Comparison of process performance of Additive Manufacturing FRTP in a lifecycle perspective for aerospace application

Diogo Rodrigues
diogo.carvalho.rodrigues@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

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Abstract

Additive manufacturing (AM) has recently been in the spotlight regarding the aerospace industry. The possibility of improving critical aspects such as weight, complex designs or material corrosion has led some manufacturers into spending some time and resources into the development of this technology, formerly used almost only in the prototyping industry, with the objective of making end use parts. This thesis focuses on the design and production of a leaf-type spring landing gear for a UAV, using an AM process known as Fused Deposition Modeling (FDM), to produce a Fiber Reinforced Thermoplastic (FRTP) component. The main objective is to develop an FRTP part by FDM from its original design while respecting the initial functional requirements i.e., the ability to sustain the landing loads. This process of design takes in account the limitations of the 3D printer, the 3D printer software and the material properties. The part will be compared with a traditional part, in this case an aluminum part manufactured by CNC Milling, a subtractive production process. For that purpose, all the required data from Milling and FDM production technology will be collected and a comparison established. The collected data includes the time of production, energy consumption, amount of material used, among others, and it will be used to develop a cost model and an environmental impact model. The life cycle costing (LCC) objective is to determine the unitary cost of one part, for the two distinct production methods, and to compare them, to understand if it is viable to produce this component using a 3D printer instead of CNC Milling, that is more implemented in the industry. Finally, it is made a life cycle assessment (LCA) to evaluate the environmental impact of both technologies for this particular component. This analysis was made using an LCA software. It was concluded that the component produced in aluminum by CNC Milling is better comparing the mass and volume of the part and has significantly lower production costs. It was also concluded that the environmental impact is lower for the FRTP part produced by AM FDM.
Keywords: Additive Manufacturing (AM), Fiber Reinforced Thermoplastics, Landing Gear, Life Cycle Costing (LCC), Life Cycle Assessment (LCA)

1. Introduction

In a world were sustainability is becoming a key word in economy, environment and society everyone is always trying to optimize existing procedures and technologies or creating new ones [1]. Additive Manufacturing (AM) is a manufacturing technology that consists in adding material layer upon layer, instead of removing the material, to obtain the desired part. This technology has advantages and disadvantages compared to other technologies. One example of AM advantages is the ability to manufacture components with complex internal geometries, mass personalization, and low material waste. The main disadvantages are the long manufacturing time, and the small production volumes possible. The AM process used in this thesis is Fused Deposition Modeling (FDM) that consists on extruding melted material trough a heated nozzle. The material is deposed layer by layer until the final component is formed. The main goal of this thesis is to develop a FRTP part produced by AM FDM and compare it to an aluminum part produced by CNC Machining, a subtractive production method. The parts and processes will be compared in terms of mechanical performance, production costs and environmental impact. The chosen part to be compared is an UAV (Unmanned Aerial Vehicle) landing gear and it must meet the same mechanical requirements with both materials. The process of designing the FRTP landing gear is an iterative process, because of the lack of tools to analyze the behavior of parts made with this material. The goal is to respect the initial requirements, the ability to support the landing loads, while exploring the possible aspects where the design could be altered for FDM, while trying to keep the volume and mass of the part as low as possible. This process is influenced by the 3D printer and its software restrictions and also by the cost of the fibers used to reinforce the part. After obtaining the best design a Life Cycle Costing (LCC) model was developed to understand which part is more expensive. In this model it is considered a cradle-to-gate assessment, which is an assessment of a partial product life cycle from resource extraction to the factory gate. Because of the lack of data, it was excluded from the model the use phase and the disposal phase. So, it was determined the unitary cost of a FRTP and an Aluminum part. A Life Cycle Assessment (LCA) model is also developed to determine which component has the higher impact on the environment. Unlike the LCC model, in the LCA it was considered a cradle-to-grave assessment, taking in account the impact of the use phase and the disposal phase. Finally, the aluminum part and the FRTP part are compared in terms of mass, volume, costs and environmental impact. The drawbacks and difficulties of this particular AM process, FDM, and equipment are mentioned. It was also explored the possible aspects where the design could be improved, if the materials used explore the full capabilities of the design and some points where the AM equipment and its software can improve. Future work is proposed to complement subjects present on this thesis and to explore some points that were not possible to address here.

2. Bibliographic Research

In the case study ahead, a comparison between a component produced in aluminum by CNC Milling and other in FRTP by FDM will be made. This comparison is focused on the mechanical characteristics, a cost analysis and a environmental analysis.

2.1. Additive Manufacturing (AM)

Additive Manufacturing is a manufacturing process that starts from a 3D model data and the designed part is formed by adding layer upon layer until the part is completed and the production is finished. Contrary to the more traditional production methods, subtractive methods, the main difference is that with AM the part is formed without material waste.[2].

AM processes main applications are prototyping and personal users (3D home printers), but nowadays it is gaining space in industry production. The improvement of AM technologies is increasing its use by companies to produce components [3]. AM can be used to produce models, prototypes, end use parts, assemblies or even tooling. AM can be used to produced parts alongside other production methods, by alternating printing and machining operations. For example, it is possible to print embedded components, which consists on one component of another material being inserted in the AM part during production [4]. This component is considered in the design of the part and in the printer software, so that the printing is optimized to accommodate the new material. In some processes, the printing can be interrupted in order to insert a material and then the printing is restarted. The flexibility of materials and procedures around AM technologies allow the production of complex shapes and designs using a wide variety of materials. AM parts have a large number of materials available that can be used in their production, from metals as aluminum or steel alloys, to plastics or even edible materials as chocolate or sugar [4][5]. One important branch of 3D printing is the polymer based low-cost 3D printers that allowed the general public to express creativity and produce its own parts as a hobby at their own home. This technology has been improving in quality and the prices are expected to drop in the near future, allowing the 3D printing market to grow even more among common users [5]. This technology applications cover a large range of industries such as automotive, aerospace, medical prosthetics, tools production, electronic components, jewelry, furniture, sports equipment and numerous other areas.

2.2. Fused Deposition Modeling (FDM)

Fused Deposition Modeling (FDM) is an additive manufacturing process which consists on extruding the material through a nozzle that also melts it. The extruded material is deposited in the print bed (base) that moves up and down allowing the layered production. This process is one of the most used within the AM technology [6].

The more common materials used with this process are thermoplastics, that are polymers which main characteristic is that after it has been heated it becomes moldable, but when it's cooled it solidifies. Some examples of these materials are ABS (Acrylonitrile Butadiene Styrene), Nylon, Polyethylene among others. These materials have relatively low strength, so, to improve this feature, it was introduced fibers in the process, such as glass fiber or carbon fiber. The resulting material is a Fiber reinforced thermoplastic (FRTP), a composite material, that combines the fiber and the thermoplastics improving the properties that both materials have by themselves.

The machine used in the case study is the Markforged Mark II, that is the first commercial available 3D printer that is able to print Fiber Reinforced

Thermoplastics, using the FDM process.

2.3. CNC Milling

As opposed to additive manufacturing, subtractive manufacturing consists in successively cutting material from a solid block of material until a 3D part is obtained. This process can be done manually, but nowadays is typically done with a CNC machine. CNC stands for computer numerical control and is the automation of machine tools that are usually manual operated. It includes any type of machining (Drilling, Milling, Water-jet, laser, etc), as long as the process is automated and controlled by computer. Milling is a machining process that uses rotary cutting tools to remove material from the initial solid block. Unlike drilling where the rotary tool only moves along the rotation axis, in milling the rotary tool can also move perpendicularly to this axis, so, the cutting occurs with the side of the cutting tool.

3. Methodology

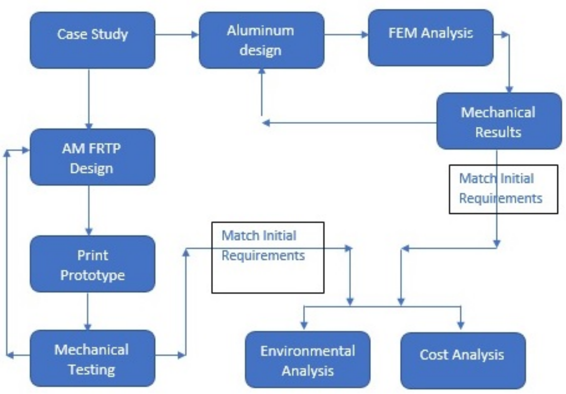

Figure 1: Case Study Methodology Diagram

The methodology for the case study, where a comparison will be made between a component produced in aluminum by CNC Milling and in FRTP by FDM, is present in the diagram of Figure 1. It starts with the aluminum design which has a set of reference values of displacement and load to achieve. This design is analyzed with a FEM software and the results are compared with the initial requirements. If they don't match the part has to be redesigned. If they match, the results will be used to perform an environmental and cost analysis.

3.1. Mechanical Properties

The mechanical test performed meant to replicate the vertical loads applied on the landing gear when landing. In Figure 2 it is possible to see that the lower section of the part is fixed with a bolt, not allowing any movement. This section, that is bolted, is the connection to the aircraft, while the upper section, where the force is applied from top to bottom, corresponds to the wheel connection. Because the objective is to compare the FRTP part with the aluminum one, the load setup is the same used in the FEM simulation made for the aluminum part.

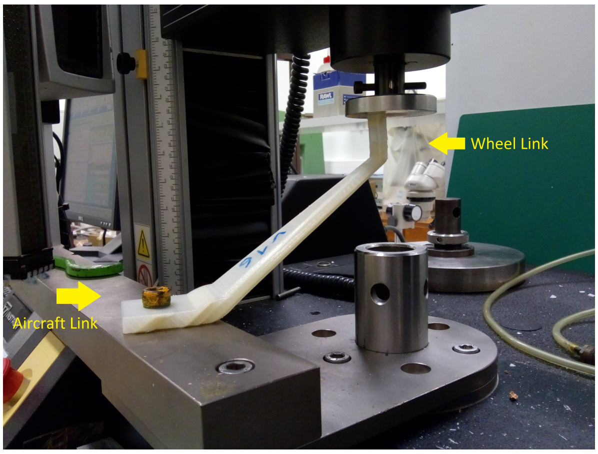

Figure 2: Mechanical Test

With this setup, the load applied is increasing gradually and at the same time the displacement is measured. So, we can determine what loads are applied in the range of displacement defined and compare them to the loads the aluminum part endures within the same displacement range.

3.2. Life Cycle Costing (LCC)

Machine Cost: The machine cost of the Markforged Mark II is calculated based on Equation 1, considering annual cost of the equipment and the annual productive hours.

$$C_{eq} = C_{aq.eq}\left[\frac{i(1+i)^n}{(1+i)^n-1}\right]\frac{1}{d_{year}h_{day}}h_{unit} \tag{1}$$

C_{eq} is the cost of the equipment that we want to calculate, $C_{aq.eq}$ is the cost of acquisition of the machine, i is the opportunity cost, n is the depreciation time in years, d_{year} is the productive days of the year, h_{day} is the productive hours of the day and h_{unit} is the hours of production of one unit.

Energy Cost: The energy cost is calculated by simply multiplying the value of the cost of the energy per KWh by the Energy used by each machine, as in Equation 2.

$$C_{energy} = C_{KWh}E_{used} \tag{2}$$

Labor Cost: The labor costs for the Markforged mark II are calculated using Equation 3, in which the first term is the hourly cost of a worker to the company and the second term is the hours the workers spend with the production of one part, resulting in the cost of labor per unit. It will be considered both specialized and not specialized workers, so this equation needs to be calculated for each type of worker and the final value is the sum of the two.

$$C_{labor} = \frac{S_{month} N_{sal} C_{soc} + 11 A_{lunch}}{d_{year} h_{day} f_p} h_{work} \quad (3)$$

S_{month} is the salary of the worker per month and h_{work} is the time in hours spent by one worker to produce one piece (note that despite the time of production of one piece being more than 11 hours, as the system is automatic, the workers are not 100% dedicated to the part the whole time), and both are different if the worker is specialized or not. N_{sal} is the number of salaries per year including vacations salaries. C_{soc} is the social contribution the company makes for each employee. d_{year} is the working days in a year. h_{day} is the working hours per day. f_p is a factor of productivity. A_{lunch} is the lunch allowance.

Finishing Cost: After printing, the parts are not yet ready to be used, needing some post processing. In the case of the aluminum part, first it needs a rotary tool to remove shavings and excess material. Then the part is sanded to provide a smoother surface and prepare for painting. Later, the part is painted providing an extra protection and an improvement in aesthetics. Finally, is applied an UV coat for protection. In the case of the FRTP part, the post processing consists in removing the support material. Because this part is not prone to corrosion and the final color of the part can be determined by the material used in the printing process, for this part the preparation for painting and painting costs are not applied. The costs for the FRTP part are calculated for each process, by dividing the cost of purchase of the tool by the number of parts that one tool can produce.

$$C_{finishing} = \frac{C_{rot}}{N_{units}} + \frac{C_{sand}}{N_{units}} + \frac{C_{UV}}{N_{units}} + \frac{C_{paint}}{N_{units}} \quad (4)$$

3.3. Life Cycle Assessment (LCA)

A life cycle assessment was made for this work case study using the software Simapro developed by Pré Sustainability.

The goal of the study is to assess the environmental impact of the production of two components with the same function and similar characteristics but produced in two different materials each using a different production process. The component is a leaf-type spring gear that is produced in FRTP (nylon and fiberglass) by FDM and is going to be compared to another one produced in Aluminum by CNC Milling.

For this study the functional unit was defined as one part (leaf-type spring gear) produced. In the case study, the reference flow are 500 parts. This number is, as used before in the LCC, obtained by considering a low-scale production of 100 parts a year for a period of 5 years.

In the case study it is used a “cradle to grave” approach, that is defined as an assessment from the resource extraction to the disposal phase. This approach was considered rather than the cradle to gate approach, because the component analyzed in the case study is part of an aircraft, thus it is important to consider the use phase of this component because it may have implications in the energy (fuel consumption) used by the aircraft as a result of the component final weight.

In Figure 3 and in Figure 4, are present the flowcharts for the CNC Milling process and the AM FDM process respectively.

Assumptions: The first assumption is that the suppliers of both aluminum, fiberglass and nylon would be within a range of 100 Kilometers of the production facilities, so the transport of the raw materials used to produce the parts is considered to be 100 Km. To measure the impact that the weight of the part has in the fuel consumption of the aircraft it will equip over the period of use, it is considered that the part has a life of 5 years and that the aircraft flies 10 000 Km per year. Fiber reinforced thermoplastics recycling is not yet a common practice. Usually these materials are disposed into landfills. Although many studies regarding the recycling of FRTP have been made, currently it is not economically attractive to opt for this process. However, environmental legislation is becoming more restrictive over the time, so, the recycling of these composites may become a reality in the future. In this case study, it is considered that the FRTP landing gear is disposed into a municipal landfill. The method of disposal chosen for the Aluminum part, in this case study, is recycling. Recycling is considered not only for the aluminum landing gear, but also for the aluminum scraps originated from the CNC Milling, resulting in a 100% rate of recycling of the original material. In this process it is considered the amount of energy used in the recycling.

4. Case Study

4.1. Restrictions and requirements

The first restriction is related to the equipment available to manufacture the AM part, the dimensions of the part should be within the printing area of the Markforged Mark II. With the purpose of establishing a relevant comparison the chosen part should meet some requirements, such as: The part should be a structural part, meaning that it should be a part essential to the aircraft operation and should support considerable loads. This is an important requirement because one of the FRTP

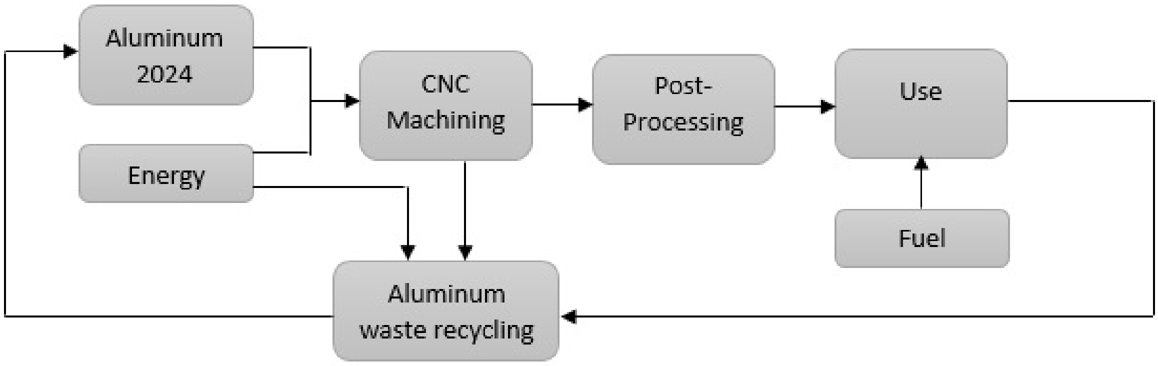

Figure 3: CNC flowchart

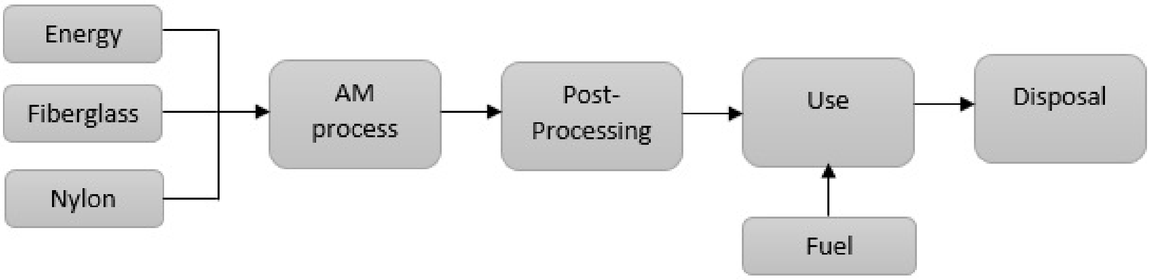

Figure 4: AM FDM flowchart

main characteristics is to have high mechanical resistance, so it will enable the AM part to achieve its full capabilities; The production scale should be small, as the rate of production of current state of the art technology in 3D printing is low. It is important to compare two parts that have similar production scale at the present time, despite what evolution will the AM technology experience; The part should be customizable, this means it should be chosen a part whose design could be altered, to improve the part performance, appearance or cost even if for certain parts, it is very difficult to alter the design because of the adjacent parts, or because of the already simplified designs.

Figure 5: Leaf-type spring gear

4.2. Landing Gear Type and Characteristics

The part to be compared in the case study is the main component of a Leaf-type spring gear.

A Leaf-type spring gear, shown in Figure 5, is a type of landing gear that equips many smaller aircrafts such as the broadly used Cessna airplanes. This type of landing gear consists on a strut that receives and dissipates the impact of the landing by transferring the impact forces to the airframe at a smaller rate than the Fixed Landing Gear. This dissipation of the impact forces is obtained because the part flexes when the forces are applied and then it returns to the original position. This type of landing gear is usually made of steel or aluminum, and sometimes is also made of composite materials that are light weight, more flexible and prevent corrosion [7].

The component of the leaf-type spring gear that is going to be studied in this work can be seen in Figure 6, pointed at with the red arrow.

Due to the restrictions of the available 3D printer dimensions, it is not possible to study a full-scale part that could be used on a passengers airplane. So, the part was down-scaled, maintaining the proportions and mechanical characteristics, with the possibility of being used in smaller aircraft like an Unmanned Aerial Vehicle (UAV), because leaf-type spring gear is commonly used in UAVs [8].

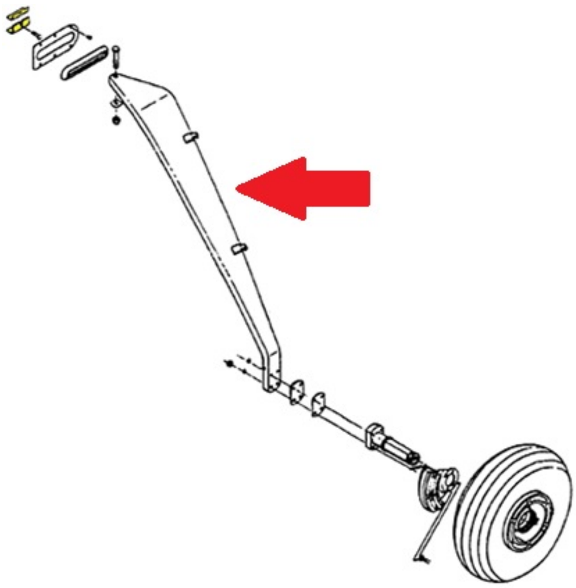

Figure 6: Leaf-type spring gear 2

So, after selecting the part to be analyzed in the case study, the leaf-type spring gear belonging to a small size UAV, it was decided that the UAV would have a Maximum Take Off Weight (MTOW) of 17.5 Kg. The landing gear meant to be compared is expensive and not easy to obtain, so because of the difficulty to obtain an aluminum landing gear and test it, this part was designed with a 3D CAD software (Solidworks) and tested with a Finite Elements Method Software (Siemens NX), that usually obtains an approximation of the mechanical properties and behavior of the part formed by an isotropic metal with a relatively low error [8]. FEM is used by major established industries such as aerospace, automobile, electronics, among others to aid design and manufacturing [8] [9].

Using as reference for a hard landing an acceleration of 1.27g [10]. We can calculate the vertical landing force. The tire is a part of the landing system that also absorbs energy and decreases the stress inflicted on the landing gear leg. In order to decrease the complexity of the system in study, the tire effects are not considered. Usually a safety factor is considered when studying an aircraft structure, but because this is an unmanned aircraft and to compensate for the absence of the tire influence in the system, no safety factor is considered.

$$F = m[Kg] \cdot a[\frac{m}{s^2}] = m \cdot g \cdot 1.27 = 218N \quad (5)$$

Using Equation 5 we multiply the mass of the aircraft by the acceleration (a=9.81 m/s2). We are going to test only one side of the landing gear that is formed by 2 symmetric legs, assuming the plane touches the ground with both wheels ate the same time, we can divide this force by 2 and obtain a vertical landing force of 109N.

4.3. Design Evolution

As this work evolved it was perceptible that the design was one of the most important points in the process of making a 3D printed part. This is not only because of the changes in the original design to improve costs, performance or aesthetics, but also the changes needed because of the machine and its software settings and capabilities.

In this sub-chapter it is going to be shown the evolution of the part design starting from the design of Figure 6, that is the design of a Cessna's landing gear. Then, by an iterative process the aluminum design was obtained. And from that, the design evolved to comply with AM FRTP. This evolution of the design is mainly based on 3 factors: part requirements, 3D printing machine restrictions and design improvement over original part. The initial aluminum design is iteratively designed and tested to withstand the vertical load caused by the landing of an aircraft with the pretended MTOW. The work goal is to achieve a similar part, that can replace the original steel or aluminum part, that matches its performance while trying to improve some characteristics such as weight, volume, cost.

Aluminum Design:

In the aerospace industry the most predominant aluminum alloys are 2024-T3 and 7075-T6 [11] [12]. For this case study the aluminum part is considered to be from 2024-T3 aluminum alloy.

The first design considered was the original design (Figure 6), it was replicated and analyzed with the FEM software. The maximum Von Mises Stress obtained was 318 Mpa (MegaPascal), very close to the yield stress of 324 MPa. This may indicate that the part is operating very close to its limit. So, the part needed to be redesigned.

With the second design it was achieved a better maximum stress and a better displacement. But, the main gains were in the volume and mass of the part that were reduced.This mass and volume improvement is very important to the aircraft operation.

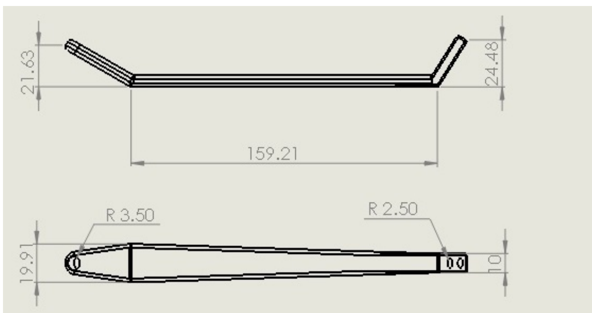

Figure 7: Second Design Dimensions

In the second design, in Figure 7, the thickness was increased and the width was reduced progressively from the aircraft link to the wheel link. As a consequence of this process it was impossible to maintain the four holes configuration in the wheel link, so it was reduced to only two bigger holes.

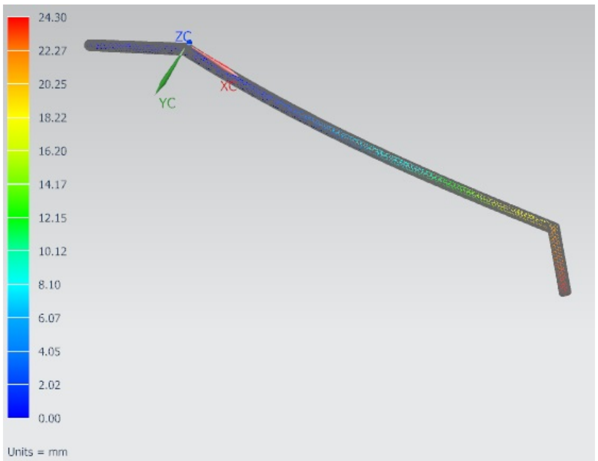

Figure 8: Aluminum part displacement

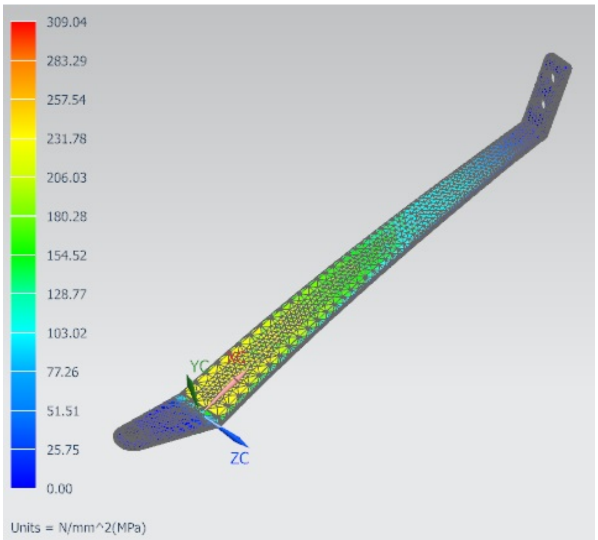

Figure 9: Aluminum part streesses

So, with an applied load of 109N, the maximum Von Mises Stress dropped from 318 MPa to 309 MPa (Figure 9), pulling this result away from the 324 MPa of the yield stress. The maximum displacement obtained (Figure 8) is 24.30 mm similar to other results of the literature [8] [11], where displacement is within a range of 20mm and 30mm.

This second design meets all the requirements established (Load, displacement, stresses) and also shows improvement in the part properties, so this is defined as the aluminum part design that will be used as base of comparison for the AM FRTP part.

FRTP Design:

This aluminum design was sliced with Eiger software, the Markforged software, that allows the user to determine which layer is fiber and which is nylon. With this software, the fiber placement, the part layout for printing, the amount of fiber in each layer and the type of fiber distribution in each layer can be personalized to obtain the best configuration and characteristics possible for the part.

The design used for the aluminum part was not suitable for this specific AM machine, because the placement of the holes was too close to the edges, and the machine software could not lay fiber around the holes, resulting in the part to be fragile in an essential location.

Because the Finite Element Method is not able to analyze the FRTP part produced in the Markforged, the analysis has to be made by trial and error, printing a new design and testing on the laboratory.

So, various designs evolved from the initial one with the objective of matching the sustained load and having a displacement in the same range of values as the aluminum part. In the process of design, besides the mechanical behavior intended, it was also always taken in consideration the cost of the materials. For example, it would be easy to match the mechanical characteristics of the aluminum part by simply adding more fiber to the initial design. But, because the fiber is expensive, this increase in fiber would increase the costs and also the weight of the part, making the part noncompetitive. Therefore, the design process was focused on making a functional part in a sustainable way.

The objective was to reinforce the mostly nylon part with fiberglass in some specific locations such as around the holes, in the edges were torque is applied and maintaining some flexibility in the center section of the part to allow the energy dissipation when the aircraft lands.

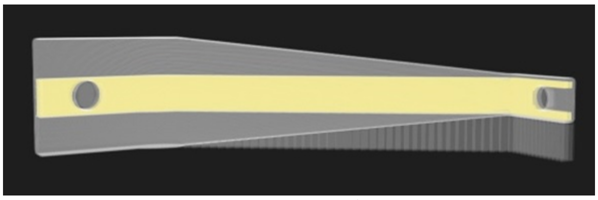

Figure 10: Final design fiber location

In Figure 11, we can see the 8th and final design being tested. On the left the test is starting with displacement zero, and on the right the part is already near the maximum displacement. This part managed to sustain a load of 107N in the range of 20 to 30 mm of displacement. This is a result very close to the required of 109 N.

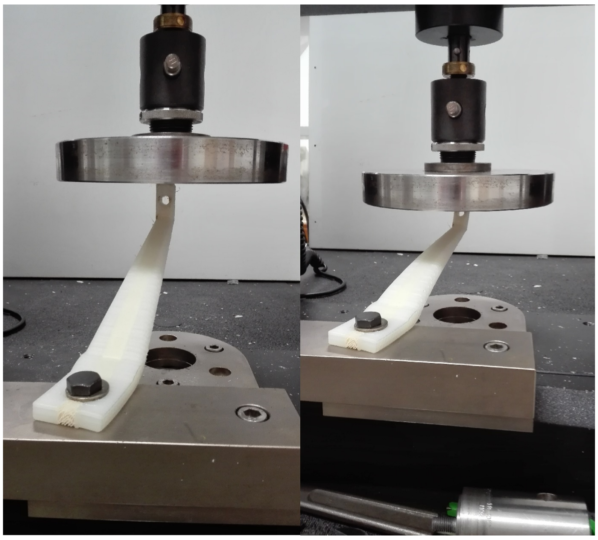

Figure 11: Final design test

Table 1: Simulation parameters

	Aluminum CNC	FRTP AM
Load Sustained (N)	109	107
Displacement (mm)	24.3	25.13
Part Volume (cm^2)	11.86	57.29
Part Mass (g)	32.96	49.06
Raw material Vol. (cm^2)	100.8	44.66
Production time (h)	1	11.5
Energy used (KWh)	1.6	2.06

5. Results & discussion

The volumes of Nylon and Fiberglass used to produce the AM part are given by the Eiger software. Then the mass is calculated using the density of each material given by Markforged, 1.1 g/cm3 for Nylon and 1.5 g/cm3 for Fiberglass. In table 1 it is possible to see that the volume of the raw material is smaller than the volume of the part, this occurs because the FRTP part, unlike the aluminum one, is not fully filled with material, resulting in some free spaces inside the part and consequently an higher volume.

The aluminum part has a raw material volume almost ten times higher than the final part volume, this is because, in CNC Milling the production of the part starts with a solid block of material from which it is removed material to obtain the final form.

From table 1 it is possible to see that the parts behave similar in terms of loads sustained and displacement. The part volume and mass is higher for the FRTP part, this may result in a worst performance when flying, considering that the weight is a very important factor in fuel consumption and also the bigger volume can cause aerodynamic problems. From the table 1 we can also see that the production time for the FRTP part is much higher than the aluminum part, forcing this type of parts to only be considered to small production batches.

In 2, all the costs of material acquisition, machines acquisition and production of both parts are summarized, and the total cost is calculated. Is important to refer that these costs only consider the production phase. The costs of the use phase (aircraft fuel consumption) and the costs of recycling are not considered in this analysis.

Table 2: Costs

Costs(€/unit)	Aluminum 2024 - CNC	Nylon + Fiberglass - FDM
Material	11.6	23.20
Machine	15.26	23.62
Energy	0.16	0.21
Labor	10	8.60
Finishing	1.76	0.1
Total	38.78	55.73

From table 2 it is possible to see that despite the big amount of aluminum waste the material cost is still higher for the FRTP part. The machine costs are also significantly higher for the FRTP part mainly because of the time needed to produce one part being higher. Summing all parcels the result is that the aluminum part is 16.95 € cheaper to produce.This result demonstrates that, for this specific component produced with these materials, CNC Machining is the less expensive technology of the two. To calculate the machine costs of the FRTP part it was considered that the machine was non-dedicated and that the hours of work per day were 8. However, the costs per unit drop considerable by increasing the work hours, for example from 8 h to 12h the cost decreases from 55.72 €/unit to 47.85€/unit. From 12 hours on, the costs continue decreasing achieving a value of 39.98 €/unit if the machine worked permanently, 24 hours a day.

Midpoint Analysis

In the graphic of Figure 12, it is present a normalization of the midpoint categories results. It is possible to understand that the AM FDM procedure have a lower impact on the environment than the CNC Milling in every single category.

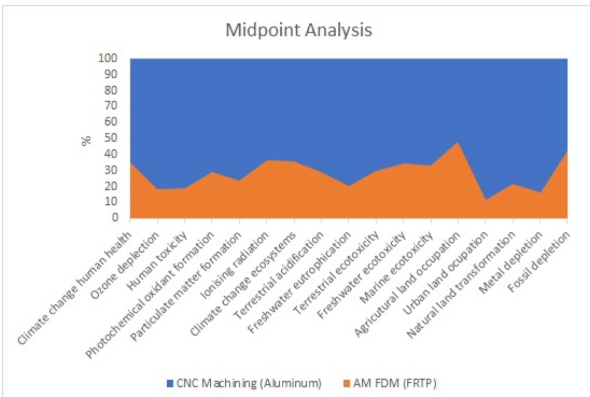

Figure 12: LCA Midpoint Analysis

Endpoint Analysis

In Figure 13 is present a single score impact assessment that compares the production of the leaf-type spring gear by CNC Milling and AM FDM. The results give the cumulative environmental impact for the two different processes, considering that each uses a different material, aluminum and FRTP. These results include three categories: human health, ecosystems and resources. From the graphic it is perceptible that, for this case study, CNC Milling has a much higher cumulative impact than AM FDM.

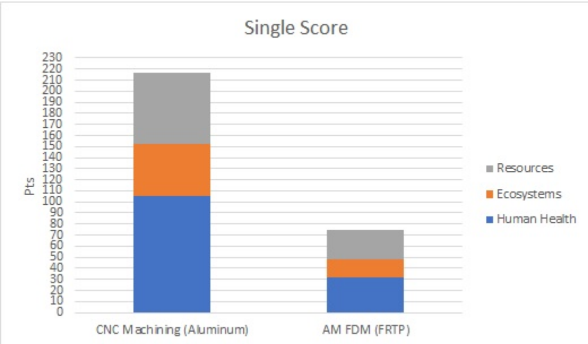

Figure 13: LCA Endpoint Analysis

From the graphics presented before, it is possible to extract as a result that this component, the leaf-type spring gear of an UAV, produced in aluminum by CNC milling has a significantly higher environmental impact than the same component produced in FRTP by FDM. One factor that contributes largely for this result is the fact that the ratio between the amount of raw material needed to produce the component and the amount of material present in the component after production, is much higher for CNC milling. In practical terms this translate into more material that has to be extracted, more material that has to be transported to the production site and more waste material that will be recycled. Considering the use phase, that is the influence the weight of the part has on its end use, the flight of the aircraft, the aluminum part has a lower weight, so less impact on the fuel consumption and the pollution. Despite the use phase, and the fact that the FRTP part is considered to be disposed of, compared to the aluminum part and waste material that are recycled, the FRTP still have a significantly lower impact on the environment.

6. Conclusions

From the results it is not possible to determine which technology performed better in this case study. On one hand, the component produced in aluminum by CNC Milling is better comparing the mass and volume of the part and has significantly lower production costs. On the other hand, the environmental impact is remarkably lower for the FRTP part produced by FDM. Despite the contrasting results it is possible to make some conclusions. In first place, it is important to emphasize that CNC milling is a technology that is already well developed and has its place in the industry for a long time, while Fused Deposition Modeling, with fiber reinforced thermoplastics, is still a relatively new technology with a large amount of improvements to be made, so this big gap that exists, in terms of production costs, can be reduced. The main parcels of the cost where FDM is more expensive is in the material acquisition and machine costs, and both of these costs can be reduced if AM gets more popular and starts to gain market share. This will increase the number of machines available in the market, the number of suppliers of materials and consequently dropping the prices of the equipment and the materials used. In terms of the part volume and mass, the FRTP part sustained the same loads as the aluminum part, displaying the same range of displacement. The only drawback was that the FRTP part, presented a higher mass and volume. This point could be improved by two ways: changing the materials used or improving the design. In terms of materials, with this particular machine, the Markforged Mark II, one way of maintaining the same behavior of the part and reducing the mass and volume could be by using carbon fiber instead of fiberglass. The use of this fiber would increase the material cost, so, it may not be the best solution as the FRTP part is already more expensive than the aluminum part. In terms of design, with the right expertise and resources, a better design could be generated in order to better exploit the capabilities of the FRTP and AM. Since the design topic was brought up, design flexibility was one of the general advantages of AM technology, but it is important to mention that for this particular production method and machine (FDM and Markforged) the design has large number of restrictions. As an example of some restrictions are the printer dimensions; the printer software, that has limited ways of placing the fibers, since each layer has to be of only one material, sometimes fiber is needed in one section of the part but is not in another section and both are in the same layer, leading sometimes to the use of more fiber than needed; and the validation of results, because nowadays it is common in industry to develop a product and evolving its design before production, resorting to FEM software or other numerical methods, but for FRTP deposited by Markforfed way there are not yet numerical methods able to predict the behavior of the part, so the process of design has to be made by iterations, producing and testing prototypes. Regarding the production size or scale, it is assumed from the start that AM is only viable for a small number of parts, and in this case study, it is shown that even if the production scale is increased the cost of the part is higher for the FRTP part. The main element holding back the production size is the production time of the part, that is much higher than CNC machining, but with the improvement of the FDM machines it may be possible to increase the production size and consequently reduce the production costs. Environmentally, the more efficient of both processes, with a big difference, is FDM. This result is largely because FDM, being an additive process, only consumes the amount of material that forms the final part, while CNC milling requires a block of material from where the part is sculpted. So, even though FRTP part has more mass and more volume than the aluminum part, the aluminum part, in total, uses much more material causing a higher impact on the environment. Environmental awareness is becoming a significant factor for companies, governments and the public in general when making decisions. Besides the increasingly restrictive laws on this subject, a fair amount of companies also want to transmit to the public the image that they care about the environment and their products are sustainable. This factor amplifies the value of the environmental results of the case study, even though the costs were almost always the more important factor in product development. Furthermore, with the development of the technology around FDM with FRTP almost all the causes for the inflated production costs, such as production times or machine software restrictions, can have their impact diminished. In conclusion, parts of Nylon reinforced with Fiberglass produced with Fused Deposition Modeling are not yet an alternative to aluminum parts made by CNC milling, mainly because of the costs involved and the software and machine limitations that do not allow for the design to be improved in detail for AM. However, mainly because of its lower environmental impact and the room for improvement, it is expected for it to be an alternative over traditional production methods in the near future.

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