Development of a metallic support bracket regarding additive manufacturing

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Abstract: Considering the technological innovation and recent market needs, related to customization, sustainability and reduction of production times and costs, in the last decades additive manufacturing has increased its applications in several sectors. In the aircraft sector, taking advantage of AM capacity to produce components of high complex geometry, it has been used in a weight reduction perspective through the redesign and material optimization of several aircraft components. This fact it's particularly interesting for the case of metallic components that are present in high numbers in an aircraft, where most of the applications are related to the "auxiliary" metallic components, that opposed to the structural and support ones, they are not limited by the security norms and certification processes demand.

Thus, this work aims to evaluate the potential of applying design for AM methods to a metallic support bracket of the aircraft sector, in order to reduce its weight.

To do so, two new configuration proposals are obtained through the application of two different design methods: topology optimization and generative design. Then, production costs related to the CNC machining of the initial configuration and the additive manufacturing of the final proposed configuration, are evaluated. Finally, the reduction potential related to the operational costs and carbon emissions given by the fuel savings obtained by the weight reduction, is also analyzed.

Keywords: Additive Manufacturing, Topology Optimization, Generative Design, Aircraft Sector, Carbon Emissions, Customization.

1. Introduction

1.1. Motivation

Additive manufacturing is a manufacturing technology that has grown at a rapid pace in recent decades, being increasingly used in various applications in different industry sectors such as aeronautics, automobiles, biomedical, among others. This commercial interest is associated with different factors such as: constant technological innovation and the ability to work with a wide range of materials. In addition, additive manufacturing responds to the growing market needs related to customization, focus on sustainability and reduction of manufacturing costs and times, taking advantage of its ability to produce components of high geometric complexity [1].

In the aircraft sector the customization capacity of additive manufacturing gains special importance. It allows for a costs and emissions reduction by reducing the mass of various components through its reconfiguration, optimizing the distribution of material and number of connections. This fact is particularly important in the case of structural and support metallic components, present in high numbers in an aircraft. However, due to safety regulations and the need for certification associated with the risk of failure, the manufacture of these components by AM is still limited [2].

That said, the work developed in this dissertation intends to evaluate the potential of applying different design methods for additive manufacturing to a case study of a metallic support component in the scope of the aeronautical industry.

1.2. Objectives

With this study, it is intended to apply two design for AM tools to a case study of a metallic bracket of the aircraft sector, in order to reduce its mass without compromising its operation and resistance to the load requested. In addition, it is intended to assess the economic impact and the potential for reducing emissions associated with this mass reduction.

To this end, two new proposals for the component's geometric configuration are obtained through topological optimization and generative design, from a design for AM and lightweight perspective. Then, a study is carried out to evaluate and compare the manufacturing costs of both, initial and final, configurations, obtained through CNC machining and additive manufacturing, respectively. And finally, two studies are carried out to assess the potential for reducing operational costs and direct emissions associated with fuel savings.

2. Literature Review

2.1. Additive manufacturing

According to ISO/ASTM 52900 standard [3], the term additive manufacturing refers to any technology that, based on a geometric representation or 3D model, creates physical components by successive additions of material layers, unlike conventional processes of subtractive nature, that are based on material removal. This definition is broadly applicable to all types of material, including metals, polymers, ceramics, composites, and biological systems.

One of its main advantages is its high capacity to obtain components of great geometrical complexity, which were not possible to obtain, or required the use of an elaborate and expensive machine configuration and/or assembly of two or more components. In addition, it is quite flexible as it allows the production of batches of different customized parts without waste and without additional costs, as would be expected if a different mold, tool or fastening device per component was needed, as in traditional manufacturing [4].

However, this technology still has a set of limitations that sometimes put its viability into question. Among others, the following stand out: the need to carry out post-processing, the high investment requirement, the restrictions regarding the maximum size of the component and the low capacity for mass production [4].

2.1. Additive manufacturing and the aircraft sector

The ability of additive manufacturing to produce components of high geometric complexity without the need for elaborate configurations of machines, molds and/or tools, allows for the reduction of manufacturing cycle times and enables localized production, contributing to more efficient supply chain systems. In addition, this flexibility of design and customization allows the achieving of better conditions for optimizing material and operation compared to conventional manufacturing, obtaining lighter components, and reducing the need for assembling several parts for a given function.

These attributes, associated with the rapid development of different technologies over the last few years, have led to the additive manufacturing being increasingly used in different applications of the aircraft industry, no longer being exclusively used to obtain prototypes [5].

The graph data of the following figure, based on [6], demonstrates the growing interest and increase in research of additive manufacturing technologies regarding the aircraft sector for recent years, illustrated by the number of publications in the field, with a high growth in the last 10 years.

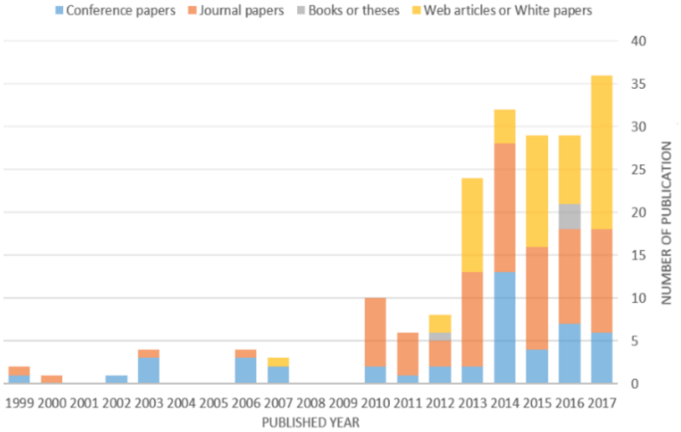


Figure 1 – AM publication regarding the aircraft sector [6].

Reducing the mass and quantity of assembled components is of special interest for this sector, as in addition to the potential for reducing manufacturing costs, they allow for greater service efficiency. On the one hand, reducing mass requires a smaller amount of fuel for each journey, reducing service costs and carbon emissions. On the other hand, by reducing the number of assembled components, the number of connections and fixings required, such as welding, screws, rivets, etc., is reduced, which reduces the labor and maintenance required and, consequently, the costs associated with them [6].

The following two examples describe two applications of additive manufacturing, regarding the aircraft sector, where the mass and quantity of assembled components were reduced:

- In 2015, General Electric Aviation developed a fuel nozzle for a jet engine (LEAP engine), Figure 3, which reduced the mass by 25% and an assembly of 20 parts into just one [7].
- Airbus Defense and Space developed an aluminum structural bracket for the Eurostar 3000, Figure 3, which allowed 35% mass reduction, and a 40% increase in stiffness, reducing an assembly of 4 pieces and 44 rivets to just one [8].

One of the biggest constraints of this technology for this sector, especially for the manufacture of support and structural metallic parts, is related to the high demand for standards, certification, and control necessary to comply with each component. Justified by the security risk in case of failure [6].

Anyway, due to its potential, with technological innovation and increasing research, additive manufacturing is gradually overcoming this barrier. In 2015, the company General Electric Aviation developed a metallic casing for the introduction of a temperature sensor, illustrated in Figure 2, being the first component produced in AM to be certified by the US Federal Aviation Administration (FAA) and to be implemented on commercial aircrafts [9].

Figure 2 – Metallic casing for T25 sensor [9].

2.2. Design for AM (DfAM)

Considering that the case-study component falls within the aircraft sector, the application of design techniques for additive manufacturing from a design for lightweight perspective is of special interest. That is, design the component in such a way that its mass is minimized or reduced without compromising the stiffness and resistance to the loads required

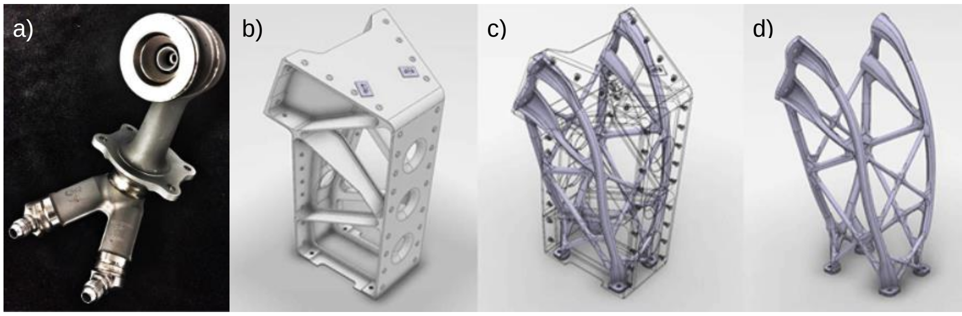


Figure 3 – Application examples: a) GE Aviation nozzle [7]; b), c) e d) Eurostar 3000 bracket [8].

That said, two distinct methods are approached for the intended purpose: topological optimization and generative design.

2.2.1. Topology optimization

Topological optimization refers to a structural optimization method that, through simulations in CAE software, calculates the best spatial distribution of material in a certain domain, respecting one or more pre-defined constraints, and minimizing or maximizing a given objective function [10].

It is usually applied in the field of mechanical or civil engineering to minimize the mass or minimize the compliance/maximize the stiffness of a given structure or component [11]. About two years ago, General Motors company resorted to this method for the development of the Chevrolet Equinox SUV, which reduced approximately 180 kg of its total weight, without compromising the operating characteristics [12].

Figure 4 presents a generic example of the redesign of a metallic support bracket through the application of the topological optimization method.

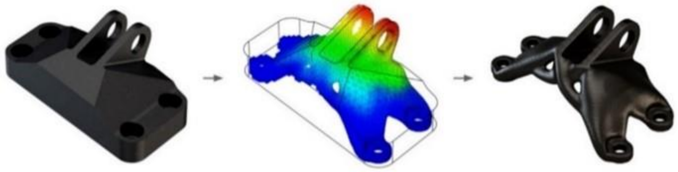


Figure 4 – TO example for a metallic support bracket [13].

The direct result given by topological optimization simulation does not correspond to a final CAD geometry ready to be directly verified or produced, but rather to a geometric representation of a possible solution. Taking this into account, it is necessary to remodel the initial component according to the changes suggested by this same result.

2.2.2. Generative design

Generative design can be described as a design optimization method that, through the application of several algorithms in CAE software, calculates a set of possible geometric configurations, through an iterative process. For this, it is necessary to define a set of parameters, including materials, requested loads, project domain, manufacturing technologies, among others, as well as establishing the intended objectives, which are similar to TO, where two main possibilities are considered: minimize mass or minimize compliance [12].

This method is referred by some authors as a process that replicates the natural evolution strategy due to its iterative character, testing and readjusting at each iteration. Furthermore, most of the geometric configurations obtained have a complex and organic shape, which are often impossible to obtain using conventional production techniques. This fact makes the additive manufacturing the most suitable candidate to manufacture the geometry solutions obtained through generative design [14, 15].

Figure 5 shows an example regarding the application of this method in a vehicle belt fastening device, where the assembly of eight pieces was reduced to just one, making it 40% lighter and 20% more resistant [16].

Figure 5 – Application example regarding generative design [16].

2.3. Process-Based Cost Model

To carry out the economic impact study of the manufacturing costs intended in this work, a model was adopted that, as the name indicates, evaluates the cost based on processes, the Process-Based Cost Model (PBCM).

This cost model was developed to counteract the discrepancy between the physical and financial models of the market, based on the idea that the cost is the result of the project synthesis, material properties and operating conditions, given by the physical parameters associated with the reality of the technology of each process [17].

Therefore, this model addresses the production of a particular component, dividing the process into different sequential tasks or activities and evaluating the cost associated with each one. The total cost of production is given by the sum of the costs of each activity.

To this end, according to Kirchain and Field [17], the model is described in three main steps:

- Identify relevant cost elements.
- Catalog the contributing factors.
- Relate process activities to the cost factor.

That said, and considering a generic manufacturing process:

The first step is carried out by defining the fixed and variable costs associated with each activity, divided into cost elements relevant to the process, such as material, labor, energy, among others.

The second step refers to the production factors that contribute to the determination of established cost elements, given by cycle times, machine properties, occupied areas, among others.

Finally, the cost per element, per activity, is obtained by multiplying the respective cost factors given by a price (electricity price, raw material price, operator price, among others).

3. Case study

In this chapter, the case study component and respective available information are presented, as well as the necessary assumptions and simulations to define parameters and enable the application of the intended design methods for additive manufacturing.

Then, the processes used in the application of these same methods are described and the respective results are presented.

3.1. Problem definition

The aircraft component in question, shown in Figure 6, corresponds to a fuselage support bracket made of Titanium alloy (Ti-6Al-4V Grade 5) that can be found on the trailing edge of an airplane's wings.

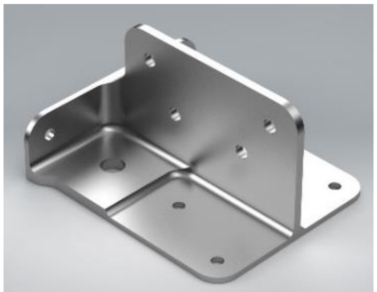


Figure 6 – Support bracket (CAD model obtained through SW2020).

The metal part is fixed to the surrounding structures through the application of six rivets with 4.1 mm in diameter and two screws with 8.1 mm in diameter, the corresponding holes are shown in Figure 7.

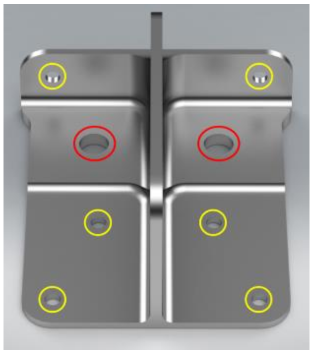


Figure 7 – Fixing holes (Screws in red and rivets in yellow).

The information available related to the component refers to the geometric characteristics of the part, its material, the generic region of the plane where it is located and the fixation mode. Thus, in order to apply both design methods for additive manufacturing intended in this study, it requires the definition of three parameters:

- Mechanical properties of the alloy.
- Mass of the component's initial configuration.
- Loading conditions.

3.1.1. Alloy mechanical properties

Ti-6Al-4V Grade 5 is the most used alpha beta titanium alloy in the industry, being widely applied in various sectors such as automobile, biomedical, petrochemical and especially in the aeronautical sector. This is mainly due to its excellent strength/weight ratio and its high resistance to corrosion at high temperatures [18, 19].

The mechanical properties of this alloy depend on the heat treatment applied and the metallurgical condition in which it is found. Therefore, in order to define the specific properties of the alloy, the typical values of [20, 21] presented in Table 1 were considered, which are in accordance with the range of values of [22]. Where the hardness, yield strength, ultimate strength, *poisson* coefficient and density are presented, in that order.

Table 1 – Alloy mechanical properties [20,21].

	Hardness [HV]	σ_y [MPa]	σ_{UTS} [MPa]	E [GPa]	ν	ρ [g/cm3]
Ti-6Al-4V (Grade 5)	345	910	1000	114	0.35	4.42

3.1.2. Part mass

This property takes on special importance for this study, as it is the one that is intended to be reduced with the application of design methods for additive manufacturing.

That said, through the CAD modeling of the component using Solidworks 2020, it is obtained its volume. Multiplying by the density of the alloy shown in the previous table, we get the mass of the component. The volume and mass of the component are shown in Table 2.

Table 2 – Original design specifications.

Material	Mass [g]	Volume [mm^3]
Ti-6Al-4V (Grade 5)	127.7	28888.7

3.1.3. Loading conditions

To make it possible to obtain new geometric configurations through the application of design methods for additive manufacturing, it is strictly necessary to define the loading conditions to which the component would be subject. As this information is not available, load requests are defined following a methodology described by the following series of steps:

- Assume three loading cases.
- Calculate maximum allowable stress.
- Iterative static linear analysis process.

Loading cases

Considering the geometry of the part, three possible loading cases were assumed: one with a vertical direction, another horizontally and a last one inclined at an angle of 45 degrees relative to the horizontal, represented by Figure 8

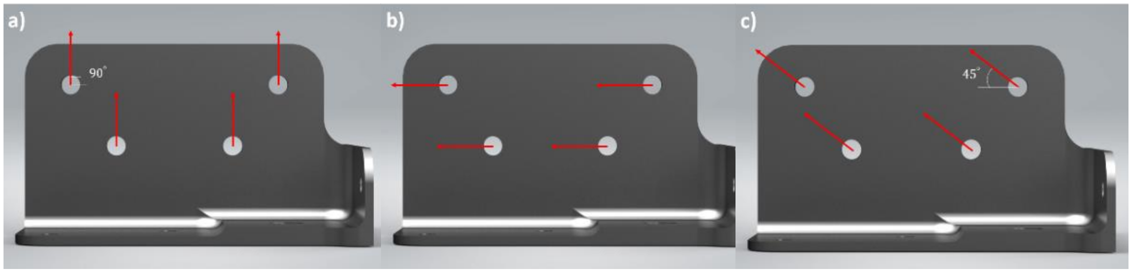


Figure 8 – Loading cases: a) Vertical case; b) Horizontal case; c) Inclined case (45 º).

The three forces are characterized by the same application points, which are applied universally along the inner section of the four holes of the central flange of the piece. To make it easier to understand, just imagine the existence of four pins going through the respective holes that would be pulled in the three directions indicated.

Maximum allowable stress - Pugsley method

With the direction and application points of each loading case established, it remains to define the intensity of each of the different loading cases. For this, it is necessary to define a universal criterion applicable to all geometric configurations (initial and final) that establishes a safety stress limit and allows comparisons to be made between them.

Therefore, the Pugsley method [23] was used, which by the definition of two terms, n_{sx} and n_{sy}, from the tables available in [23], allow to calculate a design factor through the application of equation (3.1).

Then, through equation (3.2) taken from [24], the desired safety stress is obtained.

$$n_{proj} = n_{sx} \cdot n_{sy} \tag{3.1}$$

$$n_{proj} = \frac{\sigma_y}{\sigma_{adm}} \Leftrightarrow \sigma_{adm} = \frac{\sigma_y}{n_{proj}} \tag{3.2}$$

Table 3 – Parameters classification (Pugsley).

Parameter	A	B	C	D	E
Classification	*vg*	*f*	*f*	*vs*	*vs*

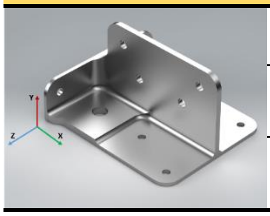
Attributing the parameters classification presented in Table 3 and consulting the tables in [25], we obtain an n_{sx} of 1.9 and n_{sy} of 1.6. Replacing values in the previous equations, we obtain a design factor of 3.04 and a maximum allowable stress (σ_{adm}) of 303.33 MPa.

Iterative process of static linear analysis

Having an established limit stress value, the load intensity applied in each case is determined through an iterative process of successive static linear analyses, which, using the finite element method, presents as a result the Von-Mises stress distribution of the component.

Thus, using the CAE Solidworks software, successive analyzes were carried out varying the value of the applied force, until the maximum Von-Mises stress corresponded to the safety stress limit, obtaining the values of the intended loads, presented in Table 4.

Table 4 – Final load conditions.

Referential	Case	Fx [N]	Fy [N]	Fz [N]
	Vertical	0	1500	0
	Horizontal	3600	0	0
	Inclined	2900	2900	0

3.2. Topology optimization

From the perspective of additive manufacturing and in order to obtain a new proposal for the geometric configuration of the component, lighter and equally resistant, a topological optimization study was carried out using CAE software Solidworks to carry out the computational procedures necessary for the process.

To this end, a design domain was defined that corresponds to the volume occupied by the component itself, except for the preserved areas, where no material is removed from the component, defined by the areas around the holes shown in red in Figure 9.

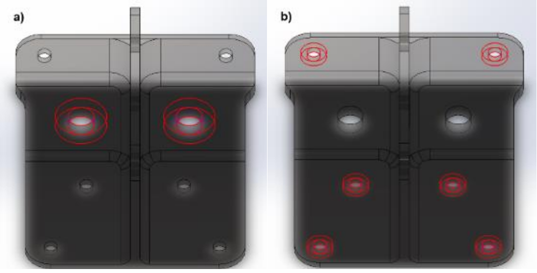


Figure 9 – TO project domain with preserved areas in red: a) screw preserved areas; b) rivets preserved areas.

The objectives of the analysis are divided into two main possibilities: minimization of mass or minimization of compliance/maximization of stiffness, being subject to three hypotheses of restrictions:

- Displacement restriction – setting a maximum value or factor.
- Mass restriction – defining a maximum mass reduction percentage relative to the original.
- Stress restriction – setting a maximum allowable stress value or maximum safety factor.

For the present case study, in a theoretical context, the most appropriate approach would be to define the objective of mass minimization and establish a stress safety constraint defined through the safety factor obtained by the Pugsley method. Initially, for simulation purposes, that was the approach, however, when analyzing the results, it was possible to verify that the amount of material removed was quite low compared to what was expected, as can be seen from the analysis of Figure 10.

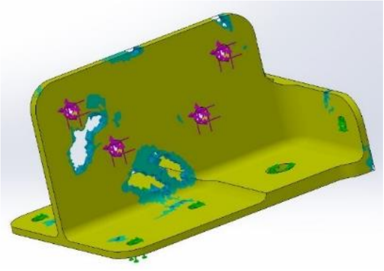


Figure 10 – Geometric representation of the stress restriction result – TO.

This phenomenon was caused by the high stress values from the singularities around the holes, which are taken into account in the stress restriction defined by the selected parameters.

In order to avoid this problem, a different approach was taken through an iterative process of topological compliance minimization studies, subject to different mass reduction percentages as restrictions.

In each study performed, a new configuration hypothesis was obtained, remodeling the original component based on the geometric representation obtained in the results, illustrated by the example in Figure 11.

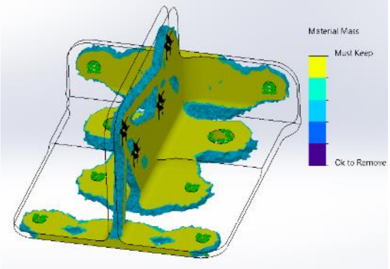


Figure 11 – Geometric representation for a 50 % mass reduction restriction.

Each new configuration obtained was submitted to a linear static analysis to verify the stress distribution along the material. The iterative process ended when the maximum allowable stress was exceeded and assumed a percentage deviation greater than 5%.

3.3. Generative design

Keeping the additive manufacturing perspective and the geometric freedom that characterizes it and using Autodesk's

Fusion 360 software for the process, a generative design analysis was carried out to obtain a new proposal for a geometric configuration with lower mass without compromising strength to the requested load.

To this end, the design domain was characterized through the definition of preserved geometry and obstacle geometry.

The preserved geometry refers to the areas where it is intended to guarantee the existence or non-removal of material, usually defined by the areas where the respective fastenings will be tightened and where there are loading application points. Illustrated in green in Figure 12.

Obstacle geometry refers to areas where it is intended that no material is present, serving as the name indicates as an obstacle to its expansion, usually defined by the interface zones with the component. Illustrated in red in Figure 12.

The design domain is represented by Figure 12 b), with preserved geometry in green and obstacle geometry in red, in Figure 12 a) the yellow component was added for the reader's better understanding.

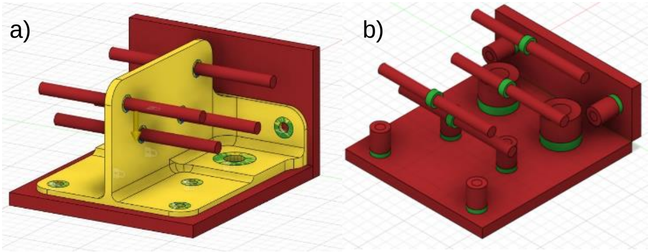


Figure 12 – GD project domain: a) With component; b) Without component.

The objectives of the analysis are characterized by the definition of one of two possibilities, mass minimization or stiffness maximization. However, they are subject to a single stress restriction hypothesis, defined by the minimum safety factor according to the Von-Mises criterion.

For this case study, intending to obtain a new lighter and equally resistant configuration, the objective was defined as the minimization of mass subject to a stress restriction defined by the safety factor obtained in 3.1.3.

3.4. Results and discussion

Topological optimization

The final configuration proposal obtained through topological optimization is presented in Figure 13, being defined by the application of the mass reduction restriction of 50% and is the result of the original component remodeling based on the representation illustrated in Figure 11.

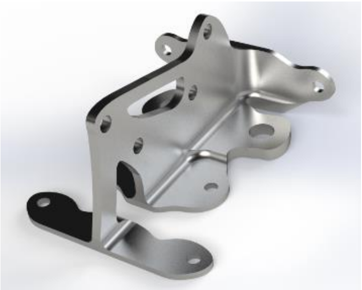


Figure 13 – TO final configuration proposal.

The comparison between the geometric configuration's characteristics related to the TO proposal and original one, is represented by the information contained in Table 5, including the Von-Mises stress values and maximum displacements of each load case, represented by σ and d, respectively.

Table 5 – Results comparison: TO vs original.

Parameter	Original	TO	Difference [%]
Mass [g]	127,7	74,13	- 41,94
Volume [cm^3]	28,89	16,77	- 41,94
σ_{max_1}[MPa]	306,20	310,70	1,47
σ_{max_2}[MPa]	307,40	313,40	1,95
σ_{max_3}[MPa]	306,30	308,80	0,82
d_{max_1}[mm]	0.178	0.223	25.4
d_{max_2} [mm]	0.097	0.159	64.24
d_{max_3} [mm]	0.087	0.116	33.14

From the analysis of the previous table, it is concluded that by applying the topological optimization method a proposal for a geometric configuration was obtained that allowed a reduction of about 42% of the mass and volume without compromising the resistance to the three load requests, assuming as acceptable a deviation less than or equal to 2%. The mass reduction value obtained is approximately 54 g.

Furthermore, it appears that the maximum displacements for all load cases increased, especially for the horizontal case with an increase of around 64%.

Generative design

For the analysis carried out, considering the restrictions of the imposed design domain, material, and safety factor, five possibilities of geometric configurations were obtained. Analyzing the properties of each one, and considering the intended objectives, the configuration proposal presented in Figure 14 was selected.

Figure 14 – Generative design configuration proposal.

The properties of the obtained proposal are presented in Table 6 together with those of the original configuration for comparison purposes

Table 6 – Results comparison: GD vs original.

Parameter	Original	GD	Difference [%]
Mass [g]	127,7	47,71	- 62,64
Volume [cm^3]	28,89	10,79	- 62,64
σ_{max_1}[MPa]	306,20	158,50	- 48,24
σ_{max_2}[MPa]	307,40	301,30	- 1,98
σ_{max_3}[MPa]	306,30	302,60	- 1,21
d_{max_1} [mm]	0.178	0.064	- 63.91
d_{max_2} [mm]	0.097	0.170	75.38
d_{max_3} [mm]	0.087	0.094	7.63

By analyzing the table above, it is possible to conclude that the application of this design method not only allowed to obtain a reduction in mass and volume compared to the original configuration in the order of 63%, but also improved the resistance to the requested loading conditions. Especially in the case of vertical load, where the maximum Von-Mises stress has been reduced to practically half. The mass reduction value obtained is 80 g.

It is also verified that the maximum displacement increases considerably in the horizontal case, remains approximately constant in the inclined case, and reduces considerably in the vertical case, in the order of 64%. This fact allows us to conclude that in relation to the case of vertical load, this proposal not only allowed to reduce the maximum stress but also reduced the maximum displacement.

Comparison of results

Considering the mass reduction objectives, it is concluded that the final proposal to be selected corresponds to the one obtained by the generative design method, being characterized by a higher mass reduction compared to topological optimization.

From the perspective of load resistance, the GD proposal also obtained better results. Because despite being comparable for the horizontal and inclined load cases, in the vertical case the maximum Von-Mises stress value is practically half.

Regarding the distribution of displacements, the GD proposal has a maximum displacement considerably lower in relation to the cases of vertical and inclined loads, being comparable in the horizontal case.

4. Costs and emissions analysis

In this chapter, two economic impact studies and an additional analysis of direct emissions associated with fuel consumption are presented.

First, the manufacturing costs per unit produced associated with each of the geometric configurations, initial configuration obtained through CNC machining and final configuration obtained through additive manufacturing are evaluated.

Then, the potential for reducing operational costs and direct carbon emissions associated with the change in fuel consumption, obtained through the reduction in the component's mass, is evaluated.

The final configuration selected for this purpose corresponds to the proposal obtained through the generative design method, as it is characterized by a higher mass reduction in relation to the topological optimization proposal.

4.1. Production costs

In this section, the manufacturing costs per unit produced associated with CNC machining of the component with initial geometric configuration and additive manufacturing with final geometric configuration were evaluated, assuming a non-dedicated production line in both cases.

For the following study to be carried out, a PBCM model was developed that divides the corresponding manufacturing process into different activities, using as reference the cost models developed in 3 master's dissertations [25, 26, 27]. Each activity is characterized by two types of cost: variable costs and fixed costs.

Fixed costs refer to costs associated with:

- Machine.
- Building.
- Maintenance.
- Tool.
- Waste collection.

Variable costs refer to the costs associated with:

- Material.
- Energy.
- Labor.

For the case of the initial configuration, produced through CNC machining, a sequence of only two activities was considered: setup and machining.

For the case of additive manufacturing of the final configuration, a sequence of four activities was considered: setup, printing, cleaning and removal, post-processing.

The post-processing treatment assumed for AM was a shot-peening treatment, described as a cold process where small spherical particles are "bombed" against the surface of the component, inducing residual compressive stresses along the surface, which results in an increase in fatigue and corrosion resistance, prolonging the component's life cycle.

Before computing the results, two manufacture simulations were carried out to obtain the lead time and material quantity related to the final configuration printing and initial CNC machining:

CNC machining

The machining time and material required for the process, were defined through a manufacture simulation carried out with Autodesk Fusion 360 CAM software, in which the different processes of milling as well as the raw machining block were defined. The material block was used as starting point for the process, illustrated by Figure 15.

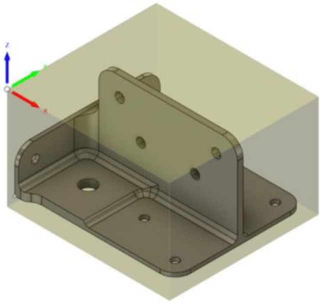


Figure 15 – Raw machining block and desired part.

Additive manufacturing

The batch printing time, as well as the number of parts per batch and material quantity required were obtained through a manufacture simulation using Autodesk Netfabb, that computes the support features for the given case, as well as the platform distribution optimization, illustrated by Figure 16.

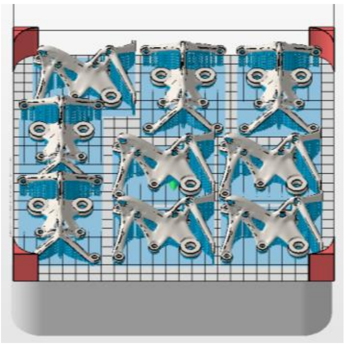


Figura 16 - AM Netfabb simulation.

The results obtained by applying cost models for CNC machining and additive manufacturing are presented below.

In Figure 17, two distribution graphs are presented where it is possible to verify the percentage of each type of cost for both models applied.

The results obtained for each type of cost associated with each model are presented in the bar graph in Figure 18, including the total manufacturing cost given by the sum of the remaining cost elements.

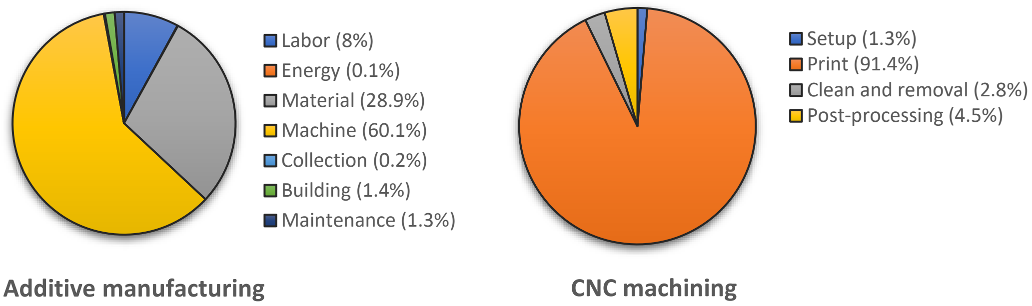


Figure 17 – Production costs distribution for each model.

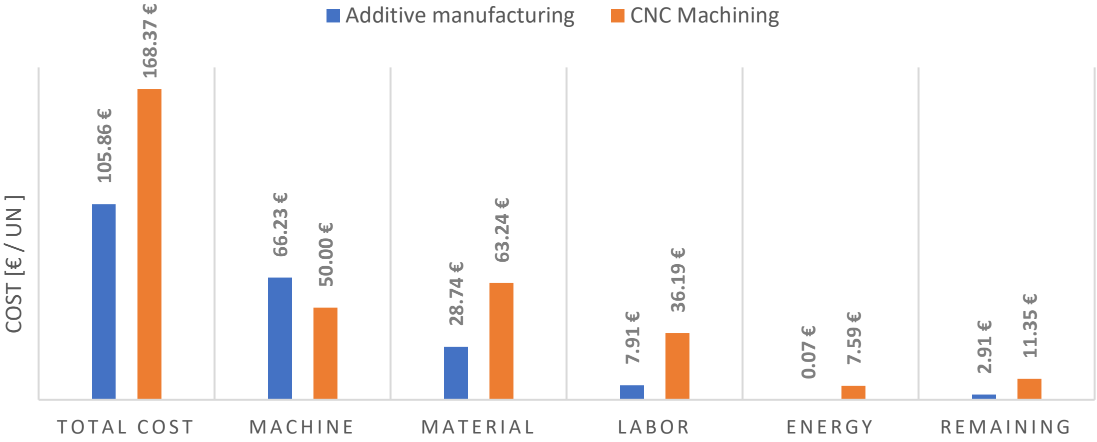


Figure 18 – Production costs comparison: CNC machining vs Additive manufacturing.

By analyzing the graph of Figure 18, it quickly appears that for this case study the production of a unit of the new configuration proposal through additive manufacturing has a total cost associated considerably lower in relation to a unit of the initial configuration obtained by CNC machining, with a difference of €62.51, which corresponds to a deviation of around 37%.

This difference is due to several factors associated with each type of cost, discussed below:

First, it should be noted that additive manufacturing only has a higher cost than CNC machining in one of the cost elements associated with the cost of acquiring the machine. This fact is due to the price of the printing machine being considerably higher than the price of the CNC milling machine, being 1.8 times higher. This investment requirement justifies the high percentage associated with the cost of the machine shown in the additive manufacturing distribution in the graph of Figure 17.

Then, it is also verified that the type of cost with the greatest discrepancy between models refers to the cost of material needed, where for machining it is more than double that for additive manufacturing. This difference is related to the component's geometry in two aspects: on the one hand the reduction in mass and volume obtained in the design for additive manufacturing of the case study, lead to the final configuration obtained in AM requiring less material, and on the other, due to the subtractive nature of the machining, the initial configuration requires a large raw block of material.

Regarding labor costs, considering that, unlike the CNC machining process, the final configuration is printed 100% autonomously, without the need for an operator, the difference between them is noticeable. However, in the case of machining, the presence of the operator in all activities of the process contributes to the fact that the percentage of machine cost and labor are comparable, as shown in the graph in Figure 17.

The energy costs of each model depend on the power required by the machine and manufacturing time per component, as CNC machining lasts one hour longer than additive manufacturing and machine power is considerably higher than that of the printing machine, the difference shown in the result of the previous graph is justified.

The difference obtained between the remaining elements of cost is mainly due to the influence of the cost associated with the wear of the cutting tool in the CNC machining process, which has a higher cost.

Therefore, it is concluded that despite the higher machine investment to produce the final configuration through additive manufacturing, with the mass reduction obtained for the present case study, the total manufacturing costs are lower by 37% comparing to the production of the initial configuration through CNC machining.

4.2. Operational costs and carbon emissions

One of the main industries related to transport that contributes to the environmental impact is the aircraft sector, due to the high carbon emissions resulting from the burning of jet fuel. Take, for example, the case of the European Union where it contributes with 3.8% of the total emissions of CO_2 [28].

Taking this into account, an analysis of the potential for reducing direct emissions associated with fuel savings, obtained by the redesign of the part proposed by the previous case study, is carried out.

In addition, since in the aeronautical sector the cost associated with the expenditure of fuel occupies about 33% of the total costs [12], in this subchapter the potential for reducing operational costs is also analyzed. Operational costs only associated with fuel burning in which maintenance costs, carbon taxes etc.… are not included.

According to Roca et al. [29], Huang et al. [30] estimate that there are around 250-500 kg of “auxiliary” metallic components per aircraft, with specifications that allow their replacement by equivalent lighter components, produced in AM. They are considered auxiliary because they are not inserted in the support or functional types, being classified by the FAA as Category 3 components, being exempt from heavy certification processes.

Therefore, assuming a maximum value of 500 kg in "auxiliary" metallic components and a potential mass reduction of 63%, based on the result obtained in the case study of the component, a mass reduction of 321.3 kg per aircraft is obtained.

Then, based on the article by Steinegger [31], the fuel reduction ratio in [kg/km] associated with a 1 kg reduction in aircraft weight is determined, given by the average value of the value range shown. Multiplying this ratio by the previous mass reduction, the fuel reduction in [kg/km] is obtained.

Considering as a case study, the mission described in Table 7 [26], and defining the fuel price and the ratio of quantity of emissions by quantity of fuel, based on [32] and [33], respectively, we obtain the results presented in Table 8.

Table 7 – Mission specifications [26].

Mission	Lisboa – Berlin
Aircraft	A319
Distance [km]	2309
Duration [h]	3.5
Annual flight hours [h]	4900

Table 8 – Operational costs and emissions reduction results.

Fuel reduction [ton / year]	**Fuel savings [€ / year]**	**Emissions reduction [ton CO_2 / year]**
25.9	14,063.7	81.6

By analyzing the results, it is possible to conclude that through the mass reduction obtained by the design for AM of the case study of the component, a potential savings in fuel-related operational costs of around €14 000 is obtained.

Furthermore, for reference purposes, the estimated equivalent emissions per flight hour of 250 [kg $CO_{2_{eq}}$ /h] presented in the study of [34] is assumed to be valid. Thus, considering the annual flight hours presented in the mission parameters table, 1225 [ton $CO_{2_{eq}}$ /year] per aircraft are obtained. That said, by analyzing the table above, the emission reduction potential obtained, only related to the aircraft's fuel combustion, corresponds to 6.7% of the aircraft's annual emissions.

5. Conclusions

This work aimed to evaluate the potential of applying different design for AM methods from a design for lightweight perspective to a metallic support component of the aircraft sector without compromising loading strength. Two design tools were applied, topological optimization and generative design, where two new component configuration proposals were obtained. Then, one of the proposals was selected and the manufacturing costs of each configuration were evaluated. Initial configuration through CNC machining and final configuration through AM. Finally, the potential for reducing operational costs and carbon emissions associated with fuel burning was evaluated.

Therefore, through the results obtained, it is concluded:

The customization capacity of additive manufacturing allows the redesign of pre-existing components, including metallic support components, and there are different methods to apply. For the present case study an airplane support bracket in Titanium alloy was reconfigured through the application of two methods: topological optimization and generative design.

Through redesign, it is possible to optimize material distribution and reduce component mass without compromising resistance to loading conditions. In some load cases, even displacement has been reduced and resistance increased. For the present case study, a mass reduction of about 63% was obtained for the generative design and 42% for the topological optimization.

The mass reduction obtained by the reconfiguration allows to reduce manufacturing costs. For this case study, the manufacturing costs in AM of the new proposal were 37% lower than the initial configuration by CNC machining. It is important to note that the investment required to purchase the additive manufacturing machine is considerably higher than CNC machine and that the biggest difference in the total manufacturing costs of each technology is associated with the cost of material. This fact reinforces the importance of AM customization capacity, because in the case of not reducing the mass through the reconfiguration, the manufacturing costs could be similar or even higher.

The application of design for AM methods and respective component redesign has the potential to reduce operational costs and direct emissions in a way that can make a difference, not only from an economic perspective, but also from an ecological and sustainable perspective. It is important to bear in mind that the analysis carried out only considered the potential associated with “auxiliary” metal parts that are not limited by certification. In the case of including the metallic support and structural components, the potential is even greater. This fact reinforces the importance of research and technological innovation focused on overcoming the necessary certification barriers.

Regarding future work, it is suggested that the same study is carried out through the application of design for AM methods to reduce the mass but keeping the displacement distribution constant instead of stresses and evaluating the results obtained. In addition, it is important to carry out other types of studies focused on overcoming the certification barrier. It is suggested to carry out fatigue analysis or other types of material behavior studies, to better understand the implications associated with this technology and in the future take more advantage of its application.

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