DESIGN FOR ADDITIVE MANUFACTURING WITH CASE STUDIES ON AIRCRAFTS AND PROPULSION SYSTEMS

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Abstract: *In order to fulfill the demands of civil and military aviation, aircraft industry needs to deal with various challenges. The major reasons of these challenges are the reduction of cost for aircraft and airline operations, minimizing the downtime for maintenance, decreasing the fuel consumption and thus the emissions, and fast delivery of newly developed products to market. As a result of these decades-long efforts of the aviation industry, there have been significant developments to overcome the abovementioned challenges. However, for this sector to approach the development limits as time passes, it is only possible to advance in the competition with the methods that present a significant innovation. Additive manufacturing, aka 3d printing, is such a method to bring many advantages for aircraft and propulsion industry being applicable for diverse material groups, allowing to production of complex geometries without tools and dies, and thus making possible lightweight and functionally improved designs. Additive manufacturing is also beneficial for low volume production which is common for aviation industry and provides decreased buy-to-fly ratios, eliminating material waste for precious alloys and cut down long machining times. However, it is important to apply this method properly and there is lack of knowledge for this emerging method. This paper presents essential principles for additive manufacturing and design issues to utilize the method properly for aviation industry. Furthermore, it benchmarks and analyze designs made for aircraft and propulsion components. Finally, the advantages and limitations utilized during design for additive manufacturing were highlighted, and research needs were emphasized*

Keywords: *Additive manufacturing, design for additive manufacturing, metals and alloys, aircraft components, propulsion system components.*

1. INTRODUCTION

The utilization of military and commercial aviation is continuously expanding, and together with this, the demand for aircrafts is also increasing. Compared to previous decades, there are many types of aircraft such as next-generation fighters, unmanned aerial vehicles (UAV), high-capacity passenger planes and giant cargo carriers. In addition to the ones that are currently in service, it is forecasted that new ones will be needed in the following years. An example can be provided from a forecast report based on commercial aircrafts. According to that, the need for new aircrafts will be double in the next 20 years and a total of more than 37500 commercial aircrafts will be delivered as the total of growing demands and also the replacement of old aircrafts [1]. Although the aircraft industry is promising when considering the number of deliveries and product sales prices, it has to meet the demands of airlines, airforces and other users to be competitive.

These demands include reduction of cost for aircraft and airline operations, minimizing the downtime for maintenance, decreasing the fuel consumption and thus the emissions, and fast delivery of newly developed products to market.

As a result of these decades-long efforts of the aviation industry, there have been significant developments to satisfy the abovementioned demands. These developments took place under different disciplines such as design, material, manufacturing and test technologies. It is well known that developments in aviation and space are the leaders of today's technology and rapidly extend to other industries. For example, some tecnologies are developed for aerospace industry and today they are utilized in different sectors such as automotive and marine [2].

Additive manufacturing (AM) is such a technology which was developed in the beginning of 1980s under the name 3d printing, and did not draw attention until it's utilization for aircraft and aircraft propulsion systems in the beginning of 2010s. At the present time, this emerging technology is the main subject of many industrial and academic research projects and is of high interest to various industries in addition to aviation. The 2017 Wohlers Report showed that AM represented a more than $6 billion global industry in 2016, including products and services to have a aerospace utilization ratio of 18% [3].

Although the promising AM technology provides many benefits in terms of design freedom, manufacturing flexibility and material diversity, it is mostly utilized in aircraft industry as a replacement of conventional manufacturing. There are a lot of subjects that need to be researched and known in order to take full advantage of this technology and to advance the products in which it is used.

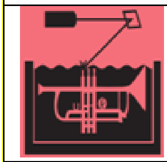
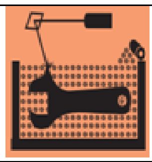
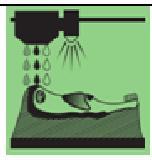
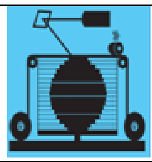
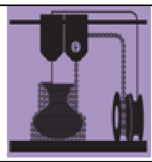
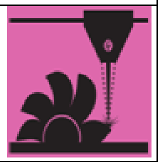
In order to cover the knowledge gaps for the related technology, this paper presents essential principles for additive manufacturing and design issues to utilize the method properly for aviation industry. Furthermore, it benchmarks and analyze designs and case studies made for aircraft and propulsion components. The rest of the paper is organized as follows: In the next section principles for additive manufacturing are presented together with different technologies. Following section explains the advantages and drawbacks of design for additive manufacturing covering the limitations and considerations of issues related to materials and manufacturing. Case studies from aircraft and propulsion system components are benchmarked in the subsequent section. The last section summarizes the paper and emphasizes prospective research.

2. ADDITIVE MANUFACTURING

Additive manufacturing (AM), also known with different names such as 3d printing, solid free-form fabrication (SFF), rapid prototyping (RP), is defined as a manufacturing process of joining materials to make objects from 3D model data usually layer upon layer, as opposed to subtractive manufacturing methodologies, such as traditional machining [4]. Although the processing methods may vary according to applied technology, a generic AM process consists of 7 basics steps [5]. It starts with the creation of 3d product model in a computer aided design (CAD) software and it is exported in a AM compatible file format such as stereolithography (STL). Later on the exported file is transferred to the machine after editing in a customized job preparation software. With the loading of job file and consumables, the additive manufacturing machine is set-up. By this way the build is started and the part is manufactured layer by layer. The last steps of the process include part removal from machine and post-processing such as cleaning, polishing, machining, etc.

Today AM is capable of manufacturing diverse material groups such as metal, ceramics and polymers with the development of sub technologies. American Society for Testing and Materials (ASTM) categorizes these sub technologies under 7 families of vat photopolymerization, powder bed fusion, binder jetting, material jetting, sheet lamination, material extrusion and directed energy deposition. All these families have also commercial names and each can be applied to specific materials. Table 1 summarizes these families with the common commercial names and applicable materials [6].

Table 1 – 7 families of additive manufacturing [6]

Vat photo polymerization	Powder bed fusion (PBF)	Binder jetting	Material jetting	Sheet lamination	Material extrusion	Directed energy deposition (DED)
						
A vat of liquid photopolymer is cured through selective exposure to light and converts exposed areas to solid part.	Powdered material is selectively consolidated and/or melted using a heat source such as laser or electron beam	Liquid bonding agents are selectively applied onto thin layers of powder material to build up parts.	Droplets of material are deposited layer by layer to build up the parts.	Sheets of material are stacked and laminated to form an object using adhesive, chemicals, ultrasound, etc.	Material is extruded through a nozzle or orifice in tracks or beads, and combined into a model.	Powder or wire is fed into a melt pool on the part build which is generated using and energy source such as laser.
Materials: Curable photopolymer resins	Materials: Metals, ceramics, plastics	Materials: Metals, ceramics, plastics, glass	Materials: Photopolymers, waxes	Materials: Metal foils, plastic sheets	Materials: Thermoplastic filaments	Materials: Metal powder and wire
Commercial Names: SLA, DLP, 3SP	Commercial Names: SLS, DMLS, SLM, EBM	Commercial Names: 3DP, ExOnei Voxeljet	Commercial Names: Polyjet, Projet, MJM.	Commercial Names: LOM, UAM	Commercial Names: FDM, FFF	Commercial Names: LMD, DMD, LENS

Although AM offers 7 families of technologies and each technology offers different method and materials, it is important to consider advantages and drawbacks of AM [7] and conduct necessary activities, such as part screening, before transforming the AM technologies within the relevant companies and/or other establishments, see FIG. 1 [8].

FIG. 1. Strategic considerations and benefits for AM adoption across value chain elements [8]

3. DESIGN FOR ADDITIVE MANUFACTURING

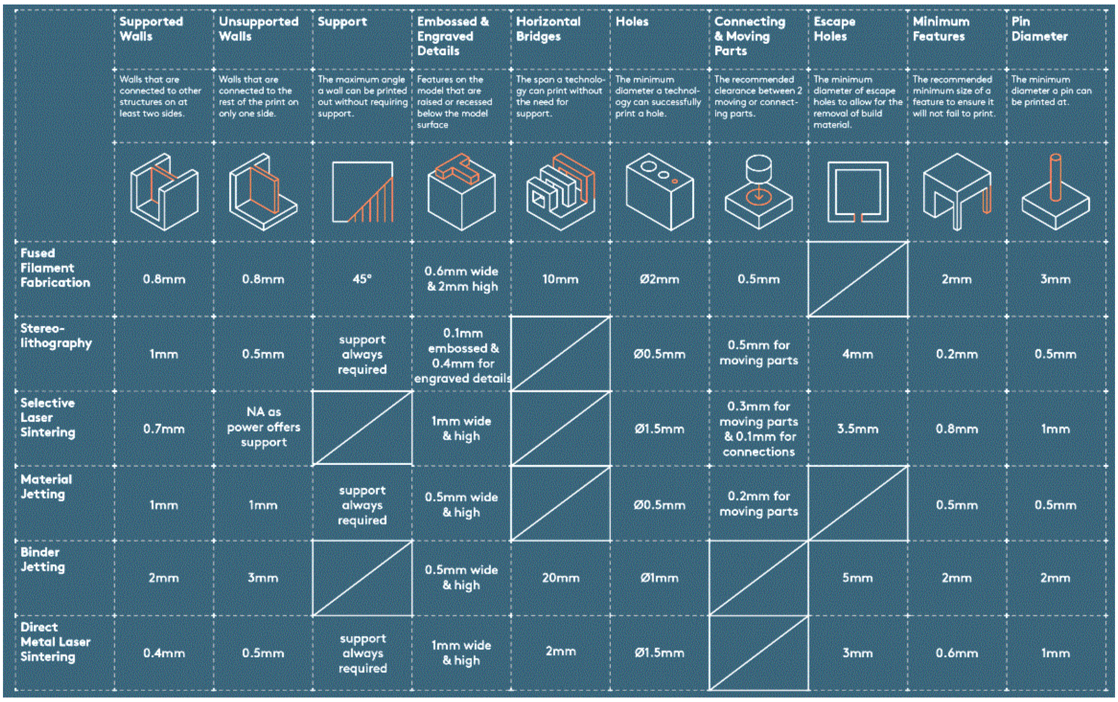
As in other industries, design for additive manufacturing (DfAM) activities should be conducted carefully in aircraft and propulsion system components production and all the above mentioned technologies, advantages and drawbacks should be consider to make the most benefit of this technology.

The very first and important step for the DfAM is the selection of the parts. Since assessment of appropriate part candidates could be time consuming, the part selection step is conducted in three phases as information, assessment and decision [9]. In the initial information phase, advantages and current product spectrum of the technology is shown and detailed technical information gathered in and provided to designers for discussing the potential parts. In the second assessment phase, the number of potential parts is reduced using systematical benchmark methodologies. In this regard considered aspects may include material availability of AM for already used parts in aerospace, size limitations of the reachable machines, part specifications and the geometric conditions as well as economical aspects of material consumption and processing time. At this phase, added values that can be obtained are taken into account, opportunities such as part simplification, weight reduction and function improvement are also considered. For the last phase decisions are made for the AM parts and redesign can be conducted when necessary [9].

With the ongoing technological developments, the types of AM compatible materials are increasing day by day. Together with the 3d printing culture in the background, polymers and their composites are already in use for many years and materials with low density, good mechanical properties and dimensional accuracy such as CarbonMide, PA 3200 GF, ULTEM [10]. Technological developments added a wide range of metal alloys such as titanium, nickel, aluminum and stainless steel to the polymers [9]. Size limitation issues are also being solved by machine manufacturers and the processing time for the so called large machines is also reduced by utilization of high power and/or multiple energy inputs to the process [11]. Today even metal AM systems can manufacture parts as large as 1 m in closed chamber systems and that can be extended using robotic arms [12].

The assessment of geometric conditions is not straightforward like material types and part sizes. It is necessary to conduct technical studies on geometric conditions and it is subject to both scientific and industrial research. Design for Additive Manufacturing (DfAM) can be used to break down a product and to make sure that AM is used to its fullest. Many times this process is used as Adaptation for Additive Manufacturing (AfAM), where AM is employed to redesign an existing product or geometry [13]. A similar classification can also be made as manufacturing driven strategy and function driven strategy [14]. Among five design complexity group, three group of simple tools/components, optimized parts and the parts with embedded features can be designed with AfAM or manufacturing driven strategy, whereas bionic or lattice parts need utilizing of DfAM or function driven strategy [15]. In all of these approaches, the assessment of geometric conditions require several investigations such as dimensional limits of geometrical features [16], support structure studies [17] for overhanging face and surface quality issues [18].

Although it is not easy to generalize the guidelines of design for additive manufacturing through hundreds of combinations considering manufacturing families, machine sizes, available materials, dimensional limits of geometrical features and other affecting factors, a summary is provided for an overview of considerations, FIG. 2 [19].



	Supported Walls	Unsupported Walls	Support	Embossed & Engraved Details	Horizontal Bridges	Holes	Connecting & Moving Parts	Escape Holes	Minimum Features	Pin Diameter
	Walls that are connected to other structures on at least two sides.	Walls that are connected to the rest of the print on only one side.	The maximum angle a wall can be printed out without requiring support.	Features on the model that are raised or recessed below the model surface	The span a technology can print without the need for support.	The minimum diameter a technology can successfully print a hole.	The recommended clearance between 2 moving or connecting parts.	The minimum diameter of escape holes to allow for the removal of build material.	The recommended minimum size of a feature to ensure it will not fail to print.	The minimum diameter a pin can be printed at.
Fused Filament Fabrication	0.8mm	0.8mm	45°	0.6mm wide & 2mm high	10mm	Ø2mm	0.5mm		2mm	3mm
Stereo-lithography	1mm	0.5mm	support always required	0.1mm embossed & 0.4mm for engraved details		Ø0.5mm	0.5mm for moving parts	4mm	0.2mm	0.5mm
Selective Laser Sintering	0.7mm	NA as power offers support		1mm wide & high		Ø1.5mm	0.3mm for moving parts & 0.1mm for connections	3.5mm	0.8mm	1mm
Material Jetting	1mm	1mm	support always required	0.5mm wide & high		Ø0.5mm	0.2mm for moving parts		0.5mm	0.5mm
Binder Jetting	2mm	3mm		0.5mm wide & high	20mm	Ø1mm		5mm	2mm	2mm
Direct Metal Laser Sintering	0.4mm	0.5mm	support always required	1mm wide & high	2mm	Ø1.5mm		3mm	0.6mm	1mm

FIG. 2. Key design considerations for 3D Printing [19]

4. CASE STUDIES IN AIRCRAFT AND PROPULSION SYSTEM COMPONENTS

The aviation sector takes into account all of the listed issues such as design for additive manufacturing and increases the use of additive manufacturing in its products day by day to benefit from the emerging technology. As a result aviation industry currently utilizes different families of AM such as powder bed fusion, directed energy deposition, binder jetting and material extrusion. The extend of this utilization reaches to airframe, cabin and engine components including metal, polymer and ceramic materials [20]. It is also worth to emphasize that the technology is not only applied for new component production but also actively used for repair purposes [21]. Today all major original equipment manufacturers (OEM) such as Airbus, Boeing, General Electric, Pratt & Whitney, Rolls-Royce and Safran are currently investigating and developing AM capabilities, with >70% of OEMs having experience with AM [22].

Today example parts of additive manufacturing in airframes, interiors, jet engines, rotorcrafts and other vehicles such as satellites include forward fuselage parts [23], stringer clips [24], cabin brackets, bleed pipes [25], fuel nozzles [26], low pressure turbine blades [27], UAV wings [28], satellite brackets [29] and toroid housings [28]. Following section presents design considerations of diverse applications of AM of different materials and processing technologies, and for various types of target products.

4. CASE STUDIES ON AIRCRAFT AND PROPULSION COMPONENTS

This section provides AM case studies on aircraft, aerospace and propulsion system components in a tabulated manner for a better understanding and benchmarking of different situations. The tables on the case studies includes various information such as description of the component and its function, component geometry before and after design for AM (where available), design features, special requirements, replaced manufacturing technology, achievements through the utilization of AM and areas of further improvements.

Table 2 – Aileron hinge fitting [30]

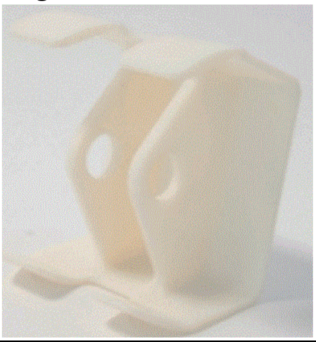
Description of the component: This case study belongs to a aileron hinge baseline fitting of a regional aircraft demonstrator. Its main function is connecting the aileron to the wing while carrying it and also allowing its movements.	
Original design 	**Design for AM** 
Design features: Original design features include mechanical assembly function from holes and it also centers the hinge. The main focus of design intent is on structural integrity.	
Special requirements: Special requirements of the design is to maintain reductions in weight and also in raw material usage. A consideration was also given for minimizing the use of support structures.	
Replaced manufacturing technology: Original aileron hinge features a set of manufacturing technologies including raw material manufacturing, milling and drilling. Used AM technology is powder bed fusion (electron beam melting) and part material is Ti-6Al-4V.	
Achievements: Achievements through AM includes reduction in weight and decrease in raw material waste comparing to traditional manufacturing technologies by utilizing novel topology optimization techniques.	
Further improvements: Further improvements may be to disseminate the use of the technology for serial production.	

Table 3 – Galley fitting [31]

Description of the component: This case study belongs to an interior cabin galley fitting of a Boeing 787 commercial aircraft. Its main function is connecting the galley to the aircraft.
Design for AM 
Design features: Original design features include mechanical assembly function from side flange holes and back slots.
Special requirements: Special requirements of the design is to maintain minimum use of support structures all over the part and give access to tools for post processes such as machining.
Replaced manufacturing technology: Original galley fitting features a set of manufacturing technologies including raw material manufacturing, milling and drilling. Used AM technology is directed energy deposition (rapid plasma deposition) and part material is titanium alloy. Following to AM, machining was conducted.
Achievements: Achievements through AM includes reduction in weight and decrease in raw material waste comparing to traditional manufacturing technologies.
Further improvements: Flight certification of the component has been completed and the component received orders for serial production. Further improvements may be done by expanding the product portfolio for the related technology by part screening.

Table 4 – Turbine frame [32]

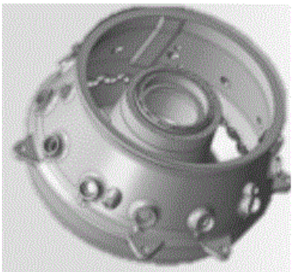
<table>
<tr><td colspan="2">Description of the component: This case study belongs to a turbine frame (assembly) of a commercial turbo-prop engine of General Electric. Its main function is to route the flow of hot gases exiting the high-pressure turbine past structural components and tubes toward the low-pressure turbine, keeping aerodynamic losses at a minimum.</td></tr>
<tr><td>Original design
</td><td>Design for AM
</td></tr>
<tr><td colspan="2">Design features: Original design features include mechanical assembly function from circumferential holes and bosses as well as flanges in aft and forward sides. The design intent comprises of structural integrity at elevated temperatures.</td></tr>
<tr><td colspan="2">Special requirements: Special requirements of the design is to maintain minimum use of support structures all over the part. A significant consideration should also be given for inner faces, where the removal of support structures is not easy.</td></tr>
<tr><td colspan="2">Replaced manufacturing technology: Original turbine frame features a set of manufacturing technologies including forging, turning, milling, drilling, fastening and welding. Used AM technology is powder bed fusion (selective laser melting) and part material is nickel base alloy.</td></tr>
<tr><td colspan="2">Achievements: Achievements through AM includes the simplification of design, reducing the number of sub parts, and reducing the weight through elimination of fasteners. It is also important to highlight that the manufacturing resources and number of engineers were also reduced.</td></tr>
<tr><td colspan="2">Further improvements: Further improvements may be to disseminate the use of the technology for larger parts.</td></tr>
</table>

Table 5 – Cabin ventilation distributor [33]

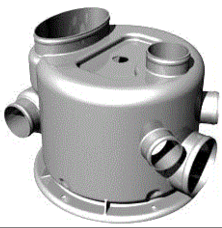
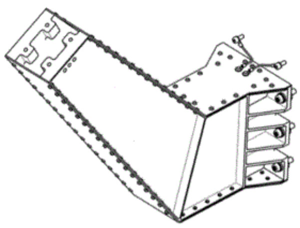
Description of the component: This case study belongs to a cabin ventilation distributor of Airbus Helicopters. Its main function is to pressurize cabin air and ventilate it.
Design for AM 
Design features: Original design features include mechanical assembly function from flanges in top and bottom sides. The design intent comprises of ventilation function as well as structural carrying.
Special requirements: Special requirements of the design is to maintain geometrical feature sizes for the used AM technology.
Replaced manufacturing technology: Original cabin ventilation distributor features a set of manufacturing technologies including draped composite manufacturing and joining. Used AM technology is powder bed fusion (selective laser sintering) and the part material is polyamide powder PA12.
Achievements: Achievements through AM includes the simplification of design, reducing the number of sub parts, decrease in manufacturing time and financial savings.
Further improvements: Further improvements may be to disseminate the use of the technology for other cabin interior parts.

Table 6 – Satellite antenna bracket [34]

<table>
<tr><td colspan="2">Description of the component: This case study belongs to a satellite antenna support bracket of SENTINEL-1 satellite developed by RUAG Space. Its main function is connecting the necessary antenna to the satellite platform and carrying it.</td></tr>
<tr><td>Original design
</td><td>Design for AM
</td></tr>
<tr><td colspan="2">Design features: Original design features include mechanical assembly function from two sides of the bracket and has a dimensional envelope of approximately 385 X 345 X 115 mm. The design intent also comprises of total weight, stiffness and eigen frequency.</td></tr>
<tr><td colspan="2">Special requirements: Special requirements of the design is to maintain a special surface angle under the overhanging struts after optimization to minimize the use of support structures.</td></tr>
<tr><td colspan="2">Replaced manufacturing technology: Original bracket features a set of manufacturing technologies including hole drilling, riveting, fastening and welding. Used AM technology is powder bed fusion (direct metal laser sintering) and part material is AlSi10Mg aluminum alloy.</td></tr>
<tr><td colspan="2">Achievements: Achievements through AM includes the simplification of design, reducing the number of sub parts, and reducing the weight while maintaining the stresses and eigen frequency values inside the limits.</td></tr>
<tr><td colspan="2">Further improvements: Further improvements may be to disseminate the use of the technology for larger parts.</td></tr>
</table>

5. CONCLUSIONS

This paper has focused on the design for additive manufacturing with case studies on aircrafts and propulsion system components. Paper presents essential principles for additive manufacturing and design issues to utilize the method properly for aviation industry.

In this regard, it benchmarked five different case studies of aircraft, aircraft interior, aircraft engine, helicopter cabin interior part and aerospace satellite part. Benchmarked case studies includes both metal and plastic components. For the manufacturing of the metal and plastic components, various AM methods were utilized but mostly the methods under powder bed fusion group was used. The reason for this is the wide range of available materials and favored dimensional and surface quality of the powder bed technology group [7]. On the other hand, diverse methods of directed energy deposition could also be seen but with a post machining need [31].

Although there are different requirements of each component according to the used technology and material, common achievements include simplification of design, reducing the number of sub parts and decrease in manufacturing times. It can be seen that in all cases, AM also provided benefits in terms of decreasing the type and number of manufacturing operations and ease of resource planning. Furthermore, other major impact of design for AM is the ability to manufacture topology optimized parts and examples of this application can also be seen among case studies.

However, the dissemination of the application of AM to aircraft and propulsion system parts should be carried out. One of the common barriers for the dissemination is the part sizes. Other barriers which are subject to different studies and not emphasized in this paper include certification procedures for aviation.

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