from these, Industry 4.0 plays a significant role in the maintenance of spare parts [22,140]. Cloud Manufacturing refers to an interconnected virtual space of manufacturing resources, intelligent management, and solution to all consumer queries requiring IoT, cloud computing, service-oriented technologies, and virtualization. In AM processes, cloud manufacturing helps increase resource efficiency [131]. Some key characteristics of cloud manufacturing are flexibility and scalability depending on market demand, multi-tenancy, intelligent on-demand manufacturing, etc. It also helps to achieve a sustainable manufacturing process [130].

In AM processes, parts can be produced with new materials, features, and shapes for better optimization of performance and features. Moreover, another challenge is to obtain the same properties in the parts produced later with feedstock arriving from different vendors, which may harm the supply chain due to more integration of parts. Aircraft spare parts are valuable and expensive products that need to be delivered from one place to another with extra caution increasing delivery time and cost. Consequently, future research can be conducted on expanding AM materials, improving part designs, and maintaining the reliability of the part produced from different feedstocks. Future research can also be conducted on how delivery cost and time of delicate parts can be reduced [141] and how AM impacts the supply chain performance [142]. The AM process is not preferred for mass production. Future research can be conducted on how AM can be used for mass production along with mass customization in the aerospace industry. Nevertheless, AM processes also have limitations on the materials they use. More materials for AM should be discovered so that conventional machining does not need to be used in the aerospace industry. Large parts (like airplane wings) cannot be manufactured using AM, which can be solved in the future. Industry 4.0 concepts should be adapted quickly, which will help to reduce the downtime in the production of spare parts as well as increase gross revenue for the manufacturers of the aerospace industry.

7. Managerial and Policy Implications

The study can play a vital role in AM spare parts supply chain with significant managerial and policy implications in the aerospace industry for the logisticians. As the demand in this field is quite unpredictable, aerospace logisticians need to take measures quickly to satisfy their customers. However, some barriers constrain providing service within the shortest period resulting in revenue loss. Based on the discussion of the review, AM and I4.0 can be potential technologies in the aerospace spare parts industry to solve constraints and problems. By understanding the material selection criteria, policymakers may adopt AM in spare parts productions, which will assist them in utilizing the resources efficiently. With the advancement of AM, logisticians can provide required spare parts in the shortest lead time possible. Therefore, AM can boost spare parts production by coping with the market demand. With AM facilities, spare parts production can be facilitated in remote locations. Logisticians can employ and manage decentralized facilities by using blockchain, big-data analysis, cyber-physical systems, artificial intelligence, cloud manufacturing, etc. Moreover, AM can produce on-demand mass-customized products in the facilities. Therefore, MROs would not require larger facilities for spare parts inventory and it may reduce the safety stock. Finally, AM and I4.0 technologies will help the managers proactively take the right initiatives to minimize lead time, safety stock, inventory, and financial loss in the aerospace spare parts industry. Thus, the outcomes of the study may bring essential guidance for policymakers and different management professionals to adopt the excellence of AM in the emerging field of aerospace spare parts.

8. Conclusions

This research aims at exploring the impact of AM technologies on the aerospace industry's spare parts supply chain. Hence, a systematic review of the literature has been conducted. This paper discusses various aspects of the spare parts supply chain, such as facility location, distribution network, material selection, comparative analysis of AM and CM technologies, and industry 4.0 perspectives. The systematic review of existing literature provides a solid reference to the companies and entrepreneurs in their decision-making regarding AM consideration in the spare parts industry. This article further contributes to the knowledge of supply chain scenarios in different conditions, choices of material for making spare parts, and trends in AM technologies.

It is noteworthy that there are some limitations to this review paper. Since the author has used Google scholar only, using other search engines and databases may affect the review result. Selected papers were published between 2005 and 2022; hence, previously analyzed data in this field are not incorporated. Moreover, changes in word strings other than mentioned keywords may present slight differences in the review outcomes. While this paper reviews the existing literature descriptively and analytically, considering any statistical models or analyzing the engineering impact is out of this study's scope.

Currently, a centralized AM facility is preferred over decentralized AM facilities for total expenses in aerospace spare parts industries. In the future, a decentralized AM is predicted to be less expensive due to increased automation, reduced price, and small-sized machines. Moreover, carbon emission is lower in a decentralized supply chain than in a centralized supply chain due to lower emissions at the manufacturing stage and reduced outbound transportation. Nevertheless, further research on the AM facility location is required. Secondly, part consolidation and quality standardization have characterized AM into a new enabler of spare parts in the aerospace industry. Various complex-shaped nozzles, blades, turbines, and other structures can be fabricated easily under AM processes than CM processes. Thirdly, in the fabrication of aerospace spare parts, the material criteria and other listed factors for spare parts selection can help conceptualize the MRO to improve its supply chain. Industry 4.0 helps to digitalize the spare parts supply chain for transforming intelligent and smart industries. Consequently, AM has good potential in the aerospace industry for spare parts production and new parts fabrication. However, there are still some constraints to adopting I4.0 technologies to make the supply chain stable and responsive. Such constraints need to be identified by engaging the manufacturer and MROs. The future requirements for AM can be critical to resolving the current limitations of the spare parts supply chain scenario in the aerospace industry.

Overall, a research gap still remains in the aerospace industry due to the commonly lower usage of AM and industry 4.0 in spare parts service logistics. A realistic explanation can be that logisticians are less aware of the capability, sustainability, and technologies of I4.0 and AM than design engineers and operations teams. Conversely, design engineers and operations teams may not be aware of the importance of logistical characteristics to satisfy the gap. Unfamiliarity from both parties may lead to the underestimation of AM potentiality. The future perspective of the spare parts supply chain should consider AM and I4.0 technologies to overcome supply chain uncertainties. Hence, it may lead to a more responsive and economical supply chain by meeting the uncertain customer demand and making a smooth path in the logisticians' decision-making. Moreover, future research may explore the impact of AM on certain phenomena like the bullwhip effect in the spare parts industry. It is hoped that this review article will further inspire researchers and industry practitioners to explore and adopt AM in the aerospace spare parts supply chain.

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