Spare Parts with Additive Manufacturing of Aviation Industry

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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. 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.

additive manufacturing spare parts aircraft industries supply chain

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 obsolesce 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]		✓		✓	✓	✓

Author name	Supply Chain	Additive Manufacturing	Industry 4.0	Spare Parts	Material Selection	Aircraft Industry
(Mehrpouya et al., 2019) [28]		✓	✓	✓		
(Yusuf et al., 2019) [29]		✓			✓	✓
(H. Khajavi et al., 2018) [30]	✓	✓		✓		✓
(de Souza et al., 2011) [31]	✓			✓		✓
This Paper	✓	✓	✓	✓	✓	✓

d 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 researchers 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 research, is illustrated in **Figure 1**. The shared portions of the frameworks are described in this research through a systematic literature search and literature review. Consolidation of information from various literature was induced towards bringing proper value to the research.

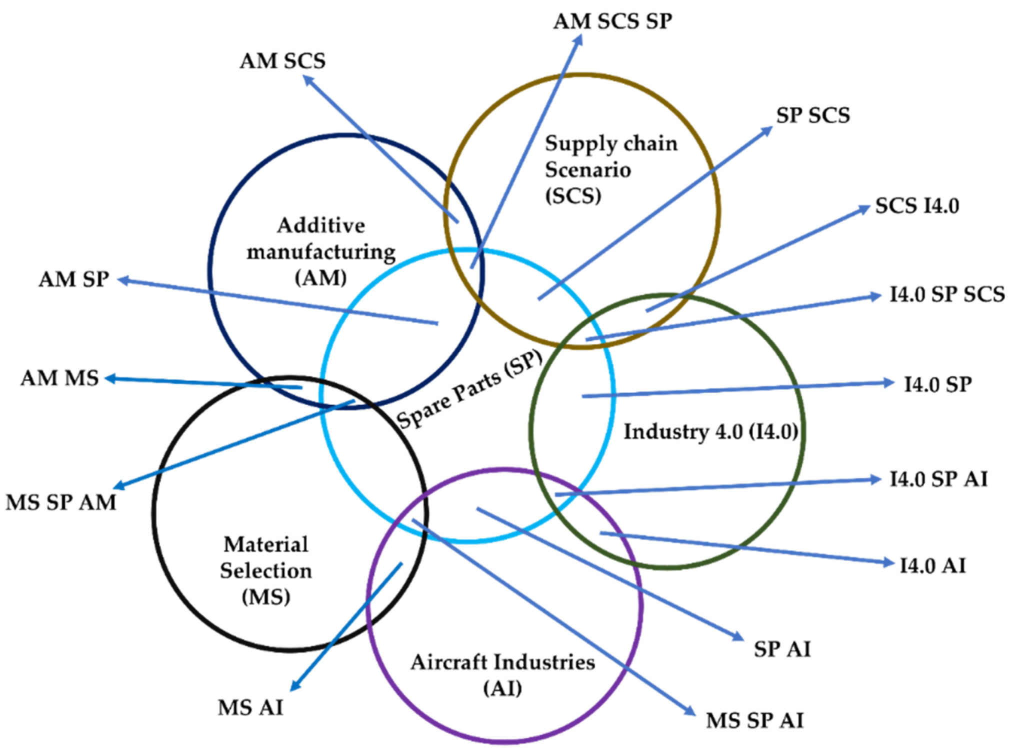

Figure 1. Framework of Core Subject Areas Mapping.

2. 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.

2.1. 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 [32]. While SAE International primarily works on aerospace-related AM standards, both ISO and ASTM are responsible for AM standard publications [33]. Therefore, FAA and EASA have established certification and testing protocols to clear any components for service on the required application [34]. Major leading regulatory bodies like ASTM, ANSI, and SAE international have collaborated frequently with aviation regulatory bodies, such as NASA, FAA, and EASA [35][36]. This effort has accelerated the certification process and ensured continued operational safety for adopting AM in the aerospace industry [37]. However, a well-established standardization has not been conducted yet, and the process is quite costly and lengthy.

2.2. 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 [38]. Moreover, any error in tolerance, misalignment, or geometric error would complicate the assembly process [39]. Additive Manufacturing can solve this problem by fabricating a complex part combining components that enables feature integration and increases reliability, sustainability, and performance [40]. Moreover, it will reduce inventory, lead time, assembly-line footprint, and supply chain pressure by increasing components' performance [5][41]. For example, a hydraulic housing tank containing 126 parts can be reduced into a single component using AM [42]. 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 [43].

2.3. Materials Selection for Spare Parts in Additive Manufacturing

Spare parts forecasting is challenging as the demand pattern is intermittent [44]. A higher service level is required to avoid downtime costs, making the spare parts planning more complicated [45]. 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 [45][46]. AM can increase responsiveness by balancing inventory levels and minimizing carbon emissions and disruptions in the supply network of spare parts [45]. AM reduces the supply risk for spare parts for low-demand parts while conventionally manufactured part is unavailable in low quantity [47]. However, a limited volume of AM, inadequate quality and post-processing requirements are the challenges for this purpose [48]. 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 [49]. Many aircraft spare parts are highly valued, ordered infrequently, and require a long replenishment lead time [50]. 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 [41]. 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 [51]. 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 [52]. A summary of factors to be considered for spare parts selection is given in **Table 2**. 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 [53]. 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 [54][55][56]. 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 2. 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.	[47][57][58]
Supplier availability, demand pattern, lead time,	Normally AM is a time-consuming process rather than the machining process depending on the process parameters and part	[58]

Spare Parts Selection Parameters	Description	Author Reference
predictability of delivery time	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	
Appropriate material	Different materials have different mechanical properties, and their application may vary depending on their characteristics.	[59]
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.	[60]
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.	[61]
Layer thickness, Build speed	Optimized layer thickness, and printing speed needed for better part quality and material consumption.	[62]
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][63]
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][64][65]

2.4. Material Criteria

Titanium, Aluminum, Nickel, stainless steel, tool steel, etc., are commonly used in AM for the aerospace industry [66]. 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 [67]. Moreover, silver, gold as well as platinum can be used for selective application in the aerospace industry [68]. Furthermore, Ti6Al4V alloy has been used extensively due to its high strength and fracture toughness, low density, low thermal coefficient, etc. [69]. In addition, the titanium alloy is used widely for mass manufacturing of turbine blades for use in commercial aircraft [70][71].

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 [72]. Moreover, Aurora Flight science and Stratasys have fabricated the largest Unmanned Aerial vehicle (UAV) with ULTEM 9085 material with the FDM process [73]. 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 [74]. 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 [75]. 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 [76][77]. Approximately 70% weight reduction of the original weight is possible in AM process [57][78]. 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% [79]. 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 [80]. 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.

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