

Review Article

The Qualification of the Additively Manufactured Parts in the Aviation Industry

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Abstract: The aviation is a highly engineered industry. It has precise manufacturing requirements. Because of these requirements, the aviation has been forced to be a pioneer for implementation of novel manufacturing techniques such as Computer Aided Design (CAD), Computer Aided Manufacturing (CAM) and newly-developed materials such as carbon fiber composites. These technologies and materials were firstly adopted by the aviation industry. Many processes and materials were used by other sectors such as automotive, ship construction and white goods etc. after the aviation industry used those as regular ones. On the other hand, the aviation industry is a booming sector because it is leveraged by increasing passenger traffic. Passenger traffic projections show that the aviation industry will continuously expand. Naturally, this expansion will attract many companies into the aviation industry and therefore attraction will conclude a fiercer competition environment in the aviation industry. At the conclusion, the companies in the aviation industry will look for implementation of novel technologies since they will not want to fall behind their competitors. On the other hand, the airworthiness authorities always keep their *decision and regulation maker position* while the companies are the followers. It can be put forward that the most difficult side of the implementation of novel technologies into aviation industry is to get along with the strict rules and regulations which are put by international and national airworthiness authorities. In this context, the question of *how to qualify the additively manufactured parts (AMPs)* is waiting for the answer. The additive manufacturing (AM) is a strong process which has been implemented into aviation industry rapidly while the qualification and certification processes still have many challenges. This paper provides the pathway and the steps of qualification for additively manufactured parts (AMPs) besides the categorization of AM technologies and the impact of weight reduction over flight operation cost.

Keywords: Additive Manufacturing (AM), Aviation Industry, Weight Reduction, Qualification, Certification

1. Introduction

AM appears perfectly suited to the aviation industry, allowing lighter parts to be produced with lower cost in less operational time with the same mechanical features as the legacy manufacturing techniques. AM is a disruptive technical innovation whose history goes back nearly three decades [1]. It is rapidly penetrating in to the aviation manufacturing sector. On the other hand, conventional *chip removal techniques* have been used in the aerospace industry almost a century and the manufacturing genome of aerospace is still under the domination of legacy manufacturing technologies. The traditional machining processes such as

milling and turning are still used in the aerospace industry because voluminous metal parts are designed for CNC machining operations. The aerospace materials are manufactured with highly engineered techniques hence these materials are generally not cheap. So the wastage and scrap is very important. The lowest wastage is the best. But the traditional CNC machining processes are subtractive techniques, and the material wastage could be as high as 98% [2]. Since the aerospace materials are expensive, the companies in the aircraft industry are under constant pressure to reduce wastage and develop manufacturing techniques for producing parts in near net shape [3]. For manufacturing cost-effective parts and having a robust position in the aviation industry the buy-to-fly-ratio is an identifier.

Buy-to-fly ratio described as;

$$\text{The Buy-to-fly ratio} = \frac{\text{The weight of the component itself}}{\text{The raw material used for a component}} \quad (1)$$

For AMPs, the buy-to-fly ratio can be as low as 1:1 [4]. Besides, scraps can be as low as 10%, parts' costs down can be as low as 50%, time-to-market down can be as low as 64%, part weight down can be as low as 64% compared with traditional machining process [5]. Because of these benefits, the AM technique becomes one of the most advantageous manufacturing technologies in the aviation industry.

2. Materials and Methods

2.1. Total Direct Operation Cost

The airline operational cost is a crucial subject for understanding the benefits of additive manufacturing technologies' implementation into the aviation industry. The Figure 1, represents that there are different inputs for the sum of the Total Direct Operation Cost (DOC).

The total distribution of airline cost is shown in Table 1. It can be seen that the percentage of fuel / oil has the highest

bid for airline companies with 33,4%.

The second item, *Aircraft Ownership* is far below from *Fuel / Oil* with percentage of 10,6 [7]. The other cost items go down consecutively from each other with small differences. It can be easily said that every effort for decreasing the fuel consumption and hence reducing the direct operational cost has a high value for both airline and airplane constructing companies.

Table 1. Total distribution of airline cost [7].

Case	Percentage
Fuel	33,4
Aircraft Ownership	10,6
Maintenance and Overhaul	9,4
General and Administrative	7,3
Flight Deck Crew	6,8
Reservation, Ticketing, Sales and Promotion	6,5
Station and Ground	6,5
Cabin Attendants	5,1
Airport Charges	4,9
Passenger Service	4,2
Air Navigation Charges	4,1
Other	1,2

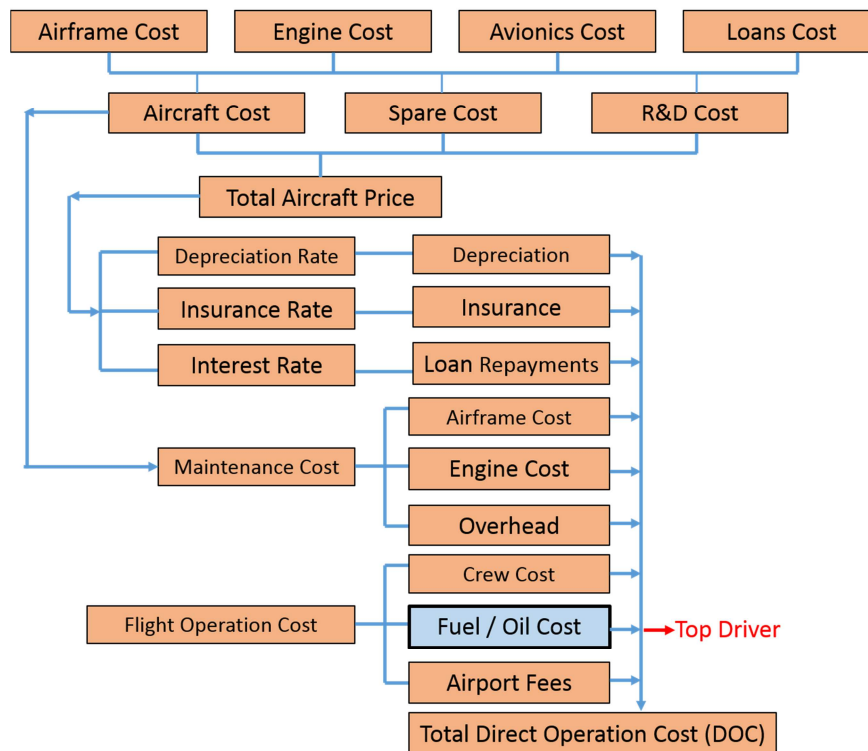


Figure 1. Breakdown structure of DOC [6].

Although fuel consumption has been increasing year-by-year the global air traffic has doubled in every 15 years since 1977 and will continue to do so regarding with the International Civil Aviation Organization's (ICAO) 2016 capacity and efficiency report [8]. While forecasting on doubling of the air traffic over the next 15 years, ICAO also takes attention for emerging aviation technologies may negatively impact the aviation safety [9]. In this context, the

qualification and certification processes have a very crucial position, because airplanes can only fly with airborne parts and components. Indeed, International Air Transport Association (IATA) forecasts that 8,2 Billion people will fly in 2037 means that there's an increasing demand from customers for flying more frequently at the global stage [10]. Consequently, the increasing traffic creates a fiercer competition environment for airliner companies. Therefore,

operational cost becomes an important item must be investigated closely. Reducing the operational cost will contribute the airliner companies for providing lower-cost operations and therefore flying requirements of the customers will be met in a cheaper way. It can be easily affirmed that there's an interrelation amongst more flying demand, increasing airliner's sortie generation tempo, higher increasing activities of airplane manufacturers and novel technological teams such as AMP manufacturers.

2.2. Collaborations in the Aviation Industry

The airplane construction companies, namely aircraft manufacturers feed the aviation and aerospace industries with brand-new aircrafts. The high competitive environment of the aircraft construction business ensures that any opportunity to lower operating costs is explored and exploited wherever possible [11]. For manufacturing cost-effective airplanes, the companies are establishing mutual-benefit relationships, such as aircraft manufacturer Lockheed Martin (LM) and Oak Ridge National Laboratory (ORNL) collaboration. LM and ORNL have been studying over additively manufactured aerospace parts for decades. LM's F-35 engine Bleed Air Leak Detector bracket (BALD), the buy-to-fly ratio is reduced to 1:1, as against the 33:1 ratio possible by legacy methods with the advantage of 50% in total cost [12]. In another case, the aircraft engine manufacturer Pratt & Whitney and University of Connecticut have started studying over additively manufactured engine parts also. Many parts have been manufactured for the *PurePower PW1500G* engines [13]. Some aerospace companies have their own AM plants like General Electric (GE) has its own in Auburn. In Auburn, GE has manufactured a fuel nozzle which is an iconic part of AM applications in the aerospace industry. As shown in Figure 2, the airborne nozzle which was made by combining 20 parts into one, manufactured in a single machine and weighed 25% less than the traditionally produced predecessors [14]. In October 2018, GE announced that 30,000th nozzle was produced for Leading Edge Aviation Propulsion (LEAP) engines at GE's facilities [15].



Figure 2. GE's fuel nozzle which is additively manufactured for LEAP engines [16].

These nozzles are reported to be five times more durable than those which were manufactured by using legacy methods [17]. In accordance with GE sources, the total manufacturing of above mentioned nozzles will be around 40,000 by 2020 [18].

Other than aircraft construction business, there are some other AM collaborations in the aviation maintenance, repair, and overhaul (MRO) area. During MRO stages aircrafts don't fly and whenever an aircraft is not flying, it means losing money for airline companies. Aircraft-On-the-Ground (AoG) is an unwanted situation as it is said that "*aircraft in the sky makes money, aircraft on the ground takes money*". For shortening the ground-time and preventing waste of money, there are some collaborations made in the MRO field. e.g. Etihad Airways Engineering, which is the largest aircraft MRO services provider in the Middle East and EOS which is a leading innovation supplier in the field of industrial AM have agreed on a strategic partnership which is a significant mutual relation [19]. Shortening the maintenance intervals is a target and in the MRO area, also some other collaborations are underway such as the collaboration between Emirates Engineering and 3D Systems Inc. The Airbus and Boeing aircrafts' video monitor shrouds are printed by using 3D Systems Inc. with flame-retardant nylon-12 thermoplastic material. Shrouds are now 9-13% lighter than the original ones. The other examples of MRO collaborations are the Airbus and Belgium based Materialise company [20], Airbus and Singapore based SIA Engineering Company (SIAEC) [21] Airbus and Stratasys [22] collaborations. In the military side, LM and Sciaky manufactured a flaperon spar made through AM Electro-Beam Direct Melting (EBDM) process could save about 100 \$ million through the lifetime of F-35 [23]. Research collaborations between aerospace institutes and universities such as LM and ORNL, BAE System and Cranfield University, NASA, Honeywell, and Ohio Aerospace Institute, and many others are currently active and evaluating various possibilities for the application of additive manufacturing for the aerospace industry [24]. In August 2012, the USA AM Innovation Institute was established in Youngstown, Ohio, with the participation of 40 member companies, 9 universities, 5 community colleges, and 11 non-profit organizations [25]. Since aforementioned collaborations will assure the part consolidation on reduced inventory and less storage fee, on-demand manufacturing, light-weighting reduced costs, lower fuel consumption and eventually smaller carbon footprints, it seems that in the future there will be more collaborations in the aviation industry. It can be easily said that, AM technologies are changing the paradigm in the aviation industry rapidly.

2.3. Airplane Manufacturing Market

There's an interrelation amongst airliners, MROs and airplane manufacturers. The competition amongst airplane manufacturing market will be fiercer with the increasing demand by airliner companies. In other words, aircraft manufacturer companies are under pressure for meeting airliners demands. For example, Boeing increased its 737-800 manufacturing capability from 42 to 47 aircraft per month to meet the strong market demand [26]. In the commercial aircraft market, until 2037 approximately 161,500 new aircraft will be delivered by the key player aircraft manufacturers globally to replace retired airplanes and support the

development of airliners as it is given in Table 2.

Table 2. The projection of the market-dominating aircraft manufacturers until 2037.

Aircraft Manufacturer	Number of Aircraft
Boeing	42.730 [27]
Airbus	37.400 [28]
Comac	42.702 [29]
Bombardier (2017-2036)	25.100 [30]
Embraer	10.550 [31]
ATR	3.020 [32]
Total	161.502

It is worth emphasizing that, the total brand-new commercial aircraft number will be more than 161.500 considering general aviation airplanes and small-sized manufacturers products.

The secondary data is used for figuring out the impact of the weight over fuel consumption and operational cost as well. The relationship between weight and fuel consumption is important. While aircraft manufacturers are working to meet the airliners booming demand, airliners want to decrease their operational cost. At that point, weight reduction can be advantageous to use less material and to avoid to consume energy transportation. It also benefits of reducing pollution emissions [33]. Consequently, airliner companies want weight-reduction since the weight is a major role player of fuel consumption.

The weight of the aircraft is categorized regarding the configuration and weight is the most important input through the design and manufacturing phases of the aircraft. The airplanes are categorized based on their weights.

3. Discussion

3.1. Weight Definitions

While flying an airplane, four forces are affecting the structure. These forces are mainly;

Thrust: Acting in a forward direction. Thrust is generated by engines.

Drag: Opposing the forward movement of the airplane acting parallel to the relative airflow. It is caused by friction and varies in air pressure.

Lift: The upward force acting vertical to the relative airflow that enables the airplane to remain airborne. The wings create most of the lift.

Weight: Acting vertically downward, dependent on the mass of the body and the strength of the gravitational force for its value.

Before providing information about the relationship between weight and fuel consumption, the categorization of the weight worth focusing on. There are many sorts of weight regarding airplanes configuration. Some of the important weight definitions are given below in the alphabetical order:

Crew Weight (W_c , W_{crew}) is the weight of occupants required for operating the aircraft.

Design Gross Weight (W_0) is equal to the Maximum Take-Off Weight (MTOW). It is the weight of the aircraft as

it begins the mission for which it was designed.

Unless particularly mentioned, W_0 is assumed to be the design weight and will be mentioned as weight henceforth.

Empty Weight (W_e , W_{empty}) is the weight of an aircraft without useful load like oil, hydraulic fluids and unusable (trapped) fuel. W_e includes structure, engines, landing gears, avionics and all other equipment which are not considered a part of the crew, payload or fuel.

Fuel Weight (W_f , W_{fuel}) is the weight of the fuel required to complete the design mission.

Maximum Zero Fuel Weight (W_{MZF}) is the maximum weight that the aircraft can carry without fuel inside.

Payload (W_p , $W_{payload}$) is the parameter that an operator can gain revenue like cargo and passenger. The difference between W_u and W_p is a key driver for airliner because lesser fuel in the aircraft means more passenger and more freight.

Useful Load (W_u) is the weight of everything the aircraft will carry besides with its own weight like the fuel, cargo, occupants etc. [34] just to name but a few.

3.2. Fundamental Weight Relations

After the definitions a quick overview of the weight relations is given in this paragraph.

The primary governing equations and ratios are given below:

Design gross weight:

$$W_0 = W_e + W_f \quad (2)$$

Useful load:

$$W_u = W_c + W_p + W_f \quad (3)$$

Design gross weight can be written in following form:

$$W_0 = W_c + W_p + W_f + W_e \quad (4)$$

Empty weight ratio (EWR):

$$\frac{W_e}{W_0} \quad (5)$$

Fuel weight ratio (FWR):

$$\frac{W_f}{W_0}$$

Equation (2-3) becomes:

$$W_0 = W_c + W_p + \left(\frac{W_f}{W_0}\right) W_0 + \left(\frac{W_e}{W_0}\right) W_0 \quad (6)$$

Then W_0 can be obtained as follows:

$$W_0 - \left(\frac{W_f}{W_0}\right) W_0 - \left(\frac{W_e}{W_0}\right) W_0 = W_c + W_p \quad (7)$$

And finally W_0 can written as follows:

$$W_0 = \frac{W_c + W_p}{\left(1 - \left(\frac{W_f}{W_0}\right) - \left(\frac{W_e}{W_0}\right)\right)} \quad (8)$$

These ratios and equations are important because the weight (W_0) is the key element of flight safety and design

operations. Raymer et al. highlights that different types of aircrafts exhibit different slopes to the trend lines of Empty Weight Ratio [35].

3.3. Additively Manufactured Parts

The lighter aircraft means less fuel burning, the capability of carrying higher payloads and ability of reaching to longer ranges. On the other hand, while reducing the weight, keeping the strength and maintaining the performance of the airworthy parts are vital subjects. Thanks to the W_0

decreasing studies in the Boeing Company, Boeing 777-300 has improved its fuel efficiency against Boeing 767-300 and managed to take up to 368 passengers compared to 269 passengers in Boeing 767-300ER [11]. That's why weight reduction studies seem exciting the airliner companies because of providing many opportunities in the name of cost-effectivity. The categorization and terminology of AM process is provided with the frame of ASTM document "Standard Terminology for Additive Manufacturing Technologies, Designation: F2792 – 12a" in Table 3.

Table 3. Additive manufacturing categorization table [37, 38].

Additive Manufacturing Categorization Table				
Process Name		Abbr.	Process Method	Processing Material
1.a	Binder Jetting	BJ	Joined with bonding agent	Gypsum, sand and metal
	Binder jetting			
2	Directed Energy Deposition	LENS	Fused With Laser	Metal
2.a	Laser Engineering Net Shape			
2.b	Electron Beam Additive Manufacturing			
3	Material Extrusion	EBAM	Fused With Electron Beam	Metal
	Fused Deposition Modelling			
3.a	Fused Filament Fabrication	FDM	Filament Melting	Composite and Plastic
		FFF		
4	Material Jetting	MJ	Cured with UV Light	Plastic
4.a	Material Jetting			
4.b	Nano Particle Jetting	NPJ	Cured with Heat	Metal
4.c	Drop on Demand	DoD	Milled to form	Wax
5	Powder Bed Fusion	MJF	Fused with agent and energy	Plastic
5.a	Multi Jet Fusion			
5.b	Selective Laser Sintering	SLS	Fused with laser	Plastic
5.c	Direct Metal Laser Sintering	DMLS	Fused With Laser	Metal
	Selective Laser Melting	SLM		
5.d	Electron Beam Welding	EBW	Fused with Electron Beam	Metal
6	Sheet Lamination	LOM	Material Cutting	Composite and Paper
6.a	Laminated Object Manufacturing			
7	Vat Photopolymerization	SLA	Cured with laser	Plastic
7.a	Stereolithography			
7.b	Digital Light Processing	DLP	Cured with laser	Plastic
7.c	Continuous Digital Light Processing	CDLP	Cured with Led and Oxygen	Plastic

Depending on the sections in the aircraft, many parts which are used currently and many of them will be manufactured by the AM processes given in the Table 3. But as ICAO gives attention of new technologies in the aerospace industry and flight safety relationship and AMPs need to be more investigated. As it was mentioned before, the airplanes can operate only with airworthy parts and components. Waive off the airworthiness requirements of the additively manufactured parts is unacceptable by certification authorities.

As it is previously mentioned, as a disruptive technology AM is a solution for reducing the W_0 , while maintaining the same mechanical features. Sometimes modern technologies need materials with unusual combinations of properties that cannot be solely provided by metals, polymers, or ceramics [39].

On the other hand, producing a component with AM techniques also gives advantages like removing the steps such as welding and bonding from whole manufacturing process. It is direct benefit while there are some indirect benefits such as removing the fixtures for welding, in-factory-travelling etc. Indeed, when welding and bonding processes are removed, it means there will be no need to produce a welding fixture. At the conclusion, AM processes save labor hours and machine hours

also. Also, it gives shorter lean-manufacturing-line advantages because there will be no need to transportation to welding shop.

3.4. The Impact of the Additively Manufactured Parts on Weight Reduction of the Aircrafts

Redesign is the core of weight reduction etudes, such as GE's nozzle which has been mentioned previously. Redesigning of the nozzle gave chances to reduce operational man and machine hours and simplifying the manufacturing process, thanks to AM techniques [40]. Another redesigning project is the Airbus company's SAVING project. By redesigning the seat buckles using AM techniques, the "SAVING" project elucidated that a 55% weight reduction is possible. Weight reduction was almost a total 72,5 kg of weight can be saved if all the seat buckles of the Airbus 380 which has 853 seats were to adopt the optimum designs, amounting to 3.3 million liters of fuel savings over the service life of the aircraft. Reportedly, total saving is about \$3 million while the cost of making the buckles using DMLS (Process shown in Table 3, 5c) is only \$256,000 [24, 41]. The reduction of one kg built-in aircraft weight is able to reduce carbon emissions by 0.94 kg for the case of the Boeing 747-400 whose W_0 is 396,890 kg and by 0.475 kg in the Airbus

A330-300 whose W_0 is 242,000 kg. [42]. The lighter airplanes have benefits to decreasing carbon emissions. At the conclusion, the weight, the carbon emissions, the fuel consumption, and the operational cost are interrelated with each other. e.g., reducing one pound of weight from each aircraft in American Airlines’ fleet could save about 11,000 gallons of fuel annually [43].

Certification is an interface procedure between a product manufacturer and airworthiness authorities. Quality of AMPs is affected by the steps of the value chain. That’s why in aerospace grade level, certification not only assures the part itself as an airworthy part, it is also a guarantee of the whole qualification system; from data capture to preparation of manufacturing the part, from production to post-processing and test, verification and validation stages [44].

4. Conclusion

In the literature, it is observed that, there is an increasing

number of publishing related to AM technology applications in the aerospace industry based on AM’s increasing popularity, however Singamneni et al. stated that there is a general lack of publishing activity related to quality control and certification of AMPs [24]. Ceruti A. et al. also reported that because of the lack of regulations by aeronautical authorities there are limitations of penetrating new technologies such as AM into aeronautical science [33]. In the military side, the situation is not so different from commercial side. Frazier E. W. et al. expressed that the ability to qualify and certify AMPs, including safety-critical metallic parts is a main barrier to its more extensive use [45]. These barriers is also stated by a study case given in Table 4, regarding the future of the AM technologies, the key challenges hindering the advancement of AM over the next ten years. The certification of finished parts and products is the first challenge for AM, hindering the mainstream commercial obstacle must be studied.

Table 4. The key challenges hindering the advancement of AM over the next ten years [46].

Challenge	Percentage
Certification of finished parts and products	76
Quality & standardization of material inputs (powders & wires)	49
Questionable quality of printed components	35
IP, legal and regulatory issues	30
The cost of the equipment	27
Slow printing times	27
Immaturity of the technology	25
The cost of raw materials/producing the parts	20
Duplicated research and lack of stakeholder cooperation	19
Miscommunication with end-users, government, and military	17
The cost of R&D	
Limited supply of raw materials (powders and polymers etc)	14
Lack of appropriate training courses and methods	
Development of alternative manufacturing processes	
The limited supply of raw materials (powders and polymers etc.)	11
Lack of appropriate training courses and methods	10
Development of alternative manufacturing processes	8

Despite the lack of publicly available certification procedures for AM the companies are gaining airworthiness authorities approvals for their ready-to-take-off parts. GE has received Federal Aviation Administration (FAA) approval for installing AM compressor inlet temperature sensor housing, known as T25, in its GE90 jet engines, which power the Boeing’s 777 aircraft [47]. GE also has dual certification of FAA and European Aviation Safety Agency (EASA) for the LEAP engines [48]. The certification process is not an approval of the product; it is for ensuring the repeatability of the products. That’s why airworthiness authorities are mainly interested in the facility including the whole manufacturing process and documentation rather than a product. It is worth noting that as the whole process is certified only then the part is also considered as an “airworthy part”. Qualification of processes and certification of AMPs requires that parts meet or exceed the criteria put by airworthiness authorities [49].

As it is shown in Figure 3, either originally creating a part with AM technologies or transforming the material in the name of weight and cost reduction requires engineering confidence and knowledge-based methodology [45]. Knowledge-Based

System is structured on the properties, geometry and processes.

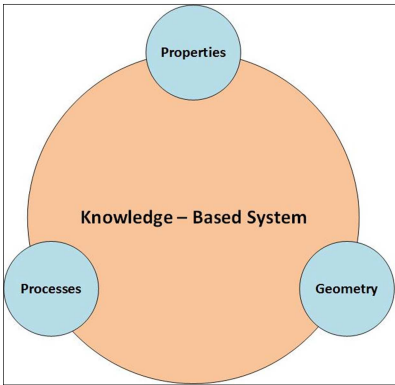


Figure 3. Developing cycle of AMPs on knowledge-based system.

Although there are serious researches and workshops on AMP in the aerospace industry like the one held in June 2016 [49], there is still a lack of publications and studies in the qualification and certification AMPs which are used in the aerospace industry. Steve R. Daniewicz from Mississippi State

University also stated that certification and standards are the ongoing challenges during the Joint Federal Aviation Administration–Air Force Workshop on Qualification/Certification of Additively Manufactured Parts [49].

4.1. Qualification of Additively Manufactured Parts

In this paper, it is aimed to create a situational awareness of the current progress in the direction of Qualification and Certification of AMPs in the aviation industry. The aviation requires both flight and ground safety and that's what stringent airworthiness requirements are for.

During industrialization phase of a product, qualification of the material, process, and part is necessary and need to be described in terms of defining, validating, and establishing the product line. The qualification steps are generally typical steps after process and material development phases. The main issue is maintaining the parts quality, during prototype and mass-production phases with verification procedures

which based on the quality documents. In the aviation industry, raw material is important so the qualification steps start with raw material providing which requires a well-established-subcontractor management. As airworthiness authority, the regulatory body will penetrate into quality documents which describes the steps from *raw material providing* to *completed part*. Describing the go / no-go criteria and controlling the whole process is important, so measurement / monitoring frequencies are the main inputs for structure of the qualification of AMPs. First Article Testing (FAT), gives clues about the stages need to be improved. The traceability must be assured from raw material depot to finished part depot.

As demonstrated in Figure 4, the technical elements which include the, system certification, part qualification and development definition and raw material, additive deposition, post-processing, and finished component phases are interrelated with each other.

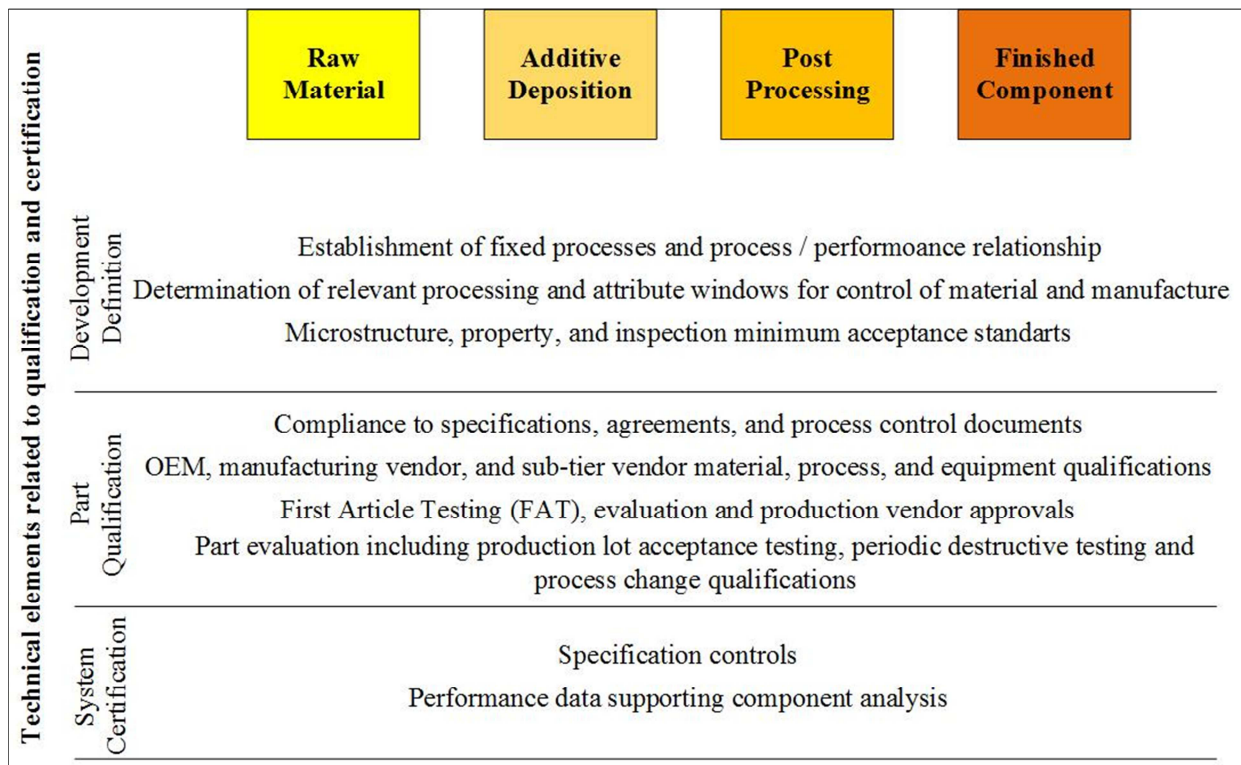


Figure 4. The process of qualification and certification with the steps of raw material, additive deposition, post-processing and finished component [44].

4.2. Pathway of the Qualification and Certification of Additively Manufactured Parts

As it was mentioned in Paragraph 4.1. the qualification and certification process of AMPs starts from raw material's qualification and concludes with acceptance activities of the final product. Raw material, e.g. powder's quality is one of the most important issue must be defined in the specification-statement-documents. Machines, and equipment's limits and working conditions are the important factors affect the quality of the final-product. After AMPs are

manufactured, a finish process like grinding, heat treatment, coating etc. may be required so these processes must be under control also. The witness part gives clues about the health of the manufacturing process so it must be evaluated in accordance with test procedure. Also Non-Destructive Evaluation (NDE) is the core of the certification which gives clues about whether the manufacturing process is confident for both ground and flight safety or not.

In Figure 5, a potential pathway (but not the only pathway) of qualification and certification of AMPs is demonstrated.

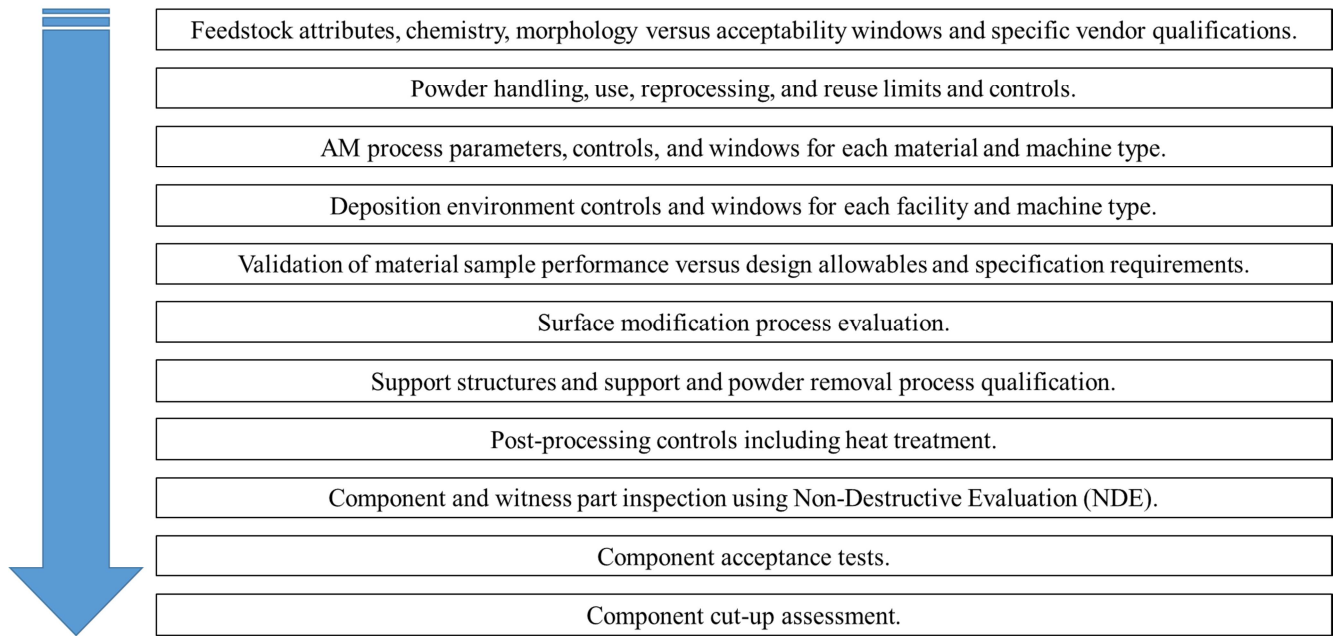


Figure 5. A typical pathway of qualification and certification for AMPs [44].

The whole qualification and certification process needs to be based on knowledge of both aerospace & aviation science and paperwork of the certification itself. For sure, the standards will not specifically dictate how to produce or certify a part whereas the requirements will identify factors that should be addressed for all steps of design, manufacture, and qualification. That's why periodic control and analysis like crack growth analysis using fatigue testing and inspections as NDE are required. Until AM process which is given in Table 3, is matured effect-of-defect must be periodically checked.

In a traditional quality assurance system, the NDE methods, and detection / treatment of defects may be affected or limited by complex geometry, surface quality, and near-net-shape spirit of AMPs. There may be some influences created by airliners and aircraft manufacturer companies for transforming the materials from heavy to lighter. But it must be kept in mind that AM technologies require deeper qualification and certification audits since this technology is still under developing as it was warned by ICAO.

In the aerospace industry, manufacturing the same geometrical part with lighter materials which have at least the same mechanical properties is the mainline of weight reduction. On the other hand, redesigning and transforming the materials of the parts from heavier to lighter, requires precise engineering calculations since the airworthiness authorities' regulations are extremely strict. e.g FAA Regulations, Title 14, Section 25, Subpart D, Subsection 25.605 indicates that; "The suitability and durability of materials used for parts, the failure of which could adversely affect safety, must -

- (a) Be established on the basis of experience or tests;
- (b) Conform to approved specifications (such as industry or military specifications, or Technical Standard Orders)

that ensure their having the strength and other properties assumed in the design data;

- (c) Take into account the effects of environmental conditions, such as temperature and humidity, expected in service." [50]. The abovementioned requirements are almost the same in EASA documents [51].

Finally, information regarding airworthiness certification of AMPs considering the weight reduction and fuel consumption relation has been provided. Carbon footprint is another important issue must be studied because reducing the aircraft weight has a vital benefit as reducing the carbon footprint. The weight reducing and environment-friendly studies must be supported by governments and Non-Governmental Organizations (NGO) for a better world that we will leave as an inheritance to the next generations.

As a disruptive technology, AM will take place of the chip-away technologies in the future. The current obstacles such as mass production effectivity, surface roughness and requirement of post-processing will be solved sooner or later. Solving these obstacles is just an engineering issue which may take some time. Using the AM technologies in the aerospace industry have benefits of reduction of the weight of aircraft, thus reducing the fuel consumption and therefore CO₂ emissions. The benefits are realized with computational and empiric studies. All these studies will create more attractiveness to novel technology teams and companies for widely usage of AM techniques in the aerospace industry.

Lowering the fuel consumption with weight reduction studies has direct impact on the flight operational cost while indirect positive impacts on lowering the CO₂ emissions. It should be noted that, fuel usage means some other energy consumed process such as extraction, processing, distribution and storage of the fuel. So the engineering etudes regarding

weight reduction, decreasing the fuel consumption and lowering the carbon footprint are very important

The studies regarding lowering the CO₂ emissions and conversion the parts from steel or aluminum to Carbon Fiber Reinforced Polymer (CFRP) is recommended. Also Glass Fiber Reinforced Polymer (GFRP) and Aramid Fiber Reinforced Polymer (AFRP) are the materials which are the candidates of exchanging the parts of steel and/or aluminum.

It is seen that in the aerospace industry the percentage of AMPs usage will increase because of AM techniques unbeatable advantages. With these advantages the technological teams and/or engineering companies may tend to design or redesign the additively-manufactured-flight-ready-parts. The qualification and certification of the parts is an important issue must be solved since they will be asked by the airworthiness authorities. Hopefully, the information provided in this study will be beneficial and useful for the academicians, researchers and technical teams who are dealing with novel manufacturing technologies such as AM in the aviation industry.

References

- [1] Dipaola M., Wodajo M. F. 3D Printing in Orthopaedic Surgery, 2019, Elsevier, UK, 2019, pp 4.
- [2] Allen, J. An Investigation into the Comparative Costs of Additive Manufacture vs. Machine from Solid for Aero Engine Parts. Manufacturing Technology Rolls-Royce plc, Unclassified Report, UK, 2006, pp 1.
- [3] Garcia-Colomo A., Wood D., Martina F., Williams S. W., A comparison framework to support the selection of the best additive manufacturing process for specific aerospace applications, International Journal of Rapid Manufacturing, Underscience Publishers, UK, 2019, pp 2.
- [4] Barz A., Buer T., Haasis H.-D., A Study on the Effects of Additive Manufacturing on the Structure of Supply Networks, International Federation of Automatic Control, Elsevier, UK, 2016, pp 4.
- [5] Deloitte University Press, Additive manufacturing takes flight, 3D opportunity in aerospace and defense, USA, 2014, pp 4.
- [6] Jenkinson Lloyd R., Simpkin P., Rhodes D., Civil Jet Aircraft Design, Arnold A member of the Hodder Headline Group, UK, 1999, pp 320.
- [7] Ferjan C., Airline Operational Cost Task Force (AOCTF), Airline Cost Management Group (ACMG), Airline Cost Conference, Swiss, August 26-27, 2014, pp 12.
- [8] International Civil Aviation Organization (ICAO), Capacity and Efficiency Report, 2016–2030 Global Air Navigation Plan, 2016, pp 7.
- [9] ICAO Journal, Issue 2, Strengthening Regional Safety Oversight, Vol. 73, No. 2, 2018, pp 11.
- [10] IATA, Forecast Predicts 8.2 billion Air Travelers in 2037, www.iata.org/pressroom/pr/Pages/2018-10-24-02.aspx, last accessed: 04th July 2019.
- [11] Mansor M. R., Nurfaizay A. H., Tamaldin N., Nordin M. N. A., Natural fiber polymer composites: utilization in aerospace engineering, In: Biomass, Biopolymer-Based Materials, and Bioenergy: Construction, Biomedical, and other Industrial Applications, Woodhead Publishing, Elsevier, UK, 2019, pp 220.
- [12] AMFG, Thinking Big: 4 Impressive Applications of Large-Scale 3D Printing, amfg.ai/2019/04/02/thinking-big-4-impressive-applications-of-large-scale-3d-printing/, last accessed: 04th July 2019.
- [13] Pratt & Whitney Partners with University of Connecticut to Advance Additive Manufacturing Research, additivemanufacturingtoday.com/pratt-whitney-partners-with-university-of-connecticut-to-advance-additive-manufacturing-research, last accessed: 04th July 2019.
- [14] GE Reveals How Greg Morris Created the 3D Printed Nozzle for the LEAP Jet Engine, www.3dprintingmedia.network/ge-reveals-greg-morris-create-d-3d-printed-nozzle-leap-jet-engine/, last accessed: 04th July 2019.
- [15] New manufacturing milestone: 30,000 additive fuel nozzles, www.ge.com/additive/blog/new-manufacturing-milestone-3000-additive-fuel-nozzles, last accessed: 04th July 2019.
- [16] 3D printing: Mind Meld: How GE And A 3D-Printing Visionary Joined Forces, www.ge.com/reports/mind-meld-ge-3d-printing-visionary-joined-forces/, last accessed: 05th July 2019.
- [17] GE9X; World's First Plant to Print Jet Engine Nozzles in Mass Production, www.ge.com/reports/post/91763815095/worlds-first-plant-to-print-jet-engine-nozzles-in/, last accessed: 04th July 2019.
- [18] Gorelik M., Additive Manufacturing for Reactor Materials and Components Public Meeting, November 28-29, 2017, North Bethesda, MD, USA, pp 35: 8.
- [19] EOS and Etihad Airways Engineering set to expand industrial 3D printing capabilities, www.eos.info/press/eos-and-etihad-airways-engineering-set-to-expand-industrial-3d-printing-capabilities, last accessed: 04th July 2019.
- [20] Airbus Bridges the Gap with 3D Printing, www.materialise.com/en/press-releases/airbus-bridges-gap-3d-printing, last accessed: 04th July 2019.
- [21] Airbus and SIAEC in corporate MRO Joint Venture in Singapore, www.airbus.com/newsroom/press-releases/en/2016/10/airbus-and-siaec-incorporate-mro-joint-venture-in-singapore.html, last accessed: 06th July 2019.
- [22] Stratasys Direct Manufacturing Selected by Airbus to 3D Print Polymer Serial Flying A350 XWB Parts, www.investors.stratasys.com/news-releases/news-release-details/stratasys-direct-manufacturing-selected-airbus-3d-print-polymer, last accessed: 04th July 2019.
- [23] "Game-changer" to aid in F-35 production, www.thefabricator.com/blog/game-changer-to-aid-in-f-35-production, last accessed: 04th July 2019.
- [24] Sarat S, Yifan LV, Hewitt A, Chalk R., Thomas W and Jordison D, Additive Manufacturing for the Aircraft Industry: A Review, Journal of Aeronautics & Aerospace Engineering, 2019, Spain, pp 11.

- [25] National Network For Manufacturing Innovation Program Annual Report, Executive Office of the President National Science and Technology Council Advanced Manufacturing National Program Office, USA, February 2016, pp 12.
- [26] Renton rolls out 47th 737 built at new 47-per-month rate, www.boeing.com/company/about-bca/washington/737-rate-increase-07-28-17.page, last accessed: 04th July 2019.
- [27] Boeing, Commercial Market Report, 2018-2037, USA, 2018, pp 3.
- [28] Airbus, Global Market Forecast, Global Networks Global Citizens, 2018-2037, France, 2018, pp 6.
- [29] COMAC releases Market Forecast Report (2018-2037), www.english.comac.cc/news/latest/201811/14/t20181114_6610546.shtml, last accessed: 07th July 2019.
- [30] Bombardier, Commercial Aircraft, 2017-2036 Market Forecast, Canada, 2018, pp 6.
- [31] Embraer, Market Outlook Report 2018-2037, Brazil, 2018, pp 6.
- [32] ATR, Turboprop Market Forecast 2018-2037, France, 2018, pp 6.
- [33] Ceruti A., Marzorca P., Liverani A., Bil C., Maintenance in Aeronautics in an Industry 4.0 Context: The Role of Augmented Reality and Additive Manufacturing, *Journal of Computational Design and Engineering*, Elsevier, UK, 2019, pp 5.
- [34] Gudmundsson S., General Aviation Aircraft Design, Butterworth-Heinemann is an imprint of Elsevier, UK, 2014, pp 135-136.
- [35] Raymer P. D., Aircraft Design: A Conceptual Approach, American Institute of Aeronautics and Astronautics, USA, 1992, pp 14.
- [36] ASTM, Standard Terminology for Additive Manufacturing Technologies, Designation: F2792 – 12a, USA, 2013, pp 1-2.
- [37] What is Additive Layer Manufacturing (ALM)?, www.farinia.com/additive-manufacturing/3d-technique/additive-layer-manufacturing, last accessed: 04th June 2019.
- [38] Additive Manufacturing Technologies: An Overview, www.3dhubs.com/knowledge-base/additive-manufacturing-technologies-overview, last accessed: 07th June 2019.
- [39] Kushan M., Additive Manufacturing of Polymer Matrix Composites. In: *Aircraft Technology*, Intechopen, 2018, pp 147.
- [40] Despeisse M., Ford S., The Role of Additive Manufacturing in Improving Resource Efficiency and Sustainability, In: *Advances in Production Management Systems, Innovative Production Management Towards Sustainable Growth*, IFIP WG 5.7 International Conference, APMS 2015, Tokyo, Japan, September 7–9, 2015, Proceedings, Part II, pp 131.
- [41] Badiru A., Valencia V. V., Liu D., Additive Manufacturing Handbook, Product Development for the Defense Industry, Taylor and Francis Group, USA, 2017, pp 272.
- [42] Tsai W. H., Chang Y. C., Lin S. J., Chen H. C., Chu P. Y., (2014). A green approach to the weight reduction of aircraft cabins, *Journal of Air Transport Management*, Elsevier, UK, 2014, pp 71.
- [43] Lyons B., Additive Manufacturing in Aerospace; Examples and Research Outlook, National Academy of Engineering, September 19th, 2011, pp 3.
- [44] Froes F., Boyer R., Additive Manufacturing for the Aerospace Industry, Elsevier, UK, 2019, pp 43.
- [45] Frazier W. E., McMichael J., Scheck C., Ensuring a Safe Technological Revolution, *Acquisition, Technology and Logistics Magazine*, USA, 2016, pp 15.
- [46] Defence IQ, Additive Manufacturing in Aerospace, Defence & Space, Trends and Analysis, UK, 2016, pp 5.
- [47] GE Aviation, The FAA Cleared the First 3D Printed Part to Fly in a Commercial Jet Engine from GE, www.ge.com/reports/post/116402870270/the-faa-cleared-the-first-3d-printed-part-to-fly-2/, last accessed: 07th June 2019.
- [48] CFM LEAP-1C integrated propulsion system achieves joint EASA / FAA certification, www.safran-electronics-defense.com/video/2181, last accessed: 04th June 2019.
- [49] Summary Report: Joint Federal Aviation Administration–Air Force Workshop on Qualification/Certification of Additively Manufactured Parts, USA, June 2016, pp 56.
- [50] Code of Federal Regulations, Federal Aviation Administration, Title 14, Title 14 Aeronautics and Space Parts 1-59, Section 25, Subpart D, Subsection 25.605, USA, Revised 2014, pp 425.
- [51] European Union Aviation Safety Agency, Certification Specifications and Acceptable Means of Compliance For Large Rotorcraft, 17 September 2018, pp 34.