Metal Additive Manufacturing in Aeronautics: a Life Cycle Cost Perspective

Diogo Simão Sequeira
diogo.s.sequeira@tecnico.ulisboa.pt

Instituto Superior Técnico, Universidade de Lisboa, Portugal

November 2019

Abstract

Currently, additive manufacturing shows enormous potential in various industries, such as aerospace, due to its advantages. Characterized by the production of layer-by-layer parts, this technology can produce more complex and lighter parts compared to conventional manufacturing. Although it has been around for a few decades for other materials, metal additive manufacturing has been developing and may prove to be fundamental in the future. In order to adopt new technologies, it is important to analyze their economic aspect. For this purpose, this work aims to develop a cost model for a metal additive manufacturing process. This model allows to identify the factors that most influence the production cost and, using a case study, compare this process with a conventional process, forging. It was also studied the impact that a weight reduction in an aircraft has on fuel savings. Combining this reduction with the production cost, the benefits arising from the use of metal additive manufacturing were observed. This technology could prove very advantageous with its necessary development. By allowing parts of different geometries to be manufactured in the same production, for low and medium production volumes, metal additive manufacturing can compete with traditional methods and generate high savings, which in the aeronautical industry could become crucial.

Keywords: Additive manufacturing, processed-based cost models, aerospace, build time estimation, powder bed fusion, fuel consumption reduction

1. Introduction

In manufacturing there is a relentless pursuit to build lighter products, to surpass existent techniques, to improve the supply chain efficiency and to accompany it with cost savings [1]. It is in this demand that additive manufacturing (AM) fits.

AM is the process of producing parts, from 3D model data, by adding successive cross-sectional layers of material. The process initiates with a creation of a three-dimensional solid model, which can be modeled or scanned as a digital file, with the software slicing the data file into individual layers. The printed object is the result of adding these layers of material, one on top of the other [2]. This formation is different from some traditional manufacturing methods, where material is removed from an initial workpiece [2].

This technology has a great potential for creating parts with high complexity, high value, and highly customized, something extremely valued in several industries such as aerospace. Notwithstanding that polymer AM has been the focus of most of the work since the early development of this technology to date, metal AM (MAM) is revealing to be an emerging technology with a significant effort being focused on metals in recent years [3]. MAM technologies have been the subject of very intensive research and there is still much study and development to be done in many areas.

In order to adopt any new technology, production costs have to be considered and scrutinized [4]. These costs are crucial in making the decision as to which manufacturing technology should be selected for a particular product. Developing a cost model can help companies see what financial options are best for them.

Therefore this work intends to increase the knowledge of the economical side of MAM in the aerospace industry. With the purpose of understanding all types of costs inherent to this type of manufacturing and in what situations AM can be competitive, a cost model and a time estimate model for a metal AM technology were developed and applied to a case study.

In addition to the cost model, with the possibility of AM producing lighter parts, there is the potential to reduce the weight of aircraft. This reduction can translate into fuel savings, which will also be studied in this work.

2. Literature review

The development of AM is influencing the manufacturing sector, with its inevitable social and economic changes, such as decentralization, flexibility in product development, individualization on demand, resource efficiency, and short development periods [5]. Aerospace companies are using AM in this context, applying new designs that reduce aircraft weight, while reducing their expenses for raw materials.

2.1. AM processes

There are two main groups of components in aerospace, metallic and nonmetallic (mainly polymer). The American Society for Testing and Materials (ASTM) International Committee F42 organizes AM technologies into seven main categories, which are binder jetting (BJ), direct energy deposition (DED), material extrusion, material jetting (MJ), powder bed fusion (PBF), sheet lamination, and vat photopolymerization [6]. Of these seven types of processes, only four of them use metal, in addition to other materials, BJ, DED, MJ and PBF.

The two most usual AM technologies for aerospace applications are DED and PBF. DED is, as stated in the ASTM definition, a process that uses thermal energy to melt materials together as they are deposited, typically taking place within an inert gas atmosphere [6]. In turn, ASTM defines PBF as a process that selectively melts powder in a bed of powder, using thermal energy, in the form of a laser or an electron beam [6].

2.2. Capabilities and challenges of AM

AM, and in particular MAM, presents a large number of opportunities in various industry sectors, particularly in the aerospace sector [1], to fill in gaps or improve existing technologies.

AM, when placed side by side with traditional manufacturing, presents numerous advantages, such as being better for prototyping, allowing more complex designs, lighter parts, a decentralized manufacturing, more customization and production of spare parts. AM also contributes to reducing material waste. This technology does not require tooling and is more effective in low productions. Finally, AM may lead to potential benefits for worker health.

Although the manufacturing paradigm can be changed globally in numerous sectors, AM technology, more in concrete MAM, is still an immature technology [7] and for that reason it presents some drawbacks, having some obstacles that prevent it from dethroning traditional manufacturing, at least in the short term. AM has to overcome certain challenges in the near future, presenting some disadvantages such as a high cost, size limitation, quality issues, regulation, lack of specialized personnel, software and knowledge, high process time, skepticism and requiring post-processing.

Understanding the weaknesses stated above may take some time, however, in the near future, it is anticipated that many of these mishaps can be overcome.

2.3. Cost Models

As referred previously, AM presents many advantages when compared with conventional manufacturing, and professionals and technology observers state that AM may disrupt the manufacturing business, being the bridge for a completely digital manufacturing [8]. Nevertheless, in order to proceed with this transition, it is necessary to have a realistic view of the economy of the complete process associated with the technology, according to each industry and business. To do so, a cost model should be built to help business professionals with decision making.

For cost models related to AM, the first relevant one was developed by Hopkinson and Dickens [9] in 2003. The authors carried out an analysis of the rapid manufacturing and rapid tooling costs, comparing the costs of these processes with the ones of injection molding (IM), in order to find out whether they were economically convenient.

In 2006, Ruffo et al. [10] analyzed the production costs of the same part as the work of Hopkinson and Dickens, manufactured using the SLS process. The cost of AM parts calculated in this work used a cost structure divided in several activities. In this work, a build time estimation was achieved using an empirical estimation algorithm, with this approach being only correct for the production of numerous parts with the same geometry.

Baumers and his research group [11] were the first to examine the economic and energetic aspects, analyzing the time necessary to complete the AM building [4]. The energy costs were listed in the direct costs and it was performed an analysis of energy consumption, making the model more accurate. However, activities like post-processing and material removal were not consider.

In turn, Lindemann [12] has developed an event-driven process chain model for all relevant cost processes in AM production. He included the building job preparation, the building job production, the support removal, and the post-processing activities.

In addition to the works presented, several other works were conducted in the area of cost modeling on AM, however the review of the cost models is not within the scope of this work, so it will not be detailed.

3. Methodology

In this work it was developed a cost model, which aims to calculate the cost of producing parts through MAM. In parallel with a study of fuel consumption, the main goal is to understand in which situations MAM can be competitive in the aerospace industry. The methodology of the work is presented in figure 1.

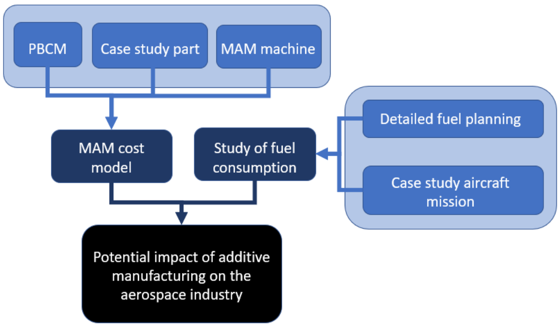

Figure 1: Study scope.

3.1. MAM machine and case study part

In order to achieve that goal, an illustrative part of the aerospace sector was used as a case study. This part has been optimized in terms of weight, outside this work, achieving a mass reduction of about 36%. A set of these parts was printed by a MAM machine, Renishaw AM 400, which belongs to the Hypermetal company. This machine uses the manufacturing process PBF and was also used in this case study. The parts were printed using a Maraging steel M300 powder.

The values from the optimization process have been made available and will be used later in conjunction with a detailed fuel planning to ascertain the importance that weight reduction provided by MAM can have in the aerospace sector.

3.2. Process-based cost modeling

PBC models are systems that focus on the processes (set of activities), that make up the main process, as basic cost objects, using these processes as building blocks to compile the costs to be known. The costs are attributed to the processes based on the consumption of resources used, with the final product projected cost being calculated from the costs of the specific processes a product has to go through [13].

The cost is divided into two categories: variable cost and fixed cost. A variable cost is a cost directly connected with the production of a unit of output and varies roughly linearly with the total number of units produced. In turn, a fixed cost is a cost that does not vary linearly with production volume, it remains the same even if there is no production [13].

4. MAM cost model

In this chapter, the developed cost model is presented, with a particular focus on the process model used to estimate the build time. A method for measuring the fuel used by an aircraft is also presented, in order to calculate the fuel savings that can be achieved by weight reduction in aircraft.

4.1. Activities

The AM process was divided in activities. The first phase of the process, pre-processing, consists in two activities: data preparation (DP) and setup. In the first activity, the operator creates the STL file from the CAD file, implementing the meshes needed for the parts and generating the necessary supports to hold the parts.

In the second activity, the operator prepares the machine with everything required for its operation. The powder feedstock required for production should be placed inside the machine as well as a new argon gas cylinder in case there is not enough gas inside the cylinder in use. The operator must certificate that the filter in use is in good conditions and if that did not occur, a new filter must be inserted inside the machine. This activity also englobes the loading and aligning of the build board, upon which the parts will be produced, the dimensional control of the board, and the laser lens cleaning. The used board is reused from previous productions, with the top of the board being thinned before each use.

The second phase is the processing, which includes every step of the AM process. The build print (BP) divides in different steps: warming up, where the board is heated; inertization, where argon gas is used to make the environment inside the chamber inert; scanning and coating, where in the first, the laser scans the section area corresponding to that layer for all parts to be produced, sintering the powder, and in the second, for each layer, a new coat of powder is scattered by the machine; and the step of cooling down the machine.

The last phase corresponds to the post-processing, which includes the build removal and cleaning (BRC), and treatment activities. First, it is necessary to remove the excess powder from the inside of the machine. Then the operator removes the build, cleans the inside of the machine and collects the debris such as burnt powder and filtered waste, storing them in a suitable place. After several productions, a company must be hired to collect the waste that has been stored to date. The last set of activities encompasses all the post-processing treatments required so that the final parts meet the desired conditions.

For each activity, there are different types of costs, as seen before, variable and fixed, that are required for production. The variable costs are divided into material, labor, energy and consumables costs, with the latter including the board, gas, debris removal and filter costs. The fixed costs are divided into machine, building, maintenance and equipment costs.

In each activity the production costs per year and the production cost per part were calculated. The production cost per part is calculated by dividing the production costs per year by the total number of parts the company requires to produce, either for internal use or according to market demand. This number differs from the number of parts actually produced by the company, as it takes into account the number of parts rejected during the activities.

The total yearly production cost is then computed by adding the annual costs of each one of the activities as can be observed in equation 1.

$$C_{Year} = C_{DP} + C_{Setup} + C_{BP} + C_{BRC} + C_{Treatments}, \quad (1)$$

with C_{DP}, C_{Setup}, C_{BP}, C_{BRC} and $C_{Treatments}$ being the annual costs of each activity.

4.2. Data preparation

The only variable cost to be taken into account in this activity is the labor cost. The cost of energy associated with the use of computers was neglected because it represents a very insignificant value when compared to the overall energy costs.

Equation 2 presents the calculation of the number of batches (runs of parts) produced per year, $N_{batches}$, with this value being used throughout the entire cost model, since each production corresponds to one batch.

$$N_{Batches} = \frac{N_{Total}}{N_{Parts\,per\,batch}}. \quad (2)$$

The labor cost for this activity, $C_{DP\,Labor}$, is the multiplication of the time devoted to the activity by the hourly cost of the operator.

For fixed costs, the costs of the building, $C_{DP\,Building}$, the purchase of equipment (software and hardware), $C_{DP\,Equipment}$, and the cost of renovation per year of the same equipment,$C_{DP\,Ren}$, are calculated.

Considering the previous costs as single payments, they require an allocation of costs to the duration of production. To do this, it is necessary to calculate the annual production time (uptime), which includes the production time of this activity corresponding to the parts for which the costs are being calculated and the remaining parts that could be produced, even if this does not happen. Production is therefore not dedicated, as the machine and tools are not only designed for the production of a certain part.

The costs are then calculated taking into account the respective time portion of the activity for the parts considered compared to the annual production time. It is also necessary to annualize the single expense, capturing its associated opportunity cost, by multiplying its value by the capital recovery factor (CRF):

$$CRF(r, n) = \frac{r(1+r)^n}{(1+r)^n - 1}, \quad (3)$$

where n represents the number of periods over which the cost is allocated, and r symbolizes the discount rate representative of the time value of tying up assets in this capital. For this equation, the number of periods may be different for each of the cost elements, even considering the same process.

The total cost of data preparation is calculated by adding the different costs, in equation 4.

$$C_{DP} = C_{DP\,Lab} + C_{DP\,Building} + C_{DP\,Equipment} + C_{DP\,Ren}. \quad (4)$$

4.3. Setup

For the Setup activity there are only variable costs, which are divided into labor costs and costs associated with the board that serves as the basis for the production of parts. Labor cost, $C_{Setup\,Labor}$, is calculated in a similar way to the previous activity.

In relation to the costs of the board, $C_{Setup\,Board}$, since each board is used several times, the cost of the board itself has been neglected, because the value divided by all uses is much lower than the cost of the necessary roughing before each production. Therefore, the cost of the board is calculated by multiplying the number of batches by the cost of roughing.

The total cost of this activity is obtained by adding the previous costs, in equation 5.

$$C_{Setup} = C_{Setup\,Labor} + C_{Setup\,Board}. \quad (5)$$

4.4. Build print

To calculate the production costs it is first necessary to address the build time. The build time, t_{BP}, is the sum of the times of each production phase, warming up, t_{Warm}, inertization, t_{Inert}, coating, t_{Coat}, scanning, t_{Scan}, and cooling down, t_{Cool}, times.

It was observed that the inertization time is a constant time that depends on the machine, different machines can have different inertization times, similar to the coating time, which also being constant varies depending on the machine. The total coating time will depend not only on the time for each layer, but also on the number of layers required for the production of the parts, hence on the maximum build height.

The heating time of the board varies depending on the board material and it is constant for boards of the same material, differing from machine to machine, depending on their specifications. The cooling time varies with the material and has been found to be almost constant for each material used, varying slightly with the height of the parts. However, since this time difference is very small compared to the rest of the production time, it has been neglected.

Lastly, the scanning time varies with the volume of the parts, since the greater the volume to be produced, the longer the laser has to sinter the powder. This variation will be analyzed in detail below, since this time is what most influences the final build time and its value varies from production to production. Together with the total coating time, these two are the times that will depend on the geometry of the parts to be produced.

In order to understand how the scanning time is influenced, the following study was carried out.

It was assumed that the total volume of a production was represented by the volume of a parallelepiped with a constant section area, $\bar{A}_{surface}$, having the same maximum height as the original section. The maximum height is the value of the highest height among the parts to be produced, since the scanning only ends after the last layer corresponding to the highest part is produced.

The total coating time is calculated by multiplying the coating time of each layer by the number of production layers, which is obtained by dividing the maximum height by the thickness of the layers.

The scanning time is therefore calculated by removing the individual times of the process phases from the total build time. It was then assumed that the scanning time for each layer was constant, $\bar{t}_{Scan\,layer}$, since the layers to be produced would have the same area, thus taking the same scanning time.

Then this average time to scan a layer was divided by the average section area, obtaining in equation 6 an average scanning time per unit area $[s/mm^2]$, for the simplifications made.

$$\bar{t}_{Scan} = \frac{\bar{t}_{Scan\,layer}}{\bar{A}_{surface}}. \qquad (6)$$

The company Hypermetal made available data from seven productions that used the same material as the case study part. This data contained the time the machine is working on the parts, i.e. the sum of the scanning time and the total coating time, the maximum height of each production, and the total volume of the productions, which includes the total volume of the parts and the volume of the supports used.

In figure 2, it is observed that the average scanning time per unit area does not vary significantly with the volume, with a difference of less than one thousandth of a second per mm^2 between the lowest and the highest value. These values indicate that regardless of the geometry of the parts to be produced, on average the scanning time per unit area remains constant.

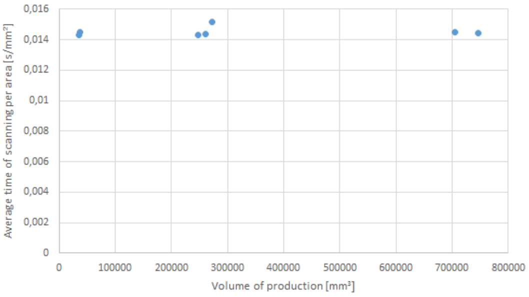

Figure 2: Average scanning time per area unit for different production volumes.

Assuming the hypothesis that the value of the average scanning time per unit area is independent of the volume of production, the average value for the production data is calculated, $Average(\bar{t}_{Scan})$. The estimated time for the total scanning time, $t_{estimated\,scan}$, is then calculated in equation 7.

$$t_{estimated\,scan} = Average(\bar{t}_{Scan}) \times \bar{A}_{surface} \times \frac{h_{max}}{d}, \qquad (7)$$

with h_{max} and d being the maximum height and the thickness of each layer, respectively.

For the present activity, the variables costs are related to material, energy, gas and filters. The cost of the material is obtained by multiplying the material price by the material required for the annual production volume, taking into account the material loss factor (percentage of powder burned during the process that cannot be reused). The cost of energy was based on the work performed by Baumers et al., 2012 [11]. This calculation is a simplification, since it assumes that the machine always works at its maximum power during the production time. The cost is then obtained by multiplying the power of the machine by the annual production time and the price of electricity. The cost of gas and filters is calculated taking into account annual production and usage rate per use.

Fixed costs consist of the cost of the machine, which is calculated taking into account its price and utilization rate, the cost of the building, which is associated with the machine area plus the safety area around it, and the maintenance cost, which can be calculated as an annual cost or as a percentage of the fixed costs. These costs are considered as investments and annualized.

The total cost of this activity is then obtained by adding the previous individual costs in equation 8.

$$C_{BP} = C_{BP\,Material} + C_{BP\,Energy} + C_{BP\,Gas} + C_{BP\,Filter} + C_{BP\,Machine} + C_{BP\,Building} + C_{BP\,Maintenance}, \quad (8)$$

4.5. Build removal and cleaning

In this activity there are only labor costs, debris removal costs and building costs. The labor cost is calculated by multiplying the hourly cost of the operator by the sum of the time to remove the parts from the board (the time to remove the supports of a part multiplying by the total number of parts) and the time to clean the machine, after each batch has been printed. The cost of debris removal is calculated taking into account the number of times it is necessary to remove debris per year and the cost per removal. Finally, the building cost, is calculated using a simplification. It is assumed that it is necessary to reserve a certain space to place the debris and that this space would be only for an annual production of a certain part. In reality, the space utilized is used for all the productions made by the machine. However, it was observed that this space is small, and that removal does not happen often, so this simplification is a good approximation.

The total cost for this activity is again the sum of the previous costs, as shown in equation 9.

$$C_{BRC} = C_{BRC\,Labor} + C_{BRC\,Debris\,removal} + C_{BRC\,Building}. \quad (9)$$

4.6. Post-processing treatments

The treatment processes are important so that the parts can obtain the desired characteristics. Different parts need different treatments, depending on their purpose. It is possible for the company itself to carry out these treatments if it acquires the necessary tools, or if it does not, the treatment is subcontracted to an external entity. This cost model has these two alternatives included.

The cost for each treatment process made in the company itself is calculated taking into account the rate of use corresponding to the parts considered. It is then calculated the labor cost, the cost of the equipment and the cost of the building in a similar way to what was previously presented, with the cost of each treatment being shown in equation 10.

$$C_{Treatment} = C_{Treatment\,Labor} + C_{Treatment\,Building} + C_{Treatment\,Equipment}. \quad (10)$$

The process-based cost model used in this work consists of an Excel-based interface that includes all the work breakdown mentioned above, in more detail.

4.7. Fuel Consumption in Aircrafts

In the previous chapter it was mentioned the process of parts optimization that can be performed due to the AM technology, creating lighter parts. Considering that an aircraft can have different parts that may go through the same optimization process, it was studied the effects that weight reduction in an aircraft has on fuel consumption.

To perform this study, several assumptions were made, based on values present in publications and values present in the aircraft characteristics. For the base case, an aircraft, A319 with 4800 annual flight hours, was assumed without any reduction in mass, 62 000 kg, and a certain mission that was present on one of TAP's routes, the Portuguese airline, from Lisbon to Berlim, taking 3,5 hours and corresponding to 1249 NAM.

The analysis of the fuel used in the mission under consideration was then carried out using the tabulated data from the Civil Aviation Authority's Flight Planning Manual [14] for the aircraft under consideration. Using these data, fuel consumption was calculated for each of the flight phases, climb, cruise and descent. The same process is performed for lower aircraft weight values. The fuel spent for a lighter aircraft weight is calculated and the difference between this value and the value first calculated for the aircraft with the weight unchanged is obtained.

Taking into account the fuel consumption reduction, the most recent value for jet fuel (August 2019) as well as the minimum and maximum values over the last fifteen years are presented, in table 1, based on the work of Laureijs et al., 2017 [15]. These values are found in table 1, where they were converted from $US\,dollar/gallon$ to $US\,dollar/kg$ using $3,04\,kg/gallon$ [14], and then converted for the euro currency (for the Euro area), using the purchasing power parities (PPP) rate of the year 2018 [16], for a better comparison between different currencies. It is then possible to quantify the financial impact of weight reduction on an aircraft, considering the cost of the part and the value of fuel saved.

Case	**Lowest**	**Recent**	**Highest**
Fuel price [$€\,PPP/kg$]	0,22	0,43	0,94

Table 1: Lowest, highest and recent jet fuel prices for the last 15 years.

5. Results

This chapter presents the results obtained for the time estimation and the cost model presented above, as well as the analysis of the fuel consumption for weight reduction in an aircraft.

5.1. Estimated build time

In order to test the hypothesis previously raised that the value of the average scanning time per unit area is independent of the volume of production, it was used the production data of the part under analysis in the case study. The estimated time for the total scanning time, $t_{estimated\,scan}$, is then calculated as shown in equation 7, with the average value for the production data calculated before.

When comparing the sum of the total scan and coating time, t_{Prod} obtained in the case study with the estimated time for this same time, in equation 11, an error of less than 1.3% was obtained.

$$Error_{Prod} = \frac{|(t_{estimated\,scan} + t_{Coat}) - t_{Prod}|}{t_{Prod}}. \tag{11}$$

The values of the errors obtained were presented in modulus, but the value of the estimates are underestimated values, being, however, very close to the values that were measured, presenting a good approximation.

5.2. Comparison between AM and Forging

For the present case study, the values needed to provide results were collected from the company Hypermetal. These values are mainly mean values and assumptions that were made considering the information given by the company.

Currently, a company that produces parts through AM for the aerospace industry needs certification. Such certification means that the company has a robust quality system and that there is control over the supplier in order to ensure the reproducibility of the properties on the type certificate [15]. For MAM, this means that a manufacturer with a machine certified to produce certain parts is not authorized to produce different parts without re-certifying the machine for the new production. Any change to the quality system is therefore subject to review by the regulatory authorities. For that reason, a certified machine, if not fully utilized, cannot be used for other applications, and consequently its production is dedicated. This lack of flexibility ultimately affects the economic viability of MAM for the production of parts in small volumes, which is the range where AM is more competitive when compared to traditional manufacturing [15].

Using a cost model for the forging process [17], it was compared, in figure 3, the difference in cost per part for the different production volumes for the forging process and for the MAM process in the cases where the production is dedicated and non dedicated. The latter case would represent a machine that could produce any part. Dedicated MAM production is found to be not economically competitive in relation to production costs, regardless of production volume, and the cost per part is extremely high when compared to traditional manufacturing. In order for this type of manufacturing to be able to compete with traditional manufacturing of aerospace parts, it is necessary to develop MAM technologies in order to ensure the reproducibility of the process, which means having a non dedicated MAM process for the aerospace industry.

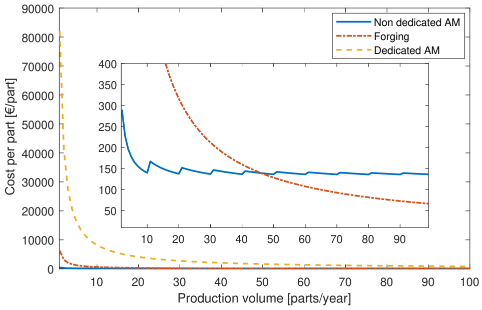

Figure 3: Comparison between dedicated and non dedicated MAM production and forging.

It can be observed that non dedicated MAM has a lower cost per part for a lower production volume when compared to this traditional process. A limit value of 10 parts per batch was also assumed, according to the case study. This is why the non dedicated MAM chart has a saw tooth shape, since for a new part produced in a new batch, the machine costs are added for the use of the machine for the extra batch containing only one part.

A comparison is then made of the cost distribution for the MAM and forging processes, in figure 4. For an annual production volume of 50 parts, the vast majority of the cost of MAM production is associated with the cost of the machine, due to the high production time and price of the machine. In forging, it is the cost of tooling that takes up the majority of the cost, for lower productions. This tooling cost, which represents almost the total cost in forging for low production volumes, does not exist in AM, which is one of its advantages.

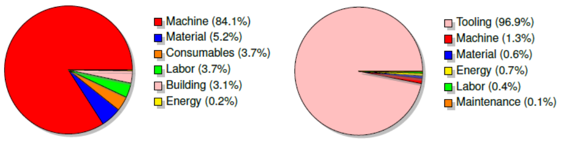

Figure 4: Distribution of the costs of MAM and forging for an annual production of 50 parts.

When comparing the costs of the process steps in the MAM, most of the cost is associated with processing, representing 94.8% of the total cost, for a annual volume of production of 100 parts. The pre-processing and the post-processing present 3.1% and 2.1%, respectively. Although the cost of post-processing treatments was not calculated for the case study, it is important to note that these costs may represent a high percentage of the final cost of the part [18].

5.3. Sensitivity analyses

In order to better understand how inputs inserted into the model can influence the cost per part, sensitivity analyses were performed. In the figure 5 is represented the variation of the cost per part for different values of parts per batch and, as can be seen, the more parts produced per batch, the lower the cost per part is.

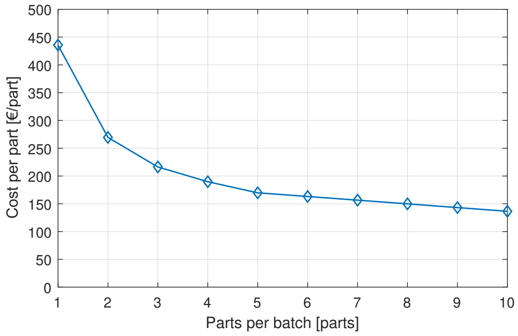

Figure 5: Sensitivity analysis for the number of parts produced per batch.

The fewer parts that are produced, the less time is needed per production, however, more batches need to be produced for the same annual production number. It should be noted that, as mentioned above, there are times that are constant regardless of the number of parts per batch. The implication of this fixed time causes the difference in cost per part of the production of only one part for the production of two parts per batch to be so accentuated. With an increase in the number of parts per batch, the cost per part is reduced, which is why the number of parts to be produced per batch in this MAM process should always be optimized.

The cost per part is also influenced by the value of the machine uptime. The higher this value is, the lower the cost per part value is. A machine that can produce a high number of hours has its cost per part reduced due to the distribution of the cost of the machine over the high number of parts it produces. The figure 6 represents the machine uptime sensitivity analysis for a production volume of 50 parts per year.

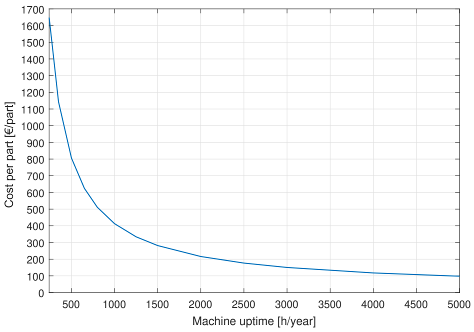

Figure 6: Machine uptime sensitivity analysis, for an annual production of 50 parts.

The first value present in the figure represents the cost per part for the dedicated production, as mentioned above. It is observed that for a high value of the machine uptime the cost per part is substantially reduced.

AM cannot be competitive for a large volume of production for the same part when compared to forging. However, given that the AM process allows the production of several parts with different geometries, for a high machine uptime, this type of manufacturing can be extremely advantageous. With a low production volume for parts of various geometries, it is possible to obtain a high machine uptime and a low cost per part for each geometry considered.

Currently the price of MAM machines is high, as machine producers try to recover the high investments they have made in research and development. The price of machines is expected to fall considerably in the future when the machines are produced on a large scale, the patents associated with the technologies expire, and the competition in the market is established [19].

For an annual production of 50 parts, a reduction in machine price directly influences the cost per part. For a decrease in the price of the machine from 500 000 € to 400 000 €, the cost drops from 149,82 € to 124,61 €. For a machine price of 300 000 €, the cost per part drops to 99,41 €. With these values, it is observed that the cost per part is considerably reduced, for a decrease in the price of the machine.

5.4. MAM parts in the aeronautic industry

Using the considerations made, the monetary value of the decrease in fuel use for a part reduction in an aircraft was calculated. It was possible to obtain the difference in fuel used between the original aircraft weight case and the case with the reduction. This value is then multiplied by the fuel price taking into account the three scenarios mentioned above, the lowest, most recent and highest fuel price in the last 15 years. It is then presented, in table 2, the amount saved for one year.

Case	Lowest	Recent	Highest
Annual savings [€PPP]	8,39	16,23	35,09

Table 2: Annual value saved for each of the scenarios considered, for weight reduction corresponding to one part.

The annual savings are representative of the difference that exists with the use of an optimized part in an aircraft. The present value is then calculated for savings made over a certain number of years, with the difference between the cost per part of MAM and forging being added.

The lifetime of the parts was not taken into account here, being neglected the difference between the parts optimized using MAM and the original parts using forging, since this study was outside the scope of this work. No consideration was given to the eventual costs that the modification of the parts would have, such as maintenance that the parts would need to undergo or any investment value associated with the optimization process.

For a part lifetime of 5, 10 and 15 years, using only the recent fuel price, the PV for fuel savings for one part used is 40,39 €, 78,61 € and 102,33 €, respectively, for a production volume of 50 parts. However, these amounts itself do not represent a large amount of money, given that it is being referred to large periods of time and only one part.

Huang et al., 2016 [20], estimate that an average aircraft can have from 250 to 510 kg of metal auxiliary parts, which covers all non-structural and non-functional components, including those with small dimensions (e.g. brackets, hinges and clips) [20]. Assuming then that 510 kg of metal parts suffer the same process of optimization as the part of the case study, it was made an analysis of how much an aircraft could save in fuel over the same time periods considered previously. For a weight reduction of 202 kg, it is possible to save per year 22 594,99 €, considering the recent fuel price case.

In table 3, it is then presented the values of PV for fuel savings, with a weight reduction of 202 kg.

Period of time	Recent [€PPP]
5 years	60 880,74
10 years	114 064,37
15 years	147 087,23

Table 3: PV for fuel savings assuming an aircraft weight reduction of 202 kg, for a parts lifetime of 5, 10 and 15 years.

It can be seen that for a 202 kg weight reduction in an aircraft, the fuel savings become more significant. These values show that there is a significant potential for MAM to be present in the industry being that certain conditions are met. Even so, there is still much to be done in the future, until the MAM can be definitively established.

6. Conclusions

AM has numerous advantages that can be used by several industries. The ability to create highly complex parts and redesign existing parts to make them lighter is a major factor and one of the reasons why the aerospace industry has shown so much interest in AM, with a particular focus on MAM.

When compared to a conventional process, such as forging, MAM presents a lower cost per part for a lower annual production volumes. The cost of the machine occupies a large part of the percentage of the final cost. In the analyzed case, this is due not only to the high purchase price of the machine, but also to the high process time, which leads to a high utilization of the machine and consequent high allocation of costs per part. Regardless of the number of parts produced annually, the machine always has the most influence. With prices of MAM machines and materials expected to drop, when MAM machines begin to be produced on a large scale and there is greater market competition, the cost per part using this manufacturing process will also decrease.

In this work, the possible use of the parts produced by this technology in terms of fuel consumption was also studied. Therefore, the effect that a reduction in the weight of an aircraft translates into a monetary saving of the spent fuel was analyzed. It is concluded that it is possible to benefit financially from the adoption of MAM. This may not be evident when is is considered a small weight reduction, but for a large weight reduction, the amounts tend to become significant. The results represent the values for only one aircraft and it is important to point out that if this change happened on several aircraft, this value would be ultimately higher.

When mentioning MAM in the aeronautical sector, there is still a critical aspect, certification of parts, that was not taken into consideration in this work. At the moment, machines certified to produce a certain part are not allowed to produce any other part, becoming dedicated machines. This scenario is a major obstacle to the implementation of MAM in the sector. Nevertheless, with the development of technology, the next step to be achieved will be the development of technology capable of ensuring the right conditions to produce several parts of different geometries. Changing the auxiliary parts in an aircraft may require less control in terms of certification [18] and could be MAM's short-term focus on this industry.

In the study case analyzed, the costs of post-processing treatments were not taken into account. This limitation prevents accurate observation of all the costs involved in the production of a part. Another constraint to be mentioned is the fact that the material considered in the cost calculation is not the most suitable for the aerospace industry. It should also be noted that the conclusions drawn in terms of fuel consumption with weight reduction are limited because only fuel savings have been considered, without taking into account other costs which might be associated with the modification of parts produced by traditional manufacturing to parts produced by MAM.

A potential future work is identified here, consisting of carrying out an analysis of the costs associated with the certification process. It is also recommended that a study be carried out that covers not only the value saved, but also a life cycle assessment, analyzing the environmental impact that this reduction in fuel use may have.

Finally, the integration and development of the cost model into a company's overall production process is suggested in order to facilitate decision making, beyond the simple decision to produce a part between two manufacturing processes. Reducing inventory costs, decreasing the time it takes to order parts and shortening supply chains could be combined with the cost of the part by conducting an overall analysis of the MAM in order to clearly understand to what extent this process can prove to be a major competitor to traditional manufacturing processes.

References

[1] Tanisha Pereira, John V. Kennedy, and Johan Potgieter. A comparison of traditional manufacturing vs additive manufacturing, the best method for the job. *Procedia Manufacturing*, 30:11–18, 2019.

[2] Wei Gao, Yunbo Zhang, Devarajan Ramanujan, Karthik Ramani, Yong Chen, Christopher B. Williams, Charlie C.L. Wang, Yung C. Shin, Song Zhang, and Pablo D. Zavattieri. The status, challenges, and future of additive manufacturing in engineering. *CAD Computer Aided Design*, 69:65–89, 2015.

[3] N. Kemakolam, A. Shokrani, S. Wikshåland, F. Xu, V. Dhokia, S.T. Newman, and C.R. Cunningham. Cost Modelling and Sensitivity Analysis of Wire and Arc Additive Manufacturing. *Procedia Manufacturing*, 11(June):650–657, 2017.

[4] M. Fera, F. Fruggiero, G. Costabile, A. Lambiase, and D. T. Pham. A new mixed production cost allocation model for additive manufacturing (MiProCAMAM). *International Journal of Advanced Manufacturing Technology*, 92(9-12):4275–4291, 2017.

[5] Heiner Lasi and Hans-Georg Kemper. Industry 4.0. *Smart Innovation, Systems and Technologies*, 132:205–215, 2014.

[6] ASTM INTERNATIONAL. Standard Terminology for Additive Manufacturing Technologies, 2013.

[7] Jaime Bonnín Roca, Parth Vaishnav, M. Granger Morgan, Joana Mendonça, and Erica Fuchs. When risks cannot be seen: Regulating uncertainty in emerging technologies. *Research Policy*, 46(7):1215–1233, 2017.

[8] Martin Baumers, Ricky Wildman, Martin Wallace, Jae Yoo, Brett Blackwell, Phil Farr, and Clive J. Roberts. Using total specific cost indices to compare the cost performance of additive manufacturing for the medical devices domain. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 233(4):1235–1249, 2019.

[9] N. Hopkinson and P. Dickens. Analysis of rapid manufacturing - Using layer manufacturing processes for production. *Proceedings of the Institution of Mechanical Engineers, Part C: Journal of Mechanical Engineering Science*, 217(1):31–40, 2003.

[10] M. Ruffo, C. Tuck, and R. Hague. Cost estimation for rapid manufacturing - Laser sintering production for low to medium volumes. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 220(9):1417–1427, 2006.

[11] M. Baumers, C. Tuck, R. Wildman, I. Ashcroft, E. Rosamond, and R. Hague. Combined build-time, energy consumption and cost estimation for direct metal laser sintering. *23rd Annual International Solid Freeform Fabrication Symposium - An Additive Manufacturing Conference, SFF 2012*, (January 2016), 2012.

[12] Christian Lindemann, Ulrich Jahnke, Matthias Moi, and Rainer Koch. Analyzing product lifecycle costs for a better understanding of cost drivers in additive manufacturing. *Proceedings of the 23th Annual International Solid Freeform Fabrication Symposium*, 23(9):177–188, 2012.

[13] R Kirchain and F R Field. Process-based cost modelling: Understanding the economics of technical decisions. *Encyclopedia of Materials Science and Engineering*, 2:1718–1727, 2001.

[14] Civil Aviation Authority. CAP 697 Flight Planning Manual. Technical Report July, 2006.

[15] Rianne E. Laureijs, Jaime Bonnin Roca, Sneha Prabha Narra, Colt Montgomery, Jack L. Beuth, and Erica R.H. Fuchs. Metal additive manufacturing: Cost competitive beyond low volumes. *Journal of Manufacturing Science and Engineering, Transactions of the ASME*, 139(8):1–9, 2017.

[16] OECD. Purchasing power parities (ppp) (indicator), 2019. Accessed: 2019-10-04.

[17] I. Ribeiro, J. Kaufmann, A. Schmidt, P. Peças, E. Henriques, and U. Götze. Fostering selection of sustainable manufacturing technologies - A case study involving product design, supply chain and life cycle performance. *Journal of Cleaner Production*, 112:3306–3319, 2016.

[18] Jaime Bonnín Roca, Parth Vaishnav, Rianne E. Laureijs, Joana Mendonça, and Erica R.H. Fuchs. Technology cost drivers for a potential transition to decentralized manufacturing. *Additive Manufacturing*, 28:136–151, 2019.

[19] C. Y. Yap, C. K. Chua, Z. L. Dong, Z. H. Liu, D. Q. Zhang, L. E. Loh, and S. L. Sing. Review of selective laser melting: Materials and applications. *Applied Physics Reviews*, 2(4), 2015.

[20] Runze Huang, Matthew Riddle, Diane Graziano, Joshua Warren, Sujit Das, Sachin Nimbalkar, Joe Cresko, and Eric Masanet. Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. *Journal of Cleaner Production*, 135:1559–1570, 2015.