Cost Model for Additive Manufacturing of Metal in Aeronautics

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Abstract

Nowadays, with the evolution of manufacturing methods, namely additive manufacturing, several industries have studied the possibility of a possible change in their manufacturing processes. Additive manufacturing in metals shows enormous potential in the aviation industry due to several advantages, including the reduction in weight of an aircraft. Among all the processes for manufacturing metal parts, forging stands out, as the most used conventional method over time. It is a well-known method that offers a reliable solution for the aerospace industry. However, the increasing complexity of the parts and the need to reduce their weights explains the emergence of additive manufacturing (AM). The two most promising processes in additive manufacturing are direct energy deposition (DED) and powder bed fusion (PBF), which allow the construction of lighter and more complex metal parts.

Keywords: Additive Manufacturing, Aerospace, Metal Parts, Forging, Life Cycle, Environmental impact

1. Introduction

Aviation has a major impact on a country's economy, as far as connecting people, faster transport of goods and supplies and cost-effective are concerned [4]. In contrast to mass-production industries, aerospace industry has been focused towards complex and low-volume production [9]. It has been a constant challenge for production engineers due to constant challenges such as environmental performance restrictions, high manufacturing costs and competition market conditions.

In the beginning of aviation, only landing gear components and the main structures were entirely metallic. Skilled craftsmen were needed to machine the metals. This machining technique was called forging[3]. Being one of the oldest known metalworking processes that involves molding the material using compressive forces, this type of technique involves significant capital expenditures on machines, tools, installation and personnel, being a technology that offers low cost at a high production rate when requested.

With the need to produce smaller, lighter, more complex parts and a low production volume, various techniques were researched and developed. With the advent of AM, many of these problems have been solved. AM is a part manufacturing technique that builds 3D objects by adding material (like plastic or metal) layer by layer. Nowadays, AM is used in a variety of industries, although it is still mostly used in the production of prototypes, a trend that is gradually being used in production processes.

With aircraft engines becoming increasingly complex and sophisticated and the need to reduce aircraft weight, it became important to study and analyze new processes of production of metal parts.

This article was developed in order to study the economic impact of various technologies in the production of a metal part, from the construction to its post-processing, as well as the environmental impact that may be associated with.

2. Literature Review

2.1. Additive Manufacturing

Additive Manufacturing, also called 3D Printing, is a relatively recent method of manufacturing parts from CAD file. In contrast to subtractive manufacturing methods, such as forging, AM generally builds the part layer by layer.

A computer-developed project is exported to the STL file format that is read by the equipment AM that build it.

The first steps of AM were in the 1980's, where parts called Rapid Prototyping were developed in a quick way to check their shape, fit and function[1, 2, 10].

In 1987, the company 3D systems developed a plastic processing system known as stereolithografy. This process consists of solidifying thin layers of polymer using a laser UV. Since then, many companies researched and made progress in order to develop new technologies, improve process and commercialize them. [2, 10]

In the 90's, the bet of several companies allowed the development of other techniques based on polymers such as, FDM, SGC, LOM and SLS.[2, 10]

In addition to the new AM techniques, processes based on metals were initially introduced through laser sintering and only later by powder sintering.[2, 10]

Nowadays, AM can produce parts using any type of raw material, from plastics, metals, ceramics to composites. There are several techniques available that can be classified according to their raw material: powder base, liquid base and solid base.

2.2. Process-Based Cost Modeling

In this work, the process-based management principle is adopted. As the name implies, PBCM is a fusion of the cost model and the process. The model was developed to respond to the gap between technical and financial understanding in practice. Process engineers are generally concerned with optimizing physical parameters to improve product and process performance, however these adjustments affect the cost of production. [5]

PBCM is a sequential approach to cost in stages for the production of a given object.

PBCM consists of three main parts: decision rules, inputs and model architecture. Decision rules can be described as a set of mathematical equations that relate to design decisions and their consequences for the process. The model inputs are based on production equipment, interviews with a specialist to identify values for these input values and based on theoretical research. The model architecture allows editing the production steps, selecting or removing production steps for a given case study.

2.3. Life Cycle Assessment

The LCA assesses the environmental aspects and the potential impacts associated with the life cycle of a product, from the extraction of the raw material to the final use of the product. The general categories of environmental impact considered in an ACL study include the use of natural resources, implications for human health and ecological consequences. the LCA study is divided into 4 phases:

- The definition of the objective and scope: Definition of the context of the study, description of the product system in terms of the functional unit and the limits of the system;

- The Life Cycle Inventory Analysis (LCI): LCI involves data collection and calculation procedures to quantify relevant inputs and outputs from a product system;

- The Life Cycle Impact Assessment (LCIA): This is the life cycle assessment phase that aims to understand and assess the magnitude and significance of the potential impacts for a product system throughout the life cycle;

- The Life Cycle Interpretation: It is the stage where the results of the inventory analysis or impact assessment are evaluated in order to reach conclusions and recommendations.

3. Integrated Cost-Model

This cost model was developed with the aim of better understanding AM technologies and in what context they are favorable compared to conventional methods. For this reason, a dynamic model has been developed where the user is allowed to edit not only the production line but some manufacturing processes. Therefore, it is necessary to have a set of inputs and processes data to feed the model that will estimate the cost of the part for the various technologies covered in this article.

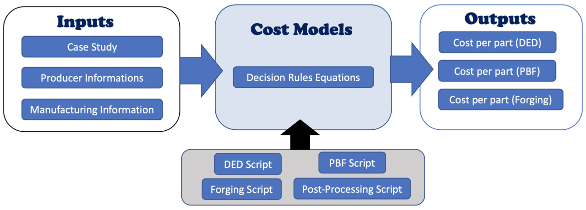

Figure 1: Cost Model Scope

3.1. Inputs

3.1.1 Part Selected

The part's choice was based on its size and shape complexity and also because it has been optimized for additive manufacturing.

In the figure 2 and 3, we can see a support, used in Sequeira's thesis [8], that was chosen for our case study. On the left side, figure 2, we have the original part, used in conventional manufacturing processes, on the right side, figure 3, we have a part optimized for AM, with the aim of reducing weight.

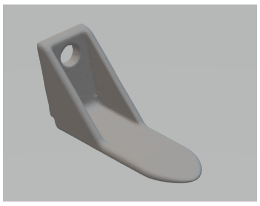

Figure 2: Case Study Original Part

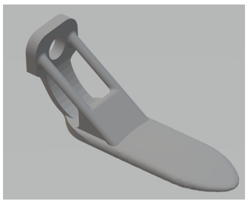

Figure 3: Case Study Optimized Part

3.1.2 Manufacturing Options

Figures 4 and 5 show the manufacturing options selected for the production of our support part by forging method and AM processes, respectively. The choice of these manufacturing options was consulted with a metal specialist and may differ from the original manufacturing options of the part.

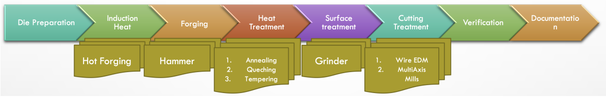

Figure 4: Line Seletected for Case Study of Forged Part

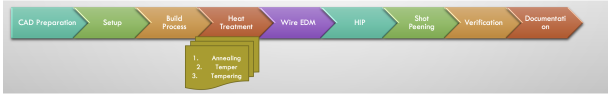

Figure 5: Line Seletected for Case Study of AM Part

3.1.3 Producer Informations

The cost model has some variables that depend on the information of the producer that can change depending on company and of the country. For this case study, the necessary data was estimated based on reasonable values validated by Hypermetal and other companies in the same area.

3.2. Main Processes Scripts

3.2.1 DED Script

1. CAD Preparation

The process starts by gathering all the information about the part to build a 3D model. This model is created through a CAD Software that contains all the necessary information for the 3D printer.

Some costs are involved in this operation. A work space or desk, a computer and software licenses are required. The CAD model involves time spent by the designer which correspond to Labor Costs.

2. Setup

In this step, the machine operator checks all the components of the 3D printer so that it does not compromise the construction of the part. The cost related to this step is essentially related to the time the operator spends checking and calibrating the machine. Setup time can be divided into 4:

- Holding time ($t_{holding}$) - 0.25 h -corresponds to the time required to execute the holding operation and locking the Build platform [7];
- Laser calibration time (t_{lc}) - 0.25 h - time required for the operator to calibrate the laser [7];
- Powder preparation time (t_{pp}) - 0.25 h - time needed to restore reserves of metallic powder [7];
- inert gas preparation time (t_{gp}) - 0.49 h - time required to supply gas to the chamber [7];

Then we can calculate the setup time as sum of all times presented before:

$$t_{SETUP} = t_{holding} + t_{pp} + t_{gp} + t_{lc} = 1.24h \quad (1)$$

3. Build Print

This is the main stage of the DED process. The construction process is the step responsible for building the part. For this estimation the Optomec DED machine, model LENS 850R. LENS 3D Technology by Optomec use lasers to build objects layer by layer directly from powdered metals. This process presents itself as one of the pioneering and most successful methods of DED.

This step involves several variables necessary for the construction of the cost model. Four parameters were estimated:

- Build Time;
- Gas consumption;
- Electric consumption;
- Maintenance Costs.

(i) Build Time

For DED technology is easily estimated knowing only the Deposit Rate ($deposit_{rate}$) through the specifications of the AM machine model (Inserir: Anexo Modelo da Maquina) and the mass of the part ($mass_{AM}$). Then, Buld Time of one part is obtained dividing the mass of the part by the deposit rate of the machine. To know the total Build Print time (t_{BPDED}), just multiply by the number of parts per batch (BS_{DED}), as shown in equation 2.

$$t_{BPDED} = \frac{mass\_AM}{deposit\_rate} * BS_{DED} \quad (2)$$

(ii) Electric consumption

The electricity consumed was based on the study by Liu et al. [6]. The author, in his study makes a comparative energy analysis of AM technologies in the production of metal parts. The estimates were made by the Optomec, model LENS 750 machine, using the metal Nistelle 625, where it obtained a used energy of 1052 MJ/ kg.

The consumption of electrical energy in kWh as shwon by:

$$Electrical\_Energy\_Consumption = 292.22kWh/kg \quad (3)$$

Where K_kWh =0.277778 is the conversion constant from MJ to kWh. Hence, the energy used in kWh is given multiplying EEC by the mass of the part, as shwon in the equation 4.

$$EU\_elect_{DED} = 292.22 * mas\_AM; \quad (4)$$

(iii) Gas Consumption

In the same study used to estimate electricity, Liu [6] estimated gas consumption for DED machines. In his study, author refers that in DED process, powder material was delivered throught argon gas to melt pool at a considerable flow rate, typically of 10L/min.

Hence, to obtain gas consumption per hour (EU_{gas_DED}) it is only necessary to convert the value, giving a consumption of 600 L/h.

$$EU\_gas_{DED} = 600L/h \quad (5)$$

(iii) Maintenance Costs

The maintenance of the DED was made by a rough estimation, where it was made taking into account the percentage of maintenance of PBF in machine price.

We conclude that the maintenance price of the PBF corresponds to about 1 % of the purchase price of the machine. Thus, the DED has a maintenance of about 7000 euros per year, equation 6.

$$MC_{DED} = 0.01 * MP_{DED} = 7000 \quad (6)$$

3.2.2 PBF Process

The PBF was based on the thesis of Eng. Diogo Sequeira (2019) [8], where the model values have been converted into a script variables. Diogo developed its model based on the Renishaw AM 400 machine. The Renishaw AM 400 printer uses the SLM 3D printing technology, with a 400 W optical system providing a reduced beam diameter of 70 μm.

3.2.3 Forging

In parallel, a cost model was developed not having the goal of evaluating this method but to have a comparison term between AM technologies and conventional technology.

3.2.4 Finishing Processes

A research and estimation of several variables was necessary to estimate the cost of our models. The following post-processing was included in this study:

- Heat Treatment;
- Surface Treatment: Grinder, Thermochemical Surface Treatment and Shot Peening;
- Cutting Treatments: MultiAxis Mills and Wire EDM;
- Hot Isostatic Pressing;
- Verification and Validation;

4. Decision Rules Equations

4.1. Time Definitions

To proceed with the production calculations it is useful to define some time variables which facilitate the calculation of costs in the model.:

- <u>Line Time Available</u> (LTA_i) - time available over the year at production step i, for the production of parts. In our model, Available Line Time was calculated as follows:

$$LTA_i = DPY(24 - NS - UB - PB - UD) \quad (7)$$

- <u>Effective Volume Production</u> ($effPV_i$)- the number of parts needed to produce throughout the year to achieve the desired "good" parts (APV). As we can see in the equation 8, the effective production volume ($effPV_i$) is calculated as the effective production volume of the next stage ($effPV_{i+1}$), in the production line, divided for the rejection rate for that stage(r_i). It should be noted that the effetive production volume of the penultimate stage is determined by the number of good parts to be produced during a year (APV) divided by the rejection rate of that same stage(r_i).

$$effPV_i = \frac{effPV_{i+1}}{(1 - r_i)} \quad (8)$$

- <u>Required Line Time</u> ($reqLTi$) - Time required throughout the year to produce Effective Volume Production. For forging and post-processing, the required line time ($reqLT_i$) is calculated using the equation 9. Here the cycle time (T_cycle_i) is the time a batch is built and the load and unload time ($T\_loadunload_i$) is the time to load and unload the machine. The batch size (BS_i) is the number of pieces that are produced together.

$$reqLT_i = \frac{effPV_i * (T\_cycle_i + T\_loadunload_i)}{BS_i} \quad (9)$$

For the case of additive manufacturing, the cycle time and load and unload time are replaced by the build print time and the machine setup time,as we can see in the equation 10.

$$reqLT_i = \frac{effPV_i * (T\_BP_i + T\_SETUP_i)}{BS_i} \tag{10}$$

- *Lines Required* (LR_i) - Number of stations required to reach the Effective volume yield per stage. The required lines are calculated as parallel production. To achieve the number of good parts per year, sometimes it is necessary to have more machines running at the same time. The machines are added to the mill line and several machines are performing the same task. The calculation of the required lines, assuming parallel production, can be seen in the equation 11.

$$LR_i = \frac{reqLT_i}{LTA - (DPY * UD_i)} \tag{11}$$

4.2. Scripts to Costs

After we have all the necessary inputs and variables for all processes, it is possible to calculate the production costs. These costs correspond to the sum of all the money spent on the production of the piece directly or indirectly. The Total production costs are given by the following equation:

$$Total\_costs = Variable\_Costs + Fixed\_Costs; \tag{12}$$

The variable costs ($Variable\_Costs$) are the costs vary proportionally with the volume of production, as material costs, electricity and gas costs and Labor Costs. While fixed costs ($Fixed\_Costs$) correspond to costs that do not vary in value with the volume of production, as maintenance costs, Building costs and capital invested.

A. Variables Costs

1) Material Usage

Raw Material per Part

Knowing the mass of part after a main build process ($mass\_forging$ or $mass\_AM$,) it is needful to know the raw material required in the first stage of the process (RM_used), that is, before preheating in the case of forging 13 and before Build print in the case of AM technologies 14. This raw material has to take into account the scrap rate (s_i) that remains in the process and the mass of the part (it is considered after the manufacturing stage, after forging ($mass_{f}orging$) or after Build Print ($mass_{A}M$) in AM technologies), as we can see in the equations bellow:

$$RM\_used = mass\_forg * (1 + s_{forg}) * (1 + s_{preheat}) \tag{13}$$

$$RM\_used = mass\_AM * (1 + s_{DED})) \tag{14}$$

Mass Requerired per Step

Then the mass required before is step i is calculated as the Raw Material per Part (RM_used) minus the scrap loss from all previous processes (s_i):

$$mass\_req_i = RM\_used * \prod (1 - s_n) \tag{15}$$

where i is the process step and n the previous steps ($n < i$).

Mass Usage left in the Stage

So, it is now possible to calculate the annual scrap mass (U_mass_i) left at each stage. This calculation is done by subtracting the mass required before step i ($mass\_req_i$) minus the mass required after process ($mass\_req_{i+1}$) for all parts manufactured annually in that step i ($effPV_i$):

$$U\_mass_i = (mass\_req_i - mass\_req_{i+1}) * effPV_i \tag{16}$$

Number of Bad Parts per Stage

Now it is necessary to calculate the number of rejected parts ($Nr\_bad\_parts_i$) left in each process, subtracting the volume of parts produced in step i ($effPV_i$) by the next step ($effPV_{i+1}$):

$$Nr\_bad\_parts_i = effPV_i - effPV_{i+1} \tag{17}$$

Total Mass Left in the stage

The total mass that remains in each step of the process is the sum of the scrap U_mass_i and the mass of the number of pieces rejected in step i:

$$Total\_mass_i = U\_mass_i + Nr\_bad\_parts_i * mass\_req_i \tag{18}$$

Note: The good part mass was added to the part construction stage, in the forging in the traditional method and in the build print in the AM technologies.

Anual Material Costs in each Step

Then Annual Material Costs in each step i is the multiplication of the total mass rejected $Total\_mass_i$ in each step i by the price of the raw material RM_price.

$$MaterialCost_i = RM\_price * Total\_mass_i; \tag{19}$$

2) Sold Scrapt

The material left over in each process, called scrap, can be resold. This resale will result in a decrease in variable costs. So, the material sold is the total rejected mass ($Total\_mass$) multiplied by the scrap resale price p_s:

$$MaterialSold_i = Total\_mass_i * p_s; \quad (20)$$

For the pre-heating, Heat Treatment and Hot Isostatic pressing processes, the scrap sold is considered zero. Once that the loss of mass in these processes is due to the atomic rearrangement and not to the scrap left by the process.

3) Labor Usage

Annual Paid Time

The annual time paid (APT_i) is the work hours per year of the worker in process i:

$$APT_i = LaborT_i * |\frac{effPV_i}{BS_i}| \quad (21)$$

Where $(LaborT_i)$ is the number of hours the worker needs to spend in process i per batch, $(effPV_i)$ is the number of part produced good and bad over a year and (BS_i) is the number of parts produced in the same group.

Annual Labor Cost

The annual labor cost per process step is calculated according to:

$$ALC_i = APT_i * sh \quad (22)$$

Where sh is the salary paid per hour.

4) Energy Usage

Annual Energy Usage

The calculation of energy used per batch (EU_elect_i) is based on the energy consumed per hour (EU_elect_i) of the machines in step i of production and the total time required $reqLT_i$ in step i to produce the total number of good parts required. The equation calculates the annual energy used per stage i AEU_i for each stage of the process for one year:

$$AEU\_elect_i = EU_i * reqLT_i; \quad (23)$$

Annual Energy Cost

To calculate the annual cost of energy AEC_i consumed by step i, multiply the annual energy used AEU_elect_i by the price of electricity p_e:

$$AEC_i = AEU\_elect_i * p_e \quad (24)$$

5) Gas Usage

Annual Gas Usage

For the calculation of the annual gas used per batch GAU_i it is based on volume per hour of gas used EU_gas_i by the machines used in that production step i multiplied by the time necessary to produce the number of good parts per step i $reqLT_i$:

$$GAU_i = EU\_gas_i * reqLT_i \quad (25)$$

Annual Gas Cost

To calculate the annual gas costs in step i, AGC_i, the gas price $p_g$is multiplied by the annual gas consumption AGC_i:

$$AGC_i = GAU_i * p_g; \quad (26)$$

B. Fixed Costs

1) Capital Costs

Capital Invested

The calculation of the cost of capital begins with the calculation of the invested capital C_i as the cost of purchasing the main machine MP_i and auxiliary equipmentAP_i:

$$C_i = (MP_i + AP_i) \quad (27)$$

Amortized Costs

Capital costs take into account the value of money over time. For this purpose, the flow of N constant payments, R, equivalent to the current sum C, where C is the capital price and N is the number of years during which the purchase is amortized and r is the discount rate, is calculated. Thus the calculation of the flow of constant payments comes:

$$AR_i = C_i * R; \quad (28)$$

$$R = \frac{(1+r)^N * r}{(1+r)^N - 1} \quad (29)$$

Annual Capital Costs

The annual cost of capital is calculated using the R multiplied by Lines required:

$$ACapital_i = \frac{AR_i * |LR_i|}{LTA_i} * reqLT_i; \quad (30)$$

2) Building Costs

Annual Building Costs

The annual cost of the building per step i is calculated through the building space required F_i per production step multiplied by the number of Lines required LR_i and the price of the building per m2 (p_b), amortized R:

$$BU_i = F_i * |LR_i| * p_b * R \quad (31)$$

The annual building Costs per stage i $ABuildingC_i$ of production is calculated by the reason of Building Used BU_i and the total time available for production LTA_i. This ratio will be a cost per hour, which is multiplied by the amount of time required per step i $reqLT_i$ of production to achieve the desired number of good parts.

$$ABuildingC_i = \frac{BU_i}{LTA_i} * reqLT_i \quad (32)$$

3) Maintenance Costs

The annual maintenance cost per step i AMC_i is calculated using the average maintenance cost of each machine in step i MC_i multiplied by the number of required lines used in step i LR_i:

$$AMC_i = MC_i * LR_i \quad (33)$$

5. Results and Discussion

Through our cost model, we obtained a production cost of 59.60 euros for a DED part and 142.39 euros for a PBF part (for an annual volume of 50 parts).

Figures 6 and 7, show pie charts where the percentage of the various costs associated with each technology can be observed. In the PBF, the highest percentage refers to the initial investment made to acquire the PBF machine, which corresponds to about 83 % of the production price of the part, the second highest being the maintenance in parallel with the material costs with 6% of the total cost.

On the other hand, in DED the purchase price corresponds to only 43 % of the total production cost. It should be noted that the cost related to the material and energy has a relevant weight in the cost of production of the part, with about 19 % and 23 % respectively.

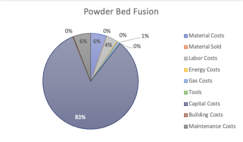

Figure 6: PBF distribution costs

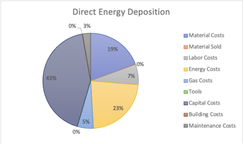

Figure 7: DED distribution costs

AM technologies show that the cost of the part is constant with the variation of production volume, the opposite happens with forging, as shown in figure 8. Forging presents high production costs for low volumes, reducing these costs as the number of units produced annually increases. In this case study, the additive manufacturing becomes advantageous for a production volume of 44 parts, in the case of the PBF, and 109 parts, for DED technology. Analyzing the price of each technology for an annual production volume of 50 parts, DED has costs under 60 euros, forging has costs around 123 euros and PBF has a cost of 142.62 euros.

The variation in the price of the forged part is easily justified by the high costs of tools dedicated to this production, such as the high price of a die, for which a high volume of production is necessary to dissolve the costs.

In this analysis, a daily uptime of 8 hours was assumed for the forging equipment and 12 hours for the AM and pre heating equipments. This number is due to the capacity of the machine to produce almost 100 hours in row, being able, in many cases, to print during the night or weekends. These periods, which in other manufacturing processes cannot be accounted because there is no the physical presence of any operator, we can use 3D printers.

In the table 1 , the costs of each of the production steps for the additive manufacturing technologies are shown and in the figures 9 and 10 their contribution to the final cost of the part. Analyzing the cost of the entire production line in our case study, the cost of printing the part has the highest percentage of the total cost, with around 85 % for the PBF and 69% for the DED, which will correspond to 25% and 31% of the production line costs to post-processing.

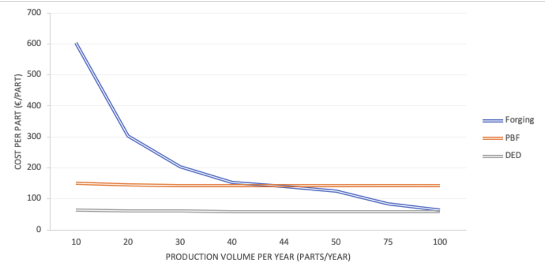

Figure 8: Comparison for different production volumes between PBF, DED and Forging

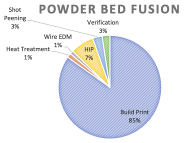

Figure 9: Percentage of PBF process steps

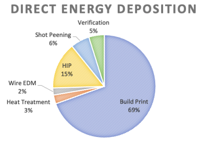

Figure 10: Percentage of DED process steps

It is important to highlight the high contribution of HIP, corresponding to 7 % and 15 % for PBF and DED, respectively. The isostatic press is by far the most expensive equipment that corresponds to 2.5 million euros, which means that its contribution to the final part is significant.

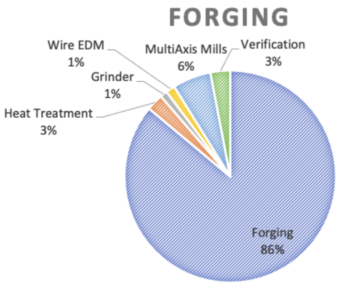

Figure 11: Percentages of each Step in final Part made by forging

When comparing the production line with forging, data from figure 11, we observe that this conventional method has a lower post-processing value, about 14 %, than the additive processing methods. It is important to emphasize that there is a greater need for finishing treatment in the case

Table 1: Costs of PBF and DED process steps

Prodution Step	**DED Costs**	**PBF Costs**
Build Print	62,15	150,86
Heat Treatment	2,49	2,46
Wire EDM	1,97	1,87
HIP	13,15	13,09
Shot Peening	5,30	5,26
Verification	4,33	4,33
Total	89,40	177,88

of AM parts than by traditional methods, namely removal of substrates, powder sensitization among others.

6. Ambiental Impact Analysis

We made a simplified analysis of the environmental impact caused by each process analyzed in chapters 3 and 4. Table 2 shows the total impact of each of them, from the environmental effect related to the exploration of the raw material to the energy used during the process. Note that these values are calculated for the production line, chosen in chapter 4, for each of the manufacturing processes. We can easily observe that for both AM technologies (DED and PBF) and the forging, the impact caused by the mass of the part is a small fraction of the total impact. This happens because the part is relatively small, weighting around 285g. However, for bigger parts we predict that the energetic fraction will be proporcional to the increasing mass, for the AM technologies, while in the case of forging this propotion isn't verified. Forging uses dies and presses, regardless of the size of the part, meaning that the process will be similar unlike AM technologies. With AM technologies, the whole mass of those larger parts will have to be deposited in the printing chamber, which implies a greater energy expenditure.

Table 2: Total Impact of AM technologies and forging in environment

	Mass	**Energy**	**Total**
PBF	0,58	16,40	16,976
DED	0,69	63,49	64,179
Forging	1,06	19,99	21,052

This cost model only considers the scrapt and energy in each production step.

In this dissection and for this case study, we opted for similar post-processing for the two AM technologies. Due to the high energy consumption that the DED process requires, the post-processing steps have an environmental impact of 23% compared to Build print. Using PBF technology, on the other hand, the greatest impact will correspond to post-processing (since it is a device with less energy expenditure), as shown in table 3.

Table 3: Impact of AM production steps

	Mass	**Energy**	**Total**
PBF	0,04	1,53	1,57
DED	0,15	65,56	65,71
HT	0,00	4,82	4,82
EDM	0,02	2,65	2,67
HIP	0,01	7,28	7,29
SP	0,01	0,12	0,12

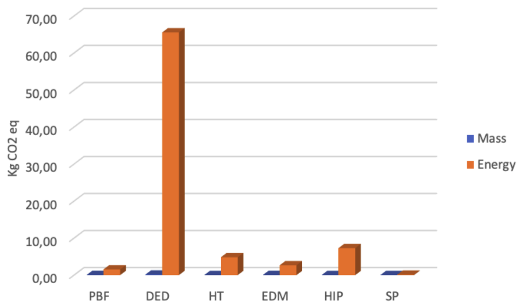

Figure 12: Impact of AM production steps

7. Conclusions

Comparing both AM technologies with forging in the production of our case study part, it was concluded that AM becomes competitive for a small to medium annual production volume. PBF showed to be profitable for an annual production of "goods" below 44 parts, while the DED is profitable bellow 118 parts compared to forging. The sensitivity of the forging and the complexity of the parts was also analyzed. This study confirmed that the production cost increases with the complexity of the part when forging, whereas in AM technologies, these costs become constant because there are no tools required. The reason for this rise is the increase in the cost of the die and the need to divide complex parts into simpler ones, increasing the number of stations in the production line.

After comparing different AM technologies, we concluded that the DED is very sensitive to the mass of the part, which makes it unprofitable for parts over 814g of mass (compared to the PBF).

When analyzing several production lines, it is important to note that post-processing corresponds between 18% - 25% of the final price of our case study (depending on the type of finishing treatment chosen and the type of AM technology being used).

Although AM technologies are economically competitive for lower production volumes, they present significant energy costs that have caused a greater environmental impact, namely the DED. PBF allows us to reduce the waste of the raw material and present energy impacts similar to conventional processes, namely the forging analyzed also in this study.

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