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Research Article

Additive Manufacturing for the Aircraft Industry: A Review

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ABSTRACT

Considering the stringent regulations, manufacturing of aircraft parts is often quite complex and time consuming. The multi-million components, multi-tier manufacturing systems and the severe constraints surrounding the sector lead to heavy inventory investments to achieve the just-in-time supply of parts often needed to reduce the airplane ground times. Additive manufacturing evolved allowing for the direct production of complex parts based on digital data with no complex tooling or machinery, a messiah of true just in time production. Appropriate integration of additive manufacturing with the aircraft industry could resolve some of the supply chain and inventory hurdles. Significant progress is already evident in these lines, but the lack of quality assurance attributes and certification standards is hampering the progress. The state-of-the-art of the application of additive manufacturing in the aircraft industry is reviewed in this paper. The supply chain configurations of the aircraft industry, the possible roles of additive manufacturing in relaxing the pressures in the system are evaluated. The application areas, enhanced attributes, and certification standards are critically reviewed and classified. The overall growth in the application of additive manufacturing in the aircraft industry, the main hurdles, and the future possibilities are evaluated and presented systematically, clearly portraying the developments.

Keywords: Aircraft; Industry; Pressures; BAE systems

INTRODUCTION

Aircraft industry consists of several players; the sellers are the original equipment manufacturers (OEMs), which include the aircraft and part manufacturers; Boeing, Airbus, GE Aviation, Lockheed Martin, BAE systems and Rolls-Royce Holdings are examples. The Maintenance, Repair and Overhaul (MRO) organizations are the service providers. The commercial airline operators and the military are the customers. Aircraft and part manufacturers sometimes also act as the service providers by selling maintenance packages to the airline operators to gain the aftermarket revenue. Airlines operators are sometimes integrated with the MRO organisations, while OEMs also often give customers the option for customization. Especially with the interior design, as high level of customization is often essential for airlines in view of the high level of competition.

Due to the stringent standards in the aircraft industry, the aircraft maintenance process is highly regulated. The MRO organizations need to be approved by aviation authorities such as the Federal Aviation Administration (FAA) and European Aviation Safety Agency (EASA). The staff and the equipment belonging to the organisations must be licensed and certified. The main task of the MROs is to ensure the airworthiness of the aircrafts, during the periodic aircraft inspections or unscheduled line maintenance. MROs are not always independent in the aircraft maintenance, as most of OEMs and part suppliers offer maintenance services to the airline's operators. For example, Rolls Royce provides the Total Care service which the customers pay as per the engine flying hours. In return, Rolls Royce offers their customers long-term aftermarket support and acceptance of risk transfer [1]. This is in a way, the suppliers becoming the MROs. The end users such as the airlines operators also have their own maintenance teams and warehouse activities, with a storage of the frequently replaced spare parts. The customers either stock the infrequently replaced parts in small quantities or buy them from the nearest MRO companies, part manufacturers, or spare parts distributors.

Due to the high market entrance barriers, there are only a few OEMs designing and manufacturing aircrafts and the main component systems. The complexity of the aircraft systems, however, often necessitates OEMs to work with several suppliers, constituting a three-tier supply chain system. Tier one suppliers are the most crucial of the industry as they are responsible for working with sub-

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tier suppliers and manufacture the most important sections such as the aircraft frame, engines, interiors, avionics systems, landing gears and other complex components. This model also creates a risk sharing partnership. The duty of the aircraft manufacturer is to oversee the final assembly of the aircraft and make sure that it performs as per the standards. The end users order airplanes or components from aircraft manufacturers or part suppliers. The overall operational structure of the aircraft industry as understood from the literature reviewed is consolidated in the form of the block diagram shown in Figure 1, identifying the critical players and the typical interactions amongst them. Recent studies indicate that a more agile and efficient supply chain network can be developed through the integration of additive manufacturing with the aircraft industry [2-8]. Individual players can produce parts locally, allowing for the true just-in-time production of parts needed suddenly and more robust supply chain system compared to the one presented in Figure 1. Consequent benefits will be reduced warehousing, inventory management, transportation, and the overall supply chain costs.

LITERATURE REVIEW

Evidently, the supply chain of aerospace industry is the most complex and the longest compared to the other industries [9]. Aircrafts are made up of many sophisticated components and subcomponents, and considering the nature of the industry, a multi-tiered manufacturing structure is often used. This configuration requires intensive effort on the supply chain management and inventory prediction to ensure a smooth operation, as any supply chain hick-up can disrupt the final aircraft assembly. Considering the complex supply chain configurations, and the need for faster maintenance service systems, the aircraft industries often maintain higher levels of inventory. The overall inventory costs are estimated to be around USD 50 billion, around the world [10].

There has always been a constant struggle to reduce the stock levels and numerous strategies such as forecasting the parts demand, employing algorithms to predict maintenance requirements and part failures, and optimising the supply chain configurations have been studied and implemented in the aircraft industry [11-14]. However, the high transaction costs and the costs of delayed aircraft servicing rendered these measures to be effective only to a limited extent. The manufacturers have been continuously striving to optimise the design and production processes and reduce the waste and production lead times by employing the lean manufacturing approaches. The use of advanced automation, computer aided design, and manufacturing have been in use to further improve the products and services. Additive manufacturing technologies (AM) are currently taking the centre-stage in this endeavour. A comprehensive review of the possible roles AM can play in the aircraft supply chain and inventory systems and the current state of application and associated quality assurance and standardisation issues will be presented in this paper.

Inventory control and supply chain issues

The aircraft MRO organizations must be approved by the aviation authorities and perform replacements of spare parts into the aircraft in scheduled or unscheduled maintenance events. Depending on the organizational structure, customers take make-or-buy decisions on the spare parts. Aircraft MRO systems can be internal divisions of the end user company, or a contractual partner from other independent MRO systems. End users like the airline operators normally focus on their core tasks such as the passenger and cargo services, while outsourcing the maintenance services. MRO activities make up 40-50% of the aerospace industry's revenues and selling spare parts often tends to generate more profits than selling the original equipment [15]. The availability of the aircraft is crucial and keeping minimum Aircraft on Ground (AOG) times will maximize the profits for airline operators. Consequently, turnaround time (TAT) is a key performance indicator of the aircraft MRO units.

Aircraft components often consist of many parts, all of which need inspections of high standards, and the demand is normally unpredictable. These are critical factors stretching the inventory levels to the limits, though regular replacement is only needed with 10% of the spare parts [16]. Parts needing fewer regular replacements, also referred to as "slow-moving parts" or "Long-Term Storage parts", are hard to predict the exchange times and become expensive. The normal inventory control strategies may not be effective in such cases and contribute largely to inventory. Generally, spare parts are classified into four types; 'Rotatable', 'Repairable', 'Expendable' and 'Consumable' [17], each of which has a different replenishment policy. The inventory analysts are responsible for assigning specific policies on hundreds and thousands of spare parts. These policies are associated with the volume of the repair and the supply lead times and need to be updated regularly to adapt to the market changes.

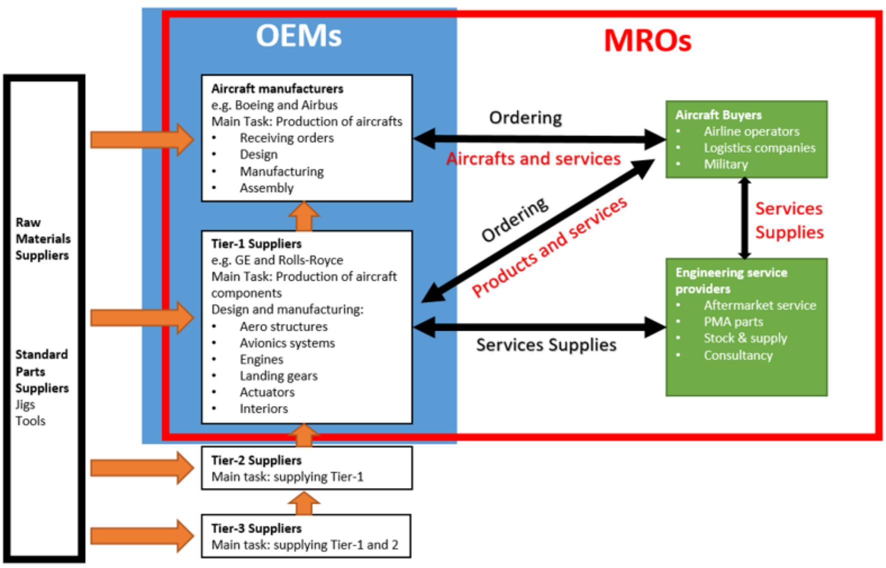

Figure 1: The aircraft production and maintenance models.

Predicting the spare parts demand is challenging and at times, a spare part might not be in production anymore. These factors make the aftermarket service difficult and lead to the overall inefficiencies in the supply chain systems of the aircraft operations industry. High inventory levels can reduce the aircraft down time, but the total financial investment becomes astronomically high. As a compromise, customers use several strategies in the material service value chain such as insourcing or outsourcing and contractual agreements with different suppliers, MROs and other distributors. The objective is that the distributors share the inventory pressure from both suppliers and buyers.

The supply chain systems associated with the aircraft industry also face complications, resulting in significant delays and associated higher costs. Problems might begin as early as at the time of ordering aircrafts, as there is often a lack of clarity on the specific type of the work to be carried out. For example, high level of customisation in the cabin area is the main competitiveness among passenger airlines as the interior design defines the brand and image of the airline companies. Considering that the cabin is only 3-5% of the total costs, airlines often tend to invest heavily on the cabin design [18]. However, a detailed specification of the interior design might come as late as 6 to 12 months before the delivery date. Financial constraints and varying business models are often at the root of such delayed decisions, while airlines also often tend to demand late changes in order to be innovative and create advantages over the competitors. Modifications to the security systems, new options for improving the fuel consumption, policy changes, and technology innovations also might necessitate design alterations from time to time. Beyond the standard parts, there are often components to be custom made, which require additional design tasks, further raising the uncertainty in the production processes and controls [19]. Customisation and delayed design decisions will lead to manufacturing complexities, supply chain problems and increased costs.

The nature of the aircraft industry, the high level of customization and the lumpiness of the less-frequently-used parts are all challenges for organizations along the aircraft supply chain. It is often problematic to provide timely production and maintenance services, while still maintaining good profits. The requirement to produce high quality components with expensive materials in short times pressurises the manufacturers, as the lead times are often stretched to several months with the conventional manufacturing techniques. Combining the high cycle service levels with the long procurement lead times, the aircraft spares industry ends up with keeping higher levels of buffer safety stock, locking up a significant amount of capital in the form of inventory costs. The economies of mass production also lure the complex supply chain systems to invest in higher inventory. Another supply chain risk is the competition for resources with material systems such as titanium and aluminium alloys, carbon fibres, and their composites. These strong and lightweight materials are equally popular among other industries such as automotive. The serious lack of design freedom, compromised product functions, and uncontrolled number of component parts; the typical attributes of traditional manufacturing will cause further constraints.

Sustainability and environmental impact concerns have become increasingly important in the modern design and manufacturing activities and are also playing definite roles in the aircraft industry. The industry is committed to reducing the impacts on the climate in terms of both improving the manufacturing activities as well as reducing the in-service emissions. However, for small volume production the traditional manufacturing methods are inefficient. Further, it was also noted that a vast majority of the aircraft spare parts are finished by machining, in which the material wastage could be as high as 98% [20]. Additionally, government regulations and global aerospace mission impose statutory conditions to reduce emissions, necessitating the weight reduction as the primary objective of aircraft OEMs. Airline operators are willing to invest heavily on aircrafts with superior fuel efficiency because fuel is their major spending, roughly 33% of the total costs [10]. However, traditional manufacturing methods have already reached the limits in achieving the weight reductions and the never-ending thirst for lighter and better designs is keeping the search alive for more advanced and alternative methods of manufacturing to stretch these limits.

Evidently, the aircraft supply chain and inventory systems are complex and multi-directional. Most problems also boil down to the time-consuming and restrictive manufacturing process currently used. Considering the recent developments in the additive processing methods and the possible improvements they may bring to the aircraft manufacturing and maintenance industries, it is necessary to have a renewed look into all these aspects. An attempt is made in this paper to review the current progress in the direction of integrating the additive manufacturing and the aircraft industries. Beginning with an overview of the recent publication trends in the field, the following sections elucidate the critical aspects reviewed and evaluated, consolidating the observations, where possible.

Additive manufacturing and the publication trends related to the aircraft industry

The point-by point and layer-by-layer material consolidation mechanics unique to the additive manufacturing methods offer promising new solutions and the technology is evolving to be one of the greatest achievements of the recent era. Direct conversion of raw materials into complex 3D forms based on the digital data generated by slicing and rasterising computer aided design files allows significant time and cost savings where the technology is suitable for producing the end use parts. The evolution from 3D printing to rapid prototyping and free-form fabrication signifies the attributes the processes attained at different stages of the technology growth [21]. According to the 2016 Wohler's report, the AM industry reached 5.165 billion USD worldwide [22].

Based on the specific techniques used, the AM processes can be classified into seven categories; powder bed fusion, binder jetting, direct energy deposition, extrusion, jetting, sheet lamination, and vat photo-polymerization. The most widely used methods are selective laser sintering (SLS), selective laser melting (SLM), electron beam melting (EBM), stereolithography (SLA), ink-jet printing, fused deposition modelling (FDM) and direct metal deposition (MD), while metals, polymers, ceramics and composites of different combinations are being developed as possible material candidates. Lower energy consumption, better mechanical efficiency, lesser material wastage, and shorter design and manufacturing lead times are typical characteristics compared to traditional manufacturing methods. The point– or layer-wise consolidation also allows for better design flexibility, higher level of customisation, lesser lead times and possible improved supply chain solutions. The ability to manufacture complex 3D forms direct from digital data, eliminating the need for complex tooling and specialised work-tool motions and the forces involved in between allow for reduced manufacturing lead times and possible localised production, contributing towards more efficient supply chain systems [23-29].

Consequently, the additive manufacturing methods rapidly gained application potentials in different fields, including the aerospace industries. Therefore, there has also been an increasing number of publications related to the use of additive manufacturing in the aircraft industry and the general trends noticed are discussed here. The systematic mapping strategy developed by Petersen et al. [30] is employed here, as was also the case with another review article on additive manufacturing [31]. The questions raised during the systematic mapping developed to capture the application of the additive technologies in the aircraft industry are centred around three aspects; publication types and trends and the general research directions.

The overarching phrase for the online search engines is ‘Additive manufacturing in the aircraft industry’. The choice of the keywords is important as it will affect accuracy of the search results and the conclusions that can be drawn from the analysis. Appropriate combinations of the Boolean operators are also needed, as search engines respond to input phrases constructed with keyword and Boolean operator combinations. Table 1 presents the main phrases and the Boolean operators used and different combinations of these are employed to extract the publications data based on different search engines as listed in the last column of Table 1. The inclusion or exclusion of articles by the search engines is based on filters that operate mainly depending on the evaluation of the abstract. With a further refinement of the search criteria, the overall number of relevant publications as identified by different search engines could be reduced to around 300. These publications are then manually verified for the convergence of the actual topics within the field of search. Based on the evaluation of the abstract, it was understood that though including the key words related to the aircraft industry, many of the publications were not actually related to the topic of interest and were therefore discarded. After a few rounds of refinement, the total number of publications directly related to the application of the additive technologies to the aircraft industry converged close to 183.

The 183 publications short listed are used for further analysis on ascertaining the number publications by year and the topics of interest. The yearly publication results are presented in the bar charts of Figure 2. It may be noted that there is a surge in the number publications related to the use of additive methods in the aerospace industry from 2010. A significant component of these publications is in the form of web articles or white papers. A careful consideration of the contents of these shortlisted publications allowed to classify them into around 10 themes. These 10 themes and their relative significances in terms of the number of publications are presented in the pie chart of Figure 3. The results indicate that most of the publications. It may be noted that commercial applications, materials studies, and tooling or indirect use of additive manufacturing take the major share of the publications in the field. Most of the web articles mainly mention the outcomes of certain commercial applications, while there is a lack of detail often, due to the confidentiality. Topics around the supply chain, energy, standardisation, certification, and quality control received relatively lesser attention so far. Most of the studies on supply chain and energy consumption are generic and non-specific, typically being mere comparisons between conventional and additive manufacturing methods based on hypothetical case studies. There is also a general lack of publishing activity related to quality control and certification of AM parts, which is understandable as most AM standards are still under development. In recent years, companies, government agencies, and consortiums in the aerospace industry are working collaboratively to develop the appropriate frameworks and guidelines to develop the standards.

CRITICAL ATTRIBUTES AND SIGNIFICANT APPLICATIONS OF AM IN THE AIRCRAFT INDUSTRY

The ability to convert raw materials into complex 3D forms without the need for elaborate tooling makes additive manufacturing particularly interesting in the aircraft industry, considering the inventory and supply chain constraints and the need for just-in-time manufacturing. Further, the point-by-point consolidation allows for more complex designs and possible material and performance optimisations, leading to lighter weight and integrated part designs and sustainable performance attributes. Consequently, the leaders of the aircraft industry have been exploring the possible use of AM to produce aircraft parts including various hinges, brackets, interior components, and even the light weight fuselage and airframe designs, targeting better fuel efficiencies. The actual applications as identified from the literature are as varied as engine components such as turbine blades with internal cooling channels, fuel nozzles and compressors and integrated piping systems [32,33]. The capabilities of additive manufacturing, advantages, benefits applied to the aircraft industry and the target results are mapped in

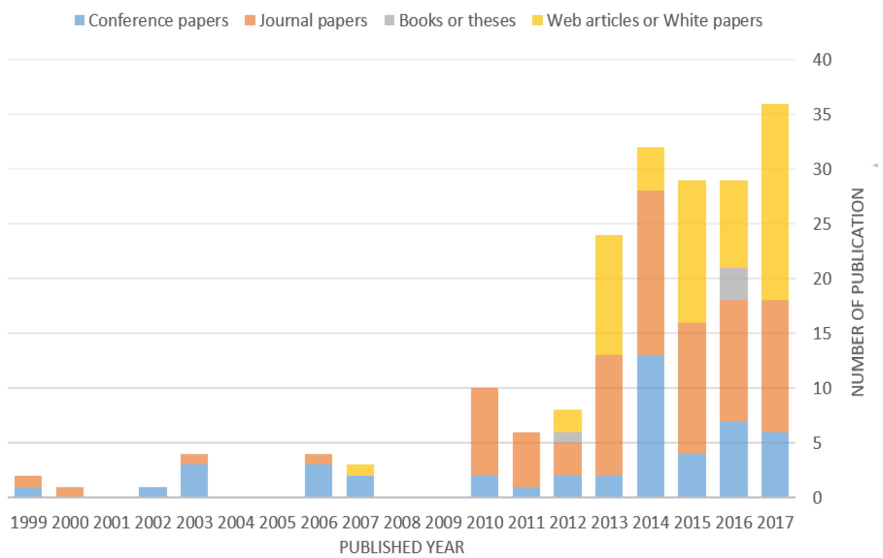

Figure 2: AM for aerospace, publication trends.

the flow diagram presented in Figure 4. The additional capabilities targeted through the application of the AM technologies in the aircraft industry are further discussed next, following a concise compilation of examples drawn from the literature.

Mixed materials

The point-by-point consolidation of materials is a key attribute of additive manufacturing, allowing for possible selective variation of material composition through the part domain [34]. While the full potential of this aspect is yet to be realised, there has been some progress in terms of embedding conductive sensors and other devices into printed parts. The application of the multi-material printing technologies has been limited in the context of the aircraft industry. However, Gibson et al. showed the possibility of printing a conductive wire sensor onto a turbine blade structure [35].

Complex geometry

Multidisciplinary design optimization is widely applied in most of engineering industries, especially in the aerospace engineering. Because of the stringent certification criteria faced by the aerospace industry, engineers must carefully consider all the design variables and constraints such as material and structural integrity, aerodynamics, weight, reliability, manufacturability, maintainability, sustainability, and cost. As a result, aircraft designers have very little design freedom often, and optimisation beyond the normal would invariably result in complex geometries that are not possible to be made by conventional means. Designers tend to compromise on the shape based on the limitations of the conventional manufacturing methods available. Advances in both computer aided design and the additive manufacturing technologies eliminate some of these limitations, opening up new opportunities in different directions as discussed in the following subsections.

Optimal design solutions: Reducing the weight is a key enabler of improved performance and efficiency in the aircraft industry. Novel geometries such as cellular structures, lattice, honeycomb and optimized structures with bionic features can improve the overall performance of the aircraft [36-38]. Additionally, optimized designs also reduce the operational cost during the aircraft assembly and maintenance. Designs that are impossible to be made by the conventional methods can now be revisited with the advent of additive manufacturing [39-45]. Topology optimisation is normally used for lightweight design, it is based on finite element analysis and the material portions stressed insignificantly are iteratively removed to achieve the final topologically optimised forms for parts. In recent years, several aerospace applications have been researched for topology optimised lattice structures [46-49]. With

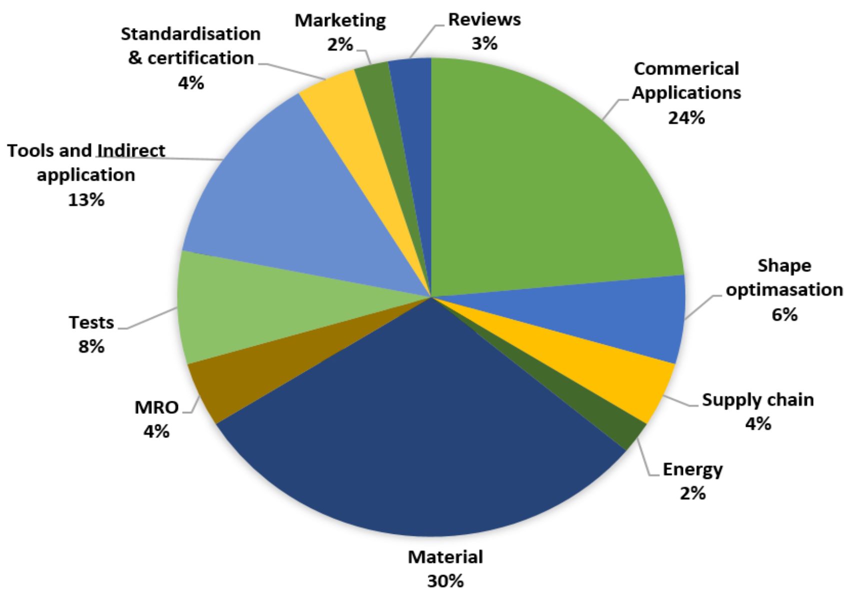

Figure 3: AM for aerospace: A classification of the topics covered in the most significant publications.

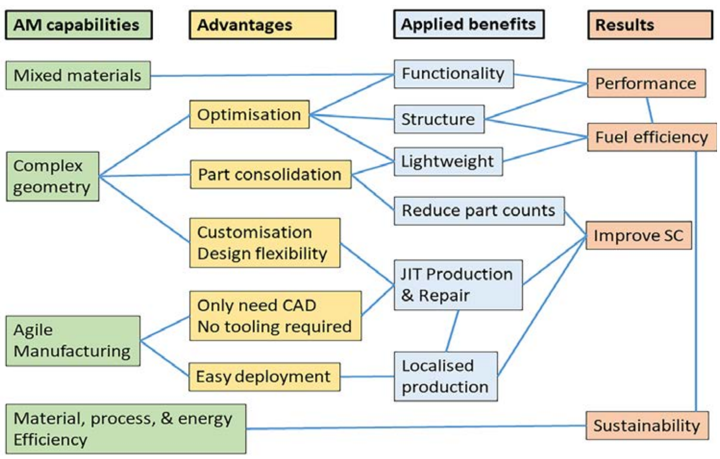

Figure 4: Critical attributes of integrating additive manufacturing within the aircraft industry.

Title		Title and Abstract			Web Results
"Additive manufacturing" OR "3D printing" OR "Rapid prototyping"	AND	Aircraft OR Aerospace OR Aeronautic* OR Aviation	NOT	Patents, Medicine, Medical, Biology, Biochemistry, Genetics and Molecular Biology, Health Professions	• Scopus: 645 • Web of science: 545 • ScienceDirect: 85 • IEEEXplore: 282 • SpringerLink: 158 • Google scholar: 465 • Microsoft Academic Search: 39

Table 1: Selected keywords for Boolean operators.

the solid isotropic material approach, the structure can be designed voxel by voxel within a defined unit cell, mapping the structural density, and possibly combining multiple materials to maximise the functional performance [50]. AM seems to be the only solution to produce these highly complex and optimised parts.

Airbus innovation group designed an optimized nacelle hinge bracket for the Airbus A320 aircraft. With a 64% weight reduction, the optimized design allowed to save about a total of 10 kg mass per plane. An eco-assessment indicated reduction in carbon emissions by about 40%, resulting from this weight reduction [48], while a redesign of the exit door hinges also was shown to result in approximately 33% of weight reduction and a moderate decrease in stiffness [51]. Other reports also indicated considerable weight reductions achieved through the design modifications applied to different brackets used on the Airbus A350XWB and A380 models [52-54]. Seabra et al. employed topology optimisation and selective laser melting to manufacture a light weight aircraft bracket [49], achieving around 28% weight reduction with an improved factor of safety.

Functional optimisation: The ability to produce complex shapes through AM also allows for optimisation of parts for specific functionalities such as stress distribution, heat dissipation, or airflow patterns. A typical example is to incorporate conformal cooling channels in critical components. EOS demonstrated that critical probes for measuring speed and temperature in the turpentine can be made utilising the AM technologies [55]. Apart from overcoming the instability and lack of fracture strength, the additively manufactured part was shown to be 150 percent more rigid than the multi-part assembly of the original design.

MTU Aero Engines, a German aircraft engine manufacturer, designed and manufactured a nickel borescope boss for the Airbus A320neo based on the EOS technology and claimed the production and part qualities to improve significantly [53]. Utilising the laser sintering method, an airflow and fuel swirling component had been optimized integrating the cooling feature with the fuel channel [54]. The overall fuel efficiency was improved, apart from a 50% and 40% reduction in cost and weight respectively. Turbomycin, a French helicopter engine manufacturer used Selective Laser Melting to manufacture the fuel injector nozzle for the Arrano engine and the combustor swirler for the Ardiden-3 engine [55]. It was stated that part integration and the advanced injection and cooling functions were made possible by the AM technology. A spoiler actuator valve block was additively manufactured by Liebherr-Aerospace for an A380 and this was the first additive manufactured flight control hydraulic component flown on an Airbus aircraft [56]. Use of selective laser sintering technology to achieve conformal cooling in an Inconel 718 turbine blade for a jet engine was demonstrated by Roca et al. [57].

Part consolidation: The design freedom can be utilised to integrate parts and manufacture multiple components as single units. This will significantly reduce the assembly effort, the supply chain pressure while also enhancing the component's performance. This is especially important for the aerospace industry, where customization of fittings often occurs [7,58]. Major leading companies like Boeing and GE have been utilizing this special capability of AM technology to consolidate and redesign critical components such as engine parts and ducting systems. A structural bracket for Eurostar E3000 telecommunications satellites made by AM technology passed the flight qualification test and was ready to be used [59]. It achieved a 35% weight reduction, integration of 4 parts and 44 rivets into one consolidated part and was 40% stiffer than the original design while also saving considerable machining time and costs.

The housing of a T25 sensor and the Fuel nozzle on the GE LEAP jet engine are the most widely projected applications of additive manufacturing in the aircraft industry. The 3D printed nozzle had 20 parts combined into one part and weighed 25% less than the traditionally made nozzle. The housing of T25 sensor was the first AM component certified by the U.S. Federal Aviation Administration (FAA) and flown in commercial airplanes. The sensor was located at the inlet of the high-pressure compressor and measured the pressure and temperature of the control system of the engine. According to GE, the exercise saved months of design and production cycle times, without compromising on the functionality [60].

The air-cooling ducts of the F-18E jet were optimised and integrated into fewer units, utilising the design flexibility possible by additive manufacturing, which also led to lesser assembly times and simpler installation processes [5,61]. Boeing claimed reduction by 50% and 67% of the total and production time respectively. Reduction of the part count and installation times lead to reduced inventory pressures and operational costs. This will also mean lowering the logistics costs, more options on selection of suppliers and elimination of the non-recurring tooling costs, critical attributes to ultimately improve the overall efficiency of the supply chain. Boeing and Advanced Laser Materials together developed a flame-retardant polyamide material which is now used to produce air ducts and fittings in commercial airplanes [8]. They claimed that the no tooling benefits from AM reduced the cost of these components production and compares with traditional methods such as injection or rotational moulding, AM give more flexibility onto the life-cycle of the products.

Agile manufacturing

Conventional methods are more efficient with large scale or batch production. The production volumes for aircraft parts are usually limited, and not more than several thousand units per part [32]. Consequently, the volume of production may also justify the choice of additive manufacturing for the aircraft industry. AM technologies do not require auxiliary tools, only CAD files are required for the production. This is very suitable for the customisation of aircraft cabin designs. In late 2015, China Eastern Airline established their own AM laboratory, and claimed that the cabin component costs were significantly reduced by adopting AM [62]. Flame retardant materials were used to produce interior components such the toilet seats, leading to a 90% reduction in total costs, and significant gains in the manufacturing lead times compared to the OEM parts. Air New Zealand also was involved in the evaluation of the additively produced cocktail trays for the business premier cabin based on the prototypes produced at Auckland University of Technology [63]. The SAVING project elucidated that a 55% weight reduction is possible by redesigning the seat buckles for producing by additive manufacturing and the prediction was that a total 73 Kg of weight can be saved if all the seat buckles of the Airbus 380 were to adopt the optimum designs, amounting to 3.3 million litres of fuel savings over the life span of the aircraft [64].

Material, process and energy efficiency

The absence of the material subtraction component together with the elimination of the need for additional tooling will make additive manufacturing more material efficient than the conventional counterparts. Almost 90% reduction in the material wastage and corresponding savings in the "cradle-to-Gate" environmental footprints were reported [64-67]. However, energy savings in the additive manufacturing process is only applicable with low volume production, as the metal powder production and the actual processing methods are quite energy consuming. By far, the most energy saving feature of the application of AM to the aircraft industry is the weight reduction that will lead to considerable savings in fuel costs over the life span of a plane [27,68,69].

Each kilogram of weight reduced on a commercial aircraft can roughly save around US$ 3000 worth of fuel and a corresponding reduction in the carbon emissions per year [8,70]. Huang et al. identified potential parts that can be redesigned and additively manufactured, the replacement of which could lead to a reduction in the fuel consumption of almost 6.4% [27]. According to them, each 100 kg of weight reduction on an airplane is equivalent to approximately 13.4-20.0 TJ of fuel savings over a 30-year period of the service life. The benefits of employing Additive Manufacturing, as assessed by "NASA' indicate around 4.9% reduction in the fuel burnt and a 8.3% reduction of NOx emissions [71]. Materials selection and geometrical optimisation are at the root of such design improvements. Conventional manufacturing methods fail to achieve the required complex geometries, bringing the focus back to the need for alternative methods such as additive manufacturing.

Buy to fly ratio is a term used in the aerospace community, referring to the weight ratio between a finished component and the original raw material. The parts manufactured by traditional methods normally have buy to fly ratios at around 15-20 [72]. According to the ICF international, in 2014 alone, the annual global total material consumption of the aircraft industry in both production and maintenance was about 680,000 tons, and it is continuously rising [73]. Further, the aerospace materials are so expensive the aircraft industries are under constant pressure to reduce wastage and develop near net shaping solutions. AM seems to be the ideal candidate, considering that the buy to fly ratio of an AM part can be as low as 1:1. For example, with the Lockheed Martin engine bleed air leak detector bracket, the buy-to-fly ratio is reduced to 1:1 based on electron beam melting method, as against the 33:1 ratio possible by traditional methods, leading to an overall 50% savings in the cost of the titanium alloy [74].

Overall, the critical attributes of additive manufacturing, design freedom, part-integration, better utilization of materials, customisation, shorter lead times for small batch production and most importantly the enhanced supply chain structures speak of the core problems and concerns of the aircraft industries. Major aircraft OEMs are now realising the potential of the new technologies and adopting them at various stages of the production of aircrafts. However, AM technologies are not fully mature, lack repeatability and suffer from anisotropy. Additionally, surface finish is one of the biggest obstacles which will also adversely affect the fatigue life. Build size limitations also restrict the uptake of the technology. All these factors limit the additively manufactured parts to be certified by the aviation authorities. There are indirect ways though, in which AM can help the aircraft industry, as discussed next.

RAPID TOOLING AND REPAIRING

Significant opportunities arise in terms of using additive methods to produce tooling such as jigs, fixtures [75], mandrels, surrogates, dies and moulds to be used in the aircraft industry, the so-called rapid tooling applications. The qualification and certification processes associated with tooling are less stringent and only need functional testing. Also, most tools are only required in small quantities, which is especially true with the aircraft industry and additive manufacturing is economic in low volume production. Both Airbus and Boeing have employed rapid tooling in their production processes [8,76].

Some tools are only made for a single-use and so, expandable plastic tools would be ideal for such applications, and lighter tools possess obvious advantages in terms of ergonomics [77]. Other tools such as master moulds or patterns for investment casting are another area of development of the rapid tooling technique, where patterns, dies, and moulds with complex geometries can be produced by AM [78]. Especially with investment casting, in which the pattern is sacrificial and single-use type, rapid casting technique is very suitable for small batch production. As the word 'rapid' indicates the short design and production time of the tools and consequent savings in the total manufacturing lead times, the enhanced casting methods can bring huge benefits to the aircraft maintenance and manufacturing operations, in which fast turnaround times are paramount [79].

Rokicki et al. used computer aided design and rapid tooling techniques to design and manufacture an aircraft turbine blade with internal cooling channels [80]. Master pattern kits were made using stereolithography which were in turn used to make silicon moulds, and then using them to produce wax patterns for investment casting. Wu et al. investigated the use of stereolithography resin patterns and ceramic gel-casting techniques to produce hollow turbine blades by investment casting [81]. The results showed that turbine blades can be made based on dimensionally accurate and integral ceramic moulds produced by the indirect application of stereolithography. Fette et al. produced metal moulds with conformal heating channels based on selective laser melting for the rapid manufacturing of fibre reinforced plastic (FRP) aircraft components [82]. The increased design freedom resulting from the use of AM could be integrated with the provision of alternative heating channels, apart from reduced manufacturing lead times. Das et al. used Large Area Maskless Photopolymerization (LAMP) technology to produce ceramic moulds with internal-cores [83], for casting equiaxed and single crystal aerofoils, demonstrating significant savings in time and cost. The rapid tooling approaches clearly elucidated the indirect use of additive manufacturing in assisting the production of specific aircraft parts with additional improvements and in much shorter time periods compared to the traditional methods and there is an increased research interest in this direction [84-86].

Aircraft MROs require to produce or repair typical parts at times, but in very small quantities and their production demand is very unpredictable and supply chains widely distributed. Sometimes, MROs are also involved in the repair or replacement of legacy aircraft components, where the associated tools may no longer be available to purchase from the OEMs [7]. According to Northup Grumman, aircraft industries tend to have a turnover three times greater than the investment. This means cost savings by applying AM technologies need to be three times greater than the initial investment on the AM equipment [87]. In a case study [88], using AM instead of CNC machining, the costs and lead time of repairing a helicopter part were reduced from US $2000 and 45 days to US$ 412 and 2 days, which is well over the 3:1 investment benchmark.

In order to reduce costs and lead times, aircraft maintenance companies use laser metal deposition techniques to repair engine housing, compressor parts, and turbine blades [32]. Franuhofer ILT used LMD and SLM to repair of the Inconel 718 turbine case and compressor seal and were eventually certified by Rolls-Royce Deutschland [89,90]. Rolls-Royce reported that 30% of the production time can be saved by using AM [91]. Hedges and Calder showed that the T700 helicopter engine parts can be repaired by the net-shape processing, laser engineered net shaping (LENS) technology [92]. Several studies on the material and mechanical properties of the repaired parts also proved the feasibility of the use of AM in the aircraft MRO tasks [90,93,94]. Other developments include the geometrically adaptive toolpath laser processing method for accurate repairing by Qi et al. [95]. the hybrid manufacturing method by Ren et al. to repair dies and cores [96], the direct laser deposition used by Wilson et al. to repair a turbine blade [97], reporting considerable energy and carbon footprint savings achieved over the replacement by new parts.

QUALITY ASSURANCE, CERTIFICATION AND STANDARDISATION

Critical components such as engine parts and some structural components are normally made by metals, which require strict assessment schemes in order to get certified. The failure of such components can lead to catastrophic events and consequent losses. Using AM to redesign these components can reduce the weight, improve their functionality and performance. However, the certification process involves demonstrating the quality of the part and consistency and repeatability of the production process to the certifying authority. Most of the critical components are developed and manufactured by the leading aircraft companies, GE, Boeing, and Airbus, each of which have enormous research and manufacturing resources as well as close relationships with the certification authorities. As a result, they are currently playing leading roles in the successful application of AM to the aircraft industry.

Other components such as interior furniture, accessories and some of the non- structural components are less critical, can be classified as either 'Minor' or 'No Safety Effect' and are normally made by lightweight alloys, polymers or composites. The use of AM could lead to potential benefits in these cases, by redesigning the non-critical parts for light weight, part consolidation and customisation goals, with an emphasis on reducing the supply-chain pressures. These applications are also more common compared to the critical metal components, considering the relatively lighter qualification and certification processes. Figure 5a is a graphical depiction of a simple classification structure relating different types of applications to the criticality levels in terms of safety, quality levels, and certification requirements. Specific examples of components at different criticality levels are shown against the certification levels in Figure 5b. For parts with higher levels of criticality, stringent damage tolerance assessments need to be performed, and as per the FAA regulation, the use of AM in the production and maintenance of such parts is classified as a major design change [28].

Evidently, the certification and qualification of AM parts is the most difficult stage for the aircraft industry to handle, as this involves acquiring the quality data related to parts within the regulatory frameworks prescribed by the certification authority. The material and process limitations, poor surface and dimensional qualities, and the general lack of repeatability render the process to be complex [98]. Further, the lack of industry-wide standards for AM materials, processes, quality assessment, and design together with the limited information on the material processing data lead to longer certification periods [6,28,44,87,99]. The main hurdles leading to certification constraints and other barriers are depicted in the flow chart of Figure 6, elucidating the root causes of the delay in the widespread use of the AM technologies by the aircraft industry.

Authorities like FAA (Federal Aviation Administration) and EASA (European Aviation Safety Agency) are responsible for standards of safety, certification, and regulation in the aircraft industry. They issued several memoranda and notices related the certification of AM parts and the use of the technology in the maintenance and alteration of aircraft components [100,101]. They have been working with the industry, government, academia and standards development organizations such as ASTM, SAE and ISO, to develop the standards, policies and guidelines for applying AM in the manufacturing and maintenance of the aircraft components. This effort is to accelerate the process of adopting AM and ensure the continued operational safety [102,103]. The collaboration among the industry, academia, government, and certification agencies is crucial for developing the appropriate regulatory frameworks for safely adopting AM into the aircraft industry. As the development of the qualification and certification is expensive and lengthy, some AM equipment manufacturers have developed

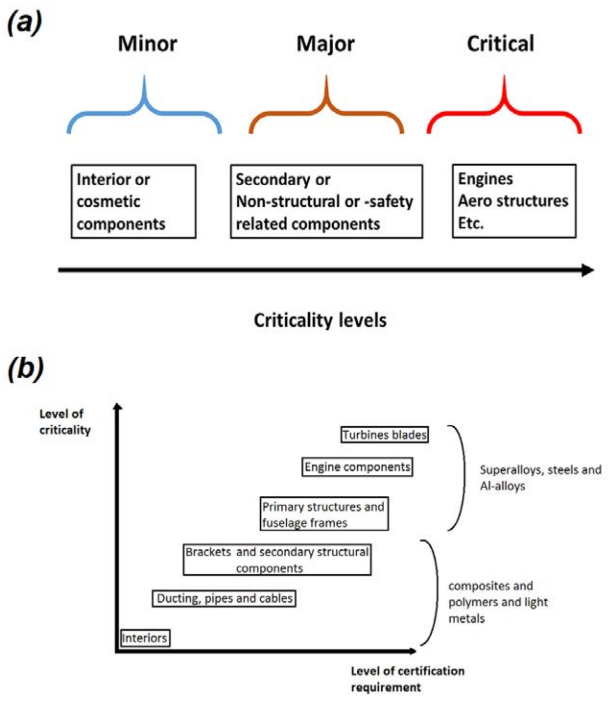

Figure 5: Criticality level of typical aircraft components.

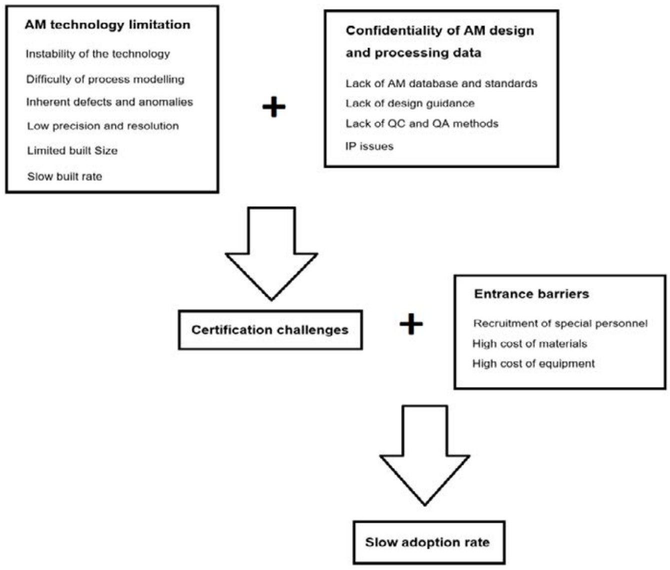

Figure 6: The challenges in the certification of AM parts.

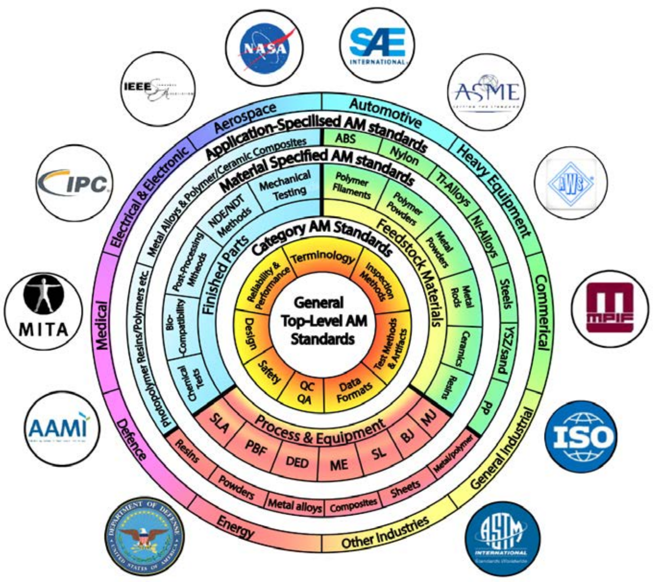

Figure 7: A classification of the standards.

solution guidelines for certifying certain aircraft components produced using their systems. For example, Stratasys developed a solution to the certification of the aircraft interior parts produced based on their systems, allowing smaller companies to build in-house documentation and adopt the AM technology [104]. In order to achieve a wider use of the technology, more systematic work is needed, and a certification and qualification frame work needs to evolve as the enabling platform. Prior to this, the following key aspects need specific research attention:

- Closer evaluation of the physics of AM processes.
- Failure mechanisms and the characteristic material anomalies.
- Comprehensive material-process-structure-property relationships.
- Industry specifications database and AM materials and processes standards.
- AM component design guidelines and rulemaking.
- Post processing methods and part quality enhancement.
- Monitoring and testing strategies for AM.

There has been some progress in terms of the development of the standards related to AM in general and AM and the aerospace industry combination. A comprehensive search for the information available led to the understanding that there are over 100 standards, mostly in development or in a few cases already developed, related to additive manufacturing directly or indirectly. The standards address various issues related to AM, such as the design of the CAD files, slicing, materials, process conditions, post processing and the quality assessment procedures. An attempt is made to classify the standards generally related to the additive manufacturing process and critical aspects they address in the form of the wheel diagram presented in Figure 7.

The wheel is organised to identify the AM standards beginning with the more general top-level ones at the central hub, which refer to the fundamental aspects of the additive technologies. The material and process specific standards are presented in the next annular ring. These will address standards issues related to the basic forms of materials, processing techniques and post-processing finishing and inspection methods. Standards related to the raw materials and the methods of producing them in the forms required for additive processing are circled in the next annular ring. The application specific standards are in the outer ring. As depicted around these rings, there are over a dozen organisations involved in the process of development of these standards. Generally, ASTM and ISO have been working together and responsible for the generation of most standards generally related to additive manufacturing. Most of the aerospace related AM standards are under development by SAE, while government organisations such as NASA appear to provide guidelines, though it is difficult to ascertain the exact role. However, the overall development of the standards related to the AM and aerospace combination is slow, which is probably due to the continuous changes taking place in the technologies that are still growing.

DISCUSSION

The aerospace materials research is picking up substantially, as there is increased research interest in the aerospace material grades such as Ti, and Ni based super alloys [105-107], flame retardant polymers and composites [108]. New processes, process modelling and enhancements, and test methods specific to the aerospace industry are also in progress recently. Boeing came up with the flame-retardant polymers for SLS and managed to get past the flammability tests [109]. Research is also ongoing embedding electronics in additively manufactured parts offering significant new options for the aerospace industry [7]. Research collaborations between aerospace institutes and universities such as Lockheed Martin and Oak Ridge Laboratory, BAE System and Cranfield University, NASA, Honeywell and Ohio Aerospace Institute, Pratt & Whitney and University of Connecticut and many others are currently active and evaluating various possibilities for the application of additive manufacturing for the aerospace industry. Leading players such as Boeing, Airbus and GE are significantly investing towards the development of better AM facilities and capabilities, exploring the better use of the technology [7,8,21,32,33,58,71,110-123].

Accumulation of the experiences from the application of AM to different components and enhancement of the overall stability of the process are key triggers for the new generation of aircrafts to be equipped with more additively manufactured parts [6]. The evolution of the AM technology appears to follow the Moore's law as numerous reports indicate that the materials and equipment prices will decline drastically in the next 10 to 30 years as the use and the demand increase. As the technology matures, there will be clearly identified standards procedures, and the aircraft industry will be at the forefront in reaping the benefits of these developments [5,115,124,125]. The AM market has grown by roughly 5.7 times over the past seven years [126]. According to an earlier Wohler's report [127], the increase in the use of the additive technologies for the aerospace industry will be in the order of around US $ 1 billion.

Resolving issues around the certification and qualification of AM parts and processes is paramount and needs to be accelerated. This is not the problem of just the aerospace industry, as automotive and medical sectors are also going through similar phases and hurdles. A recent development is that several standards development organisations began working together to develop the necessary standards. An association by the name Additive Manufacturing Standardization Collaborative (AMSC) was created in March 2016 through the America Makes and American National Standards Institute (ANSI) initiatives, with the goal to accelerate the development of AM and AM related standards [128], They have been working closely with standards development organisations, ASTM, ISO, ASME, SAE, AWS, IEEE, MITA, AAMI, IPC and MPIF, identifying the existing standards and the gaps and finally converging on the new standards frameworks targeting different industrial sectors. Several meetings and workshops were held bringing different standards development organisations together, to further speed up the process [129]. These are all positive signs and it is envisioned that AM technologies will be heavily adopted and implemented within the next 30 years especially for the benefit of the aircraft industry, apart from the other sectors.

CONCLUSION

The current state-of-the-art of the use of the additive technologies in the aircraft industry is ascertained reviewing the available literature. The multi-tier supply chain systems surrounding the operations of the OEM and MRO organisations of the aircraft industry are identified, critiquing on the complexities. The beneficial roles additive manufacturing technologies can play in the inventory and supply chain systems of the aircraft industry are elucidated. A systematic classification is developed mapping the critical attributes of additive manufacturing and the typical requirements of different types of aircraft components. The application areas are classified based on the specific benefits achieved, substantiating with examples based on the applications reported. The benefits and examples of the indirect use of additive manufacturing within the aircraft sector are highlighted. The quality assurance and certification obstacles hampering the wider uptake of the AM technologies are identified. The progress with the development of AM standards is reviewed and the numerous standards at different stages of development specific to additive processing are classified based on a wheel diagram. It is evident from this review that additive manufacturing has a significant role to play in the aircraft industry, the full utilisation of which will only be realised when the technology standards are fully developed.

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