Introduction of Additive Manufacturing at OGMA, Indústria Aeronáutica De Portugal SA

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Abstract

The aerospace industry is always in search of progress and technological breakthroughs in order to increase efficiency in a way that results in a decrease of its environmental impact. This has lead to additive manufacturing being one of the concepts that has garnered more attention in the recent years. These kinds of technology are defined as the process of joining materials to make parts from three dimensional model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing. Additive manufacturing brings multiple benefits to the aerospace industry, such as, more geometric freedom, shortened design to product time, reduction in process steps and component mass reduction. One of the companies that has shown interest in these kinds of technologies is OGMA.

This work provides a roadmap for the implementation of additive manufacturing at OGMA, considering the organizational structure of the company, the state-of-the-art of additive manufacturing technologies and presenting a case study of parts that are manufactured trough traditional methods that could possibly transition to AM.

Keywords: Additive manufacturing, aeronautical industry, technology implementation, implementation roadmap.

1. Introduction

The aerospace industry is constantly in search of progress and technological breakthroughs. This need for evolution comes from different concerns, namely the need to increase the efficiency of its various sectors in a way that results in the decrease of its environmental impact. Despite not being the biggest contributor of pollution in the world, the tendency for the number of flights is to increase, and so, the material waste, the fuel and energy consumptions and the noise are some of the areas in which the aerospace industry has been focusing on, in order to protect the environment.

Because of this, one of the concepts that has been gaining a lot of attention in the aeronautical community is additive manufacturing (AM). AM is defined as the "process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative manufacturing" [1]. These kinds of processes bring various benefits to the aerospace industry, such as, more geometric freedom, shortened design to product time, reduction in process steps and component mass reduction [2].

One of the companies that has shown interest in these kinds of technologies is OGMA, Indústria Aeronáutica de Portugal. OGMA is a Portuguese company with Part 145 certification (by the European Aviation Safety Agency, EASA), it is a Design Organization Approval (DOA) and a Production Organization Approval (POA) (by EASA). With the recent developments in AM, it became of OGMA's interest to study the possibility of the implementation of AM processes in the company, targeting the possibility of manufacturing aircraft parts, producing prototypes to test the shape and functionality of design projects in development, and tooling to assist in traditional manufacturing methods. This work's objective is, therefore, to provide a roadmap to the implementation of AM at OGMA, considering the organizational structure of the company, the state-of-the-art of AM technologies and presenting a case study of parts that are manufactured trough traditional methods that could possibly transition to AM.

2. State of the Art
2.1. Additive Manufacturing

In its early years, AM was mostly applied for the fabrication of conceptual and functional prototypes, also known as Rapid Prototyping (RP) [3]. However, The goal of building non-functional or semi-functional prototypes from 3D computer models changed to building fully-functional components directly from 3D computer models, hence, rapid prototyping methods developed various freeform fabrication technologies for direct manufacturing [4].

In more recent years, AM technology as seen various applications in the aerospace industry, with such as the partnership between Boeing and Norsk Titanium AS [5] [6], the partnership between Liebherr-Aerospace and Airbus [7], and the investments and research and development made by General Electric [8] [9] [10] [11] [12].

Generic AM process

Different products will involve AM in different ways and to different degrees. Parts production through AM generally follows the same process, described by Gibson and co-authors [13], that follows 8 steps: Computer-Aided Design (CAD), conversion to an STL/AMF, transfer to AM machine and STL/AMF file manipulation, machine setup, building the part, removal from the machine, post-processing, and finally application.

It is important to note that AM processes fall outside of most materials and process standards, which led to the creation of the ASTM F42 Technical Committee on Additive Manufacturing Technologies, which is working to address and overcome this problem [14].

Classification

There are numerous ways to classify AM technologies. Seen as though this work is based on the implementation of AM in a company, it was concluded that a classification method that relies on the separation of technologies, in which processes which use a common type of machine architecture and similar materials transformation physics are grouped together, would be beneficial for the posterior market survey. Using this classification scheme, all current AM processes fall into one of seven categories as shown in figure 1: Vat Photopolymerization, Powder Bed Fusion (PBF), Material Extrusion, Material Jetting, Binder Jetting, Sheet Lamination and Direct Energy Deposition (DED) [13].

3. Present manufacturing processes at OGMA

Before proposing methods for the implementation of AM in OGMA, one must first study and understand the company's current situation as a manufacturing and design organization, as well as the aeronautical legislation in play that will affect said implementation.

In order to work in the aeronautical industry, a company must follow a varied set of legislations established by two types of authorities: international authorities (like EASA and the FAA) and national authorities (like ANAC, which is the Portuguese civil aviation authority) [15]. As OGMA is an European organization, focus will be given to European legislation established by EASA.

It is of particular interest Annex I (also known as Part 21) of the Commission Regulation (EU) No 748/2012 of 03/08/2012 that lays down implementing rules for the airworthiness and environmental certification of aircraft and related products, parts and appliances, as well as for the certification of design and production organizations [16]. OGMA is certified by EASA under Part 21 as both a Design Organization Approval (DOA) and a Production Organization Approval (POA) [17].

3.1. Design organization approval

While having DOA certification, OGMA has some privileges when it comes to project design. The holder of a DOA is entitled to perform design activities and has a certain liberty to perform changes to aircrafts [16].

The first step of OGMA's design process is to go through and analyze the basis of specifications that will impact the design and its certification [15]. After taking into account both the design and the different specifications, the materials are selected according to the necessary mechanical and chemical characteristics for the design to perform its function without putting at risk the aircraft's integrity and of those that travel in it [15]. All the parts and assemblies are then modelled and drawn with 3D CAD software (CATIA) and then exported to finite elements calculation software (MSC Patran + MSC Nastran) so that stress analysis can be made [15]. The parts and/or assemblies are then built and ran through destructive and/or non-destructive tests to confirm that the design performs as intended [15]. All the drawings and calculations are reviewed by one or more Compliance Verification Engineer (CVE) that, depending on the subjects (for example structures or cabin safety) that the design involves, validates the work made by the design engineer. Each subject that is used in the design requires a CVE, that is an engineer certified by the regulation authority, to review the design [15].

Changes to aircrafts can be classified as either "minor" or "major" according to Subpart D of Part 21 [16]. If a project is classified as a minor change, the holder of a DOA has authority to approve the project without needing to obtain further approval from a regulation authority [16].

Regarding AM and its possible application on aircraft modifications, and using the Acceptable

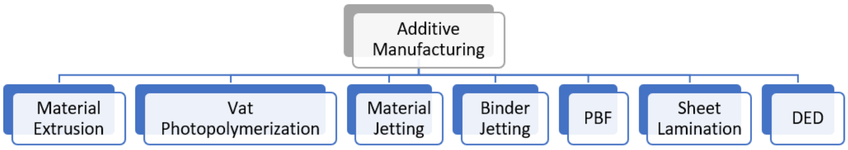

Figure 1: Additive Manufacturing technology classification [13].

Means of Compliance and Guidance Materials (AMCs and GMs) provided by EASA [18], it is complicated to classify a modification that uses AM processes as a 'minor change'. The possible applications that could be approved are if AM is used to manufacture parts that are secondary structural elements, parts that don't fall under the definition of primary structure, which is the structure that carries flight, ground, or pressurization loads, and whose failure would reduce the structural integrity of the aircraft [18]. Another interesting application would be for the creation of mock ups (prototypes to attest the functionality of a design) [15].

3.2. Production Organization Approval

OGMA also has privileges when it comes to the production of aeronautical parts, seen as though it holds a Production Organization Approval. These privileges state that the holder of a POA may perform production activities under Part 21, and issue airworthiness certificates to the parts produced [16].

To obtain this approval, an organization must, among other things, demonstrate that it has established and is able to maintain a quality system [16]. The organization must also have sufficient, certified and competent staff, as well as facilities with appropriate and controlled working conditions and environment and with the equipment and tools necessary to perform the production activities required [16] [18].

The production of parts at OGMA, and subsequently at a POA holder organization, follows a build-to-print philosophy, where the production engineering team receives the 3D CAD drawings or models from its client, generally the company responsible for the design of the part or a company that subcontracted the POA holder to manufacture a part [19]. It is based on these drawings/models that the production engineering team then creates the internal routings and work sheets that specify all the different procedures involved in creating the part [19].

OGMA has parts production in both metal and composite materials and is therefore important to understand the differences and similarities in the manufacturing processes of parts in these kinds of materials.

Metals

The logistical process of manufacturing metal parts is the one described previously (build-to-print). There are two main types of metal raw materials, when it comes to shape, that are worked at OGMA: metal sheets and blocks [19]. Parts that are made from metal blocks (for example, parts that contain ribs) are made using 5- or 3-axis Computer Numerical Control (CNC) machines [19]. To work with metal sheets, there is machinery and tools to manufacture through Hydroforming, Stamping, Bending, Welding and Cutting [19].

The production of a part through these traditional methods doesn't require a very intensive certification process because they are so well documented and studied that the outcome of using them is almost assured [19]. The only additional certification required is when methods considered 'special processes' are used, or in other words, processes that have fully controlled variables and still don't ensure the result is the same every time. Examples of special processes are heat treatments and chemical baths [19].

Composites

The production of composite parts also follows the build-to-print logistical process, which means the main differences arise when comparing the manufacturing processes.

The materials are kept in refrigerated storage rooms and spend limited and controlled time outside of them, are debited from the said storages and go through an automated cutting section for the composite sheet [19]. The production of parts is made in a room with a controlled environment when it comes to temperature, humidity and foreign particles, all with regular verification [19]. After being built, the composites are then sent to the curing stage in an oven or autoclave [19]. Then it undergoes the necessary post-processing stages and goes through quality control [19].

The main difference between metal and composite part production when it comes to certification is that the production of composite parts includes processes that are considered 'special processes' [19]. Because of this, further certification to ensure the capability to produce parts is necessary and OGMA undergoes regular audits for this purpose [19].

When it comes to additive manufacturing, it would be interesting that, as an introductory step, it was used to make tools for the production of parts, for example, as molds to give the desired shape to a metal sheet during forming or a composite during deposition [19].

3.3. Assembly

OGMA also manufactures sections of aircrafts like the central fuselage of the recent Embraer KC-390 military transport aircraft [20] and as such requires an assembly area [21].

AM can produce more geometrically complex parts that traditional manufacturing methods can't achieve without the use of multiple parts and assembly [12]. This means that the use of assembly lines to produce parts could be severely reduced by using AM processes. It also means that, in the case that AM is used to manufacture a part that will be featured in a more complex assembly, the tolerancing provided by the machine used must meet the assembly's requirements.

4. Additive Manufacturing implementation

It has been proposed through history [22] [23] that innovation in production technology can be used as a powerful competitive weapon and that technology is perhaps the most important single source of major market share changes among competitors and is the prominent cause of the demise of an otherwise solid and dominant firm. This section studies the implementation of AM at OGMA.

AM implementation framework

Mellor et al. [3] put forward a conceptual AM implementation framework. The framework proposes that both external forces and internal strategy incite companies to consider AM as a means for manufacture and that the implementation of AM will be influenced by factors that can be put together in five groups: strategic, technological, organizational, operational and supply chain factors [3].

Strategic factors dictate that the implementation must be preceded by strategic alignment of the business, manufacturing and R&D strategy [3].

Although the ability to link the technology benefits to the business strategy is of high importance, it is equally important to understand the inherent technological factors, the trade-offs of using this new manufacturing technology [3].

Previous study into new manufacturing technology suggests that the structure of an organization is the key factor within the organizational factors umbrella [3]. It is also suggested that the largest but unknown impact could be on company culture and how it changes to accommodate rapid manufacturing [3].

Operational factors encompass all the changes to the operational structure brought forth by the change in an organizations technology [3].

There are also supply chain factors to take into consideration. AM implementation stands between two supply chains: the first one from the machine vendors to the purchaser of the technology and the second one in which the purchasers will embed the technology in their respective supply chain and consequently influence their customers and suppliers [3].

Overall, the success parameters for the implementation and resulting changes suggested by other authors [24] are contemplated in the framework suggested by Mellor et al. so, although this work will follow Mellor's framework more closely, the parameters suggested by these other authors will also be taken into consideration.

4.1. Possible applications

The possible applications for additive manufacturing at OGMA presented were found when the topic was discussed with the organization's engineers [15] [19]. As seen, OGMA works in aircraft maintenance, design and modification, and in aeronautical parts manufacturing. This leads to three major production areas in which AM processes could have an impact: parts production [15], tooling [19] and prototyping [15].

Parts

Perhaps the most interesting and simultaneously challenging application for AM is the production of parts to be directly incorporated in an aircraft. When taking modifications into consideration, as seen before, it's complicated to classify a part manufactured through AM processes as 'minor change' if it has an appreciable effect on the primary structure of the aircraft [18]. This means that in order for AM parts to be more easily certified, the available scope of parts is reduced to parts considered as secondary structural elements. Parts which have a high geometric complexity and that would otherwise be made from an assembly of smaller and simpler parts are also one of the possible applications of AM. There's also the possibility of AM being used for decorative parts, manufactured with a focus on their design to be aesthetically pleasing, to be incorporated in executive aircrafts.

Tooling

Another interesting application of AM processes would be for the creation of tools to aide in the traditional manufacturing methods [19] through, for example, molds manufactured by AM processes. Overall, tooling certification is not very restrictive. The tool must generate a part as per the specifications intended by the client. Tools are usually designed according to the needs of the project and afterwards are approved through a First Part Qualification (FPQ) test that verifies if the manufacturing process, inspection techniques and the final part properties are in accordance to the design requirements.

Prototyping

In OGMA, the creation of mock-ups, i.e., functional prototypes that most likely can't be flown and allow designers to test the functionality or fit of the part to be created, would see no restriction when it comes to certification making it a valuable application. In some cases, prototypes are requested from the final part manufacturer, meaning a high cost to test the validity of a design, as well as a time constraint due to the waiting times involved in both manufacturing and shipping an outsourced prototype. This make AM a useful design tool that would shorten design to production time and the necessary process steps.

For both tooling and parts manufacturing, it is important, certification wise, that the system chosen provides a repeatable and reliable process. Repeatability translates to an easier time certifying the manufacturing process of a part/tool.

4.2. Market survey

Nowadays there is already a large offer of 3D printing machines and materials, both the home printer kind of machines and the more industrial kinds. As a first step to narrow down the number of options to choose from, it was necessary to make selection between the different kinds of printing technology the machines use before considering the different printers and materials. Taking into account the classification method described above and illustrated in Figure 1, it was found that some of the classes are the topic of published research more often than others.

In the end, three out of the seven types of technology were chosen based on the availability of the technologies, the history of AM and the amount of research being made on these technologies: Material Extrusion, Vat Photopolymerization and PBF.

After choosing from the different types of technology, the next step was to search for companies that produced machines and materials for additive manufacturing. Since OGMA is more interested in plastic material additive manufacturing [15] [17], the survey was more focused in companies that had machines to print in plastic materials. Having this in mind and after looking into the different companies, three of them were selected: Stratasys, 3D Systems and EOS. These companies represented varied means of production and materials and are among the biggest producers of additive manufacturing technology [25] [26].

Stratasys

When looking at the different lines of Stratasys printers, the one that best provides solutions for the problem at hand is the Production Series, which offers the most interesting combinations of machines and materials and is specifically tailored for the manufacturing environment [27].

The main differences between the printers of the Production line are mainly the build volume and the materials that they can work in [27]. Without analyzing the materials available to these printers, the final use that the printer will have will determine if and which of these will be chosen, because it may not be necessary to have a larger build volume if only small jigs and fixtures are to be manufactured.

Of the materials available, the ULTEM family is of particular interest because both ULTEM 1010 and ULTEM 9085 have FAA certification according to 14 CFR/FAR 25.853 for flammability, smoke and toxicity [27]. This means that if parts were to be made with these materials, they would require less steps to be ready for flight, basically reducing the certification process that OGMA must do, for parts produced by additive manufacturing, to the certification of the design and the production process.

EOS

EOS has printers to work both plastic and metal materials, both employing PBF processes to manufacture parts. For both types of materials, this company offers systems that range from an entry level to additive manufacturing, to the production of parts for industrial manufacturing or for processing high performance polymers [28] but, considering OGMA's interest in additive manufacturing of parts in plastic materials, printers that manufactured metal parts were not considered.

The main differences between the EOS printers is build volume, the materials available to them and the building speed [28] meaning different printers would allow for parts built in different materials and concluded in different time-frames.

EOS, like Stratasys, also has a material that was certified by aeronautic regulators (HT-23 from Advanced Laser Solutions [29]) and also has materials that passed tests that could easily lead to certification(EOS Peek HP3, PA 2210 FR and PA 2241 FR [28]).

3D Systems

Regarding 3D Systems' solutions, like EOS, it also offers additive manufacturing of plastic and metal materials. For the manufacturing of plastic materials, 3D Systems presents printers based on three types of technology: Multijet, SLA and SLS [30]. The Multijet technology from 3D Systems is classified as a Material Jetting technology and, because it doesn't fit under the classes chosen to be studied, it isn't going to be considered.

Despite the variety of materials available to SLA, none were conceived towards aerospace applications [30] so this technology was not considered.

In regards to SLS, there are some materials provided by 3D Systems that are tailored towards aerospace applications and specific printers to transform the powdered material into parts [30]. Once again, the main differences between printers is build volume, the building speed and the materials available [30] but, the materials 3D Systems provides don't have the same flammability rating (UL 94 HB) as the materials presented by Stratasys and EOS (UL 94 V-0) [30]. This gives the materials provided by Stratasys and EOS an easier certification process, which in turn provides a faster implementation.

4.3. Implementation Roadmap

4.3.1 Technology Roadmapping

In terms of intended purpose, there have been eight types of roadmaps [31]: product planning, Service/capability planning, strategic planning, long-range planning, knowledge asset planning, program planning, process planning and Integration planning. There have also been identified 8 types of roadmaps when it comes to format: multiple layers, bars, tables, graphs, pictorial representations, flow charts, single layer and text [31].

A successful roadmap contains a clear statement of the desired outcome followed by a specific pathway to achieve it. This pathway should include the following components [32]: goals, milestones, gaps and barriers, action items and priority time lines.

If designed correctly, a successful roadmap should provide the ability to link any project or activity through this logical structure and demonstrate how it contributes towards achieving the goals [32].

4.3.2 Roadmap for the implementation of AM at OGMA

Considering all that was presented up until now, this section includes the roadmap that illustrates the steps for a successful implementation of additive manufacturing at OGMA. This will be achieved when OGMA is capable of manufacturing parts, tools and/or prototypes through AM processes for either internal use or to market to interested clients. Figure 2 is the graphical representation of this roadmap.

Strategy

As of now, AM is a growing sector in manufacturing technologies that has the capability of creating new business opportunities by bringing new capabilities to OGMA's production lines and, the implementation of AM at this company can be seen as technology push business strategy. The business strategy can therefore be seen as the basis for the implementation. In the future, when AM is successfully integrated in OGMA, the strategy can switch to more of a market pull oriented business strategy, where client's requirements would be fulfilled by having AM at the disposal of the manufacturing unit.

Organizational preparation

After establishing the strategy it is important to understand the state at which OGMA is at, in terms of manufacturing capabilities, and what the market has to offer to the organization to improve or add to these capabilities. This means studying the different application possibilities that the technology has, like prototyping, tooling and parts production, while performing a market study to look for solutions that allow for those applications.

Afterwards, it is necessary to perform a deep cost analysis. Despite all the possibilities AM can bring, the technology is still expensive and it might not be cost-effective to use it. High-volume and low-complexity parts are still more cost-effective to manufacture through conventional methods [26].

The final part of the preparation is the selection and purchase of a system for AM, and ties in with the next stage of the reforms needed to ensure a successful implementation.

Organizational reform

At this stage, OGMA will have to go through a phase of preparation in order to properly accommodate the selected system.

Another phase that OGMA would need to go through and that's considered to be of high importance [3] [24] will be the training and/or hiring of workers.

The final phase of the the reform stage will be the certification process. At this phase, the whole process of manufacturing a part or tool will have to be certified and a solid quality control system must be implemented as well.

During this stage, the collaboration and support from the technology supplier will be a critical factor for success [3]. It will be a great assistance especially in training employees by, for example, providing workshops catered to the specific needs of different jobs (design engineers, production personnel).

Application

After the certification process is finalized, OGMA will be fit to manufacture and sell AM products.

In order to further cement AM as a viable manufacturing process, OGMA will then have to seek out new business opportunities by making new clients or by proposing to existing clients the possibility of AM for the projects OGMA is hired to do.

In time, when AM is successfully implemented and OGMA as established itself as an organization capable of providing quality AM produced parts, the business strategy may shift to a market pull oriented one, where the technology's benefits correspond to the requirements imposed to the manufacturing unit.

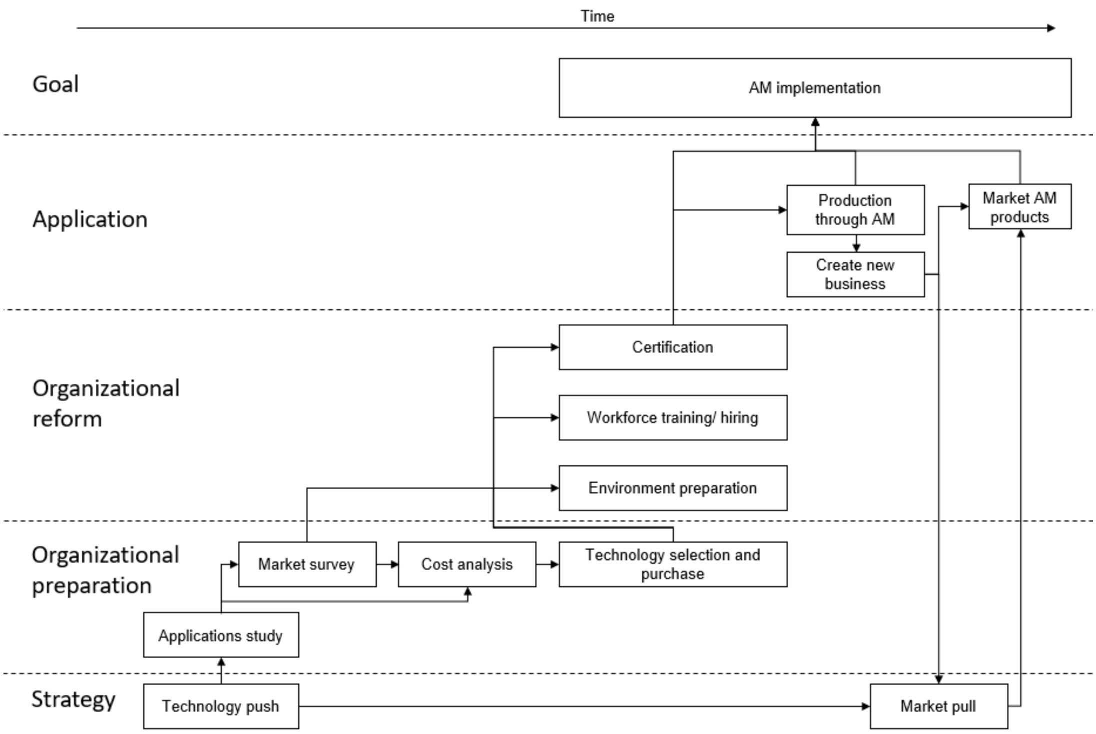

Figure 2: Implementation Roadmap

5. Case Study

As a way to better understand the impact additive manufacturing can have at OGMA, a case study was performed that compares the time necessary and the costs involved in the additive manufacturing of a part that would usually be produced trough the traditional manufacturing methods employed at OGMA.

5.1. Part studied

For this case study, the part analyzed is not the exact part manufactured by OGMA. Instead, parts that served as example for the part manufactured by OGMA will serve as the basis for this study [15]. Figure 3 shows one of the examples used by OGMA to design and manufacture this part.

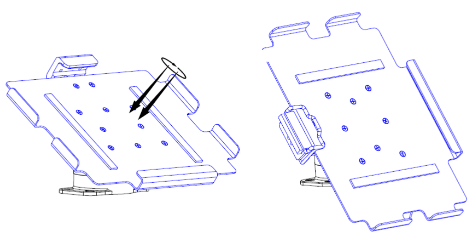

Figure 3: Drawing of one tablet holder [15].

Seen as though the part was made to support different models of Apple's iPad, using the dimensions of the Apple iPad Air 2 (selected at random between the supported models) of 240 mm×169,5 mm×6,1 mm and the support model from figure 3 to reverse-engineer the part, a simplified CAD model was designed.

5.2. Manufacturing at OGMA

A quotation was asked of OGMA and it was estimated that the in-house production of this part would cost between 1300 and 1500 EUR [17].

5.3. Manufacturing through AM processes

For an estimation of the cost of manufacturing this part through AM processes, an evaluation model was selected to better estimate this value [33]. This model was adapted to calculate for AM processes in general considering the material cost, the processing cost and the pre- and post-processing costs.

The material cost per part is calculated by taking into account the material cost and the material used for the model and the supports needed [33].

Processing costs are calculated taking into account the cost of the machine, the maximum time usage for the machine and it's building speed. Since the price of these printers hasn't gone down in the years it's been on the market [34], it was considered that the cost of the machine was divided by a 10 year useful life in order to estimate the yearly cost of the machines. It was considered a utilization of 6000 hours per year since these machines are built to be printing 24 hours a day for a whole year, apart from the time dedicated to maintenance, accounting for a utilization of around 70% [34]. The build time is obtained using an auxiliary 3D printing software (GrabCAD Print).

Pre-processing consists of setting up the machine and post-processing of cleaning the part, support removal and treatments the part may require (like painting and assembly), and are the only time the process requires labor.

The machines selected for this cost analysis was the Stratasys Fortus 450mc and Fortus 900mc, and the materials selected were the ULTEM family of 9085 and 1010.

Table 1 lists the costs of the different printers and materials, as well as the extra costs incurred in the purchase of these machines, as commercialized by CODI, a company specialized in additive manufacturing and rapid prototyping solutions and a representative of Stratasys in Portugal [34]. The prices provided by CODI for the machines include 4 building material cannisters and 4 support material cannisters and, as a naive method to obtain the price for the printers alone, the average price of the 4 materials considered was subtracted from the price provided. Both the building and the support materials have the same price.

Table 1: Prices of Stratasys products [34].

Printer related prices (EUR)	
Fortus 450mc 135.5k	Fortus 900mc 455.0k
Installation, calibration and training service	6.8k
Three-phase transformer	1.2k
Maintenance contract	2.8k
Material price per cannister (EUR)	
ULTEM 9085	Certified ULTEM 9085
731	923
ULTEM 1010	ULTEM 1010 certificate grade
668	769

For the cost per part estimation, the prices of the services needed and of the three-phase transformer were added to the cost of the machines.

Table 2 demonstrates the contribution of each term to the total cost per part.

As shown, for the part studied, the selected AM process with the corresponding printers and materials give an estimated cost per part much more appealing. The transition of the production of this part from traditional methods to AM would represent a decrease in cost between 74 and 84%.

It is necessary to remember this cost estimation is made taking into account that the printers would be working nearly 70% of the year which could prove unrealistic. It also doesn't take into account the electric power spent manufacturing the parts.

This cost estimation is also made only taking into account one specific part that wasn't redesigned to better fit the capabilities that AM has and could possibly be optimized to use less material.

6. Conclusions

The state-of-the-art of AM technologies shows that manufacturing parts to be incorporated almost directly into aircrafts is possible through the use of AM processes.

From OGMA's standpoint, AM can have interesting and promising applications in the production of parts, tooling and as a prototyping tool. There are also market solutions that can offer OGMA the added capabilities of AM tech.

This leads to the roadmap designed during this work that illustrates the different phases necessary for a successful implementation of AM at OGMA, shown in figure 2.

The case study shows that for the part studied and under the conditions established, the transition from traditional manufacturing processes to AM would result in a cost decrease between 74 and 84%.

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A. Appendix

Table 2: Evaluation model of part cost for AM with Stratasys solutions.

Number of parts produced per job	1				
		ULTEM 9085	ULTEM 9085 certified for aerospace use	ULTEM 1010	ULTEM 1010 certificate grade
Material cost	(EUR/cm^3)	0.484	0.611	0.442	0.509
Part volume	(cm^3)				
	Fortus 450mc:	389.516 (360.101 of building material + 29.415 of support)			
	Fortus 900mc:	330.19 (297.841 of building material + 32.349 of support)			
Material cost per part	*(EUR)*				
	Fortus 450mc:	188.53	237.99	172.17	198.26
	Fortus 900mc:	159.81	201.15	145.94	168.07
Labor	(EUR/h)	20 [33]			
Set-up time per build	(h)	0.5			
Pre-processing cost per part	*(EUR)*	10			
		Fortus 450mc		Fortus 900mc	
Machine cost per year	(EUR/year)	14620.823		46567.859	
Hours per year	(h/year)	6000			
Machine cost per hour	(EUR/h)	2.437		7.761	
Build time	(h)	13.4		12.7	
Machine cost per build	(EUR)	32.66		98.56	
Processing cost per part	*(EUR)*	32.66		98.56	
Labor	(EUR/h)	20 [33]			
Post-processing time per build	(h)	1 [34]			
Aditional Post-processing costs	(EUR)	0			
Post-processing cost per part	*(EUR)*	20			
Total cost per part	**(EUR)**	ULTEM 9085	ULTEM 9085 certified for aerospace use	ULTEM 1010	ULTEM 1010 certificate grade
	Fortus 450mc:	251.19	300.65	234.83	260.92
	Fortus 900mc:	288.37	329.71	274.50	296.63