TÉCNICO LISBOA

Metal Additive Manufacturing in Aeronautics: a Life Cycle Cost Perspective

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Thesis to obtain the Master of Science Degree in

Aerospace Engineering

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November 2019

To Isaura and Joaquim

Acknowledgments

First of all, I would like to express my sincere gratitude to Professor Inês Ribeiro and Professor Joana Mendonça for all the support, guidance and remarks throughout this dissertation and for giving me the opportunity to work in an area that I find interesting and important.
I would also like to extend a special thanks to Engineer Gonçalo Cardeal for having shown availability to help me, advise me and make suggestions whenever it was necessary.
I would like to thank all the members who worked alongside me during this time and who were always ready to help and give advice.
I would like to mention my dear friends, for their constant support not only in these months, but throughout my journey both academically and personally. I would like to thank my faithful childhood friends, my high school friends, the friends I met on my sports path and the magnificent friends I met in this institution, all of whom were extremely important to me.
Finally, I would like to thank the most important people in my life, my family, for their support and unconditional love throughout my life. For always caring about me, for always believing in me, regardless of everything, and for making me who I am today. I would like to thank and mention my grandmother Aida who has always been like a second mother to me, my aunt Silvia, who played the role of older sister, whenever I needed, and especially the two most important people in my life, my father José and my mother Paula, because without them I would not have been able to reach this point.

Resumo

Atualmente, o fabrico aditivo mostra um enorme potencial em várias indústrias, como a aeroespacial, devido às suas vantagens. Caracterizada pela produção de peças camada a camada, esta tecnologia consegue produzir peças mais complexas e leves quando comparada com o fabrico convencional. Apesar de existir há algumas décadas para outros materiais, o fabrico aditivo em metal vem emergindo, podendo revelar-se fundamental no futuro.

Para se proceder à adoção de novas tecnologias, é importante analisar o seu aspeto económico. Com este intuito, esta tese pretende desenvolver um modelo de custo para um processo de fabrico aditivo de metal. Este modelo permite identificar os fatores que mais influenciam o custo de produção e, usando um caso de estudo, comparar este processo com um convencional, forjamento. Foi estudado ainda o impacto que uma redução de peso numa aeronave tem na poupança de combustível.

Aliando esta redução ao custo de produção, observaram-se os benefícios que advêm da utilização do fabrico aditivo. Esta tecnologia poder-se-á revelar muito vantajosa com o seu necessário desenvolvimento. Ao permitir o fabrico de peças de diferentes geometrias na mesma produção, para volumes de produção baixos e médios, o fabrico aditivo de metal pode competir com os métodos tradicionais e gerar poupanças elevadas, algo que na indústria aeronáutica poderá ser uma mais valia.

Palavras-chave: Fabrico aditivo, modelo de custos baseado em processos, aeroespacial, estimativa do tempo de produção, fusão em cama de pó, redução do consumo de combustível.

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 thesis 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

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Nomenclature

$A_{Building\,DP}$ Building space for data preparation.

$A_{Building\,Machining}$ Space required for the machining process.

A_{Debris} Area reserved for waste disposal.

$A_{Machine}$ Area occupied by the machine.

A_{Safety} Safety area around the machine.

$\bar{A}_{surface}$ Constant section area.

$Average(\bar{t}_{Scan})$ Average value of scanning time per unit area for the production data.

C_{BP} Annual cost of build print.

$C_{BP\,Building}$ Building space for build print activity.

$C_{BP\,Energy}$ Build print energy cost.

$C_{BP\,Filter}$ Build print filter cost.

$C_{BP\,Gas}$ Build print gas cost.

$C_{BP\,Machine}$ Machine cost.

$C_{BP\,Maintenance}$ Maintenance cost for build print activity.

$C_{BP\,Material}$ Build print material cost.

C_{BRC} Annual cost of build removal and cleaning.

$C_{BRC\,Building}$ Building space for build removal activity.

$C_{BRC\,Debris\,removal}$ Annual debris removal cost.

$C_{BRC\,Labor}$ Annual build removal and cleaning labor cost.

$C_{Debris\,removal}$ Cost of removing debris.

C_{DP} Annual cost of data processing.

$C_{DP\,Building}$ Annual data preparation building cost.

$C_{DP\,Equipment}$ Annual data preparation equipment cost.

$C_{DP\,Ren}$ Annual data preparation renewal equipment cost.

CF Cash flow.

C_{Hard} Hardware cost.

$C_{Machining\,Labor}$ Annual machining labor cost.

$C_{Machining}$ Machining total cost.

$C_{Machining\,Building}$ Building space for machining activity.

$C_{Machining\,Equipment}$ Machining equipment cost.

$C_{Maintenance}$ Maintenance cost.

$C_{Operator}$ Operator hourly cost.

C_{Part} Cost per part.

$C_{Ren\,Hard}$ Hardware renewal cost.

$C_{Ren\,Soft}$ Software renewal cost.

CRF Capital recovery factor.

$C_{Rough\,Board}$ Cost of roughing the board.

C_{Setup} Annual cost of setup.

$C_{Setup\,Board}$ Total cost of the board.

$C_{Setup\,Labor}$ Setup labor cost.

C_{Soft} Software cost.

$C_{Treatments}$ Annual cost of treatments.

C_{Year} Annual cost or production.

d Layer thickness.

$Days$ Working days per year.

$C_{DP\,Labor}$ Annual data preparation labor cost.

$Error_{Prod}$ Total production time error.

$Error_{Scan}$ Scanning time error.

h_{max} Maximum height of a production.

$Inv_{Building\,BP}$ Building space investment for build print activity.

$Inv_{Building\,BRC}$ Building space investment for build removal activity.

$Inv_{Building\,DP}$ Building space investment for data preparation.

$Inv_{Building\,Machining}$ Building space investment for machining activity.

$Inv_{Equipment\,Machining}$ Machining equipment investment.

Inv_{Hard} Hardware investment.

$Inv_{Machine\,BP}$ Machine investment.

Inv_{Soft} Software investment.

m_{part} Part mass.

n Number of periods.

$N_{Batches}$ Number of batches produced per year.

$N_{Filters}$ Number of filters used until removal is required.

$N_{Gas\,uses}$ Number of uses per cylinder.

N_{Layers} Number of layers.

$N_{Parts\,per\,batch}$ Number of parts per batch.

$N_{Required}$ Parts required for production.

N_{Total} Total number of parts produced per year.

$P_{Machine}$ Power of the machine.

$Pr_{Building}$ Building square meter price.

$Pr_{Electricity}$ Price of electricity.

Pr_{Filter} Price of a filter.

Pr_{Gas} Price of a gas cylinder.

$Pr_{Machine}$ Price of the AM Machine.

$Pr_{Machining\,Equipment}$ Price of machining process equipment.

$Pr_{material}$ Price of the material.

PV Present value.

r Discount rate.

RR_{BRC} Rejection rate of the build removal.

$RR_{Treatments}$ Rejection rate of the post-processing treatments.

t_{Filter} Hours of use of a filter.

$t_{Annual\,production}$ Annualy number of machine working hours.

t_{BP} Build print time.

$t_{cleaning}$ Machine cleaning time.

t_{Coat} Coating time.

$t_{Coat\,layer}$ Coating time for one layer.

t_{Cool} Cooling time.

t_{DP} Total data preparation time.

$t_{DP\,1}$ Data preparation time for the first batch.

$t_{DP\,n}$ Data preparation time for the following batches.

$t_{estimated\,scan}$ Estimated total scanning time.

t_{Inert} Inertization time.

$t_{Machining}$ Total machining time.

t_{Prod} Total scan and coating time.

$t_{Production\,line}$ Annual machine uptime.

$t_{removal}$ Part removal time.

t_{Scan} Scanning time.

$\bar{t}_{Scan\,layer}$ Average scanning time per layer.

$\bar{t}_{Scan}$ Average scanning time per unit area.

t_{Setup} Setup time.

t_{Warm} Warming time.

$Uptime$ Working hours per day.

$V_{production}$ Total volume of a production.

$X_{Line\,allocated}$ Percentage of process utilization.

$X_{Maintenance}$ Percentage of maintenance cost.

$X_{material\,loss}$ Material loss factor.

Acronyms

AM Additive manufacturing.
ASTM American Society for Testing and Materials.
BJ Binder jetting.
CAD Computer-aided-design.
DED Direct energy deposition.
DMLS Direct metal laser sintering.
EBM Electron beam melting.
FAA Federal Aviation Administration.
IM Injection molding.
Kt Knots.
MAM Metal additive manufacturing.
MJ Material jetting.
NAM Nautical air miles.
PBCM Process-based cost model.
PBF Powder bed fusion.
PPP Purchasing power parities.
SLA Stereolithography.
SLM Selective laser melting.
SLS Selective laser sintering.
WR Wohlers Report.

Chapter 1

Introduction

1.1 Topic overview and motivation

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

There are several related terms that usually represent AM, such as 3D printing, additive fabrication, direct digital manufacturing, and freeform fabrication [2]. These denominations all refer to 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, using a computer-aided-design (CAD), and then the software slices the data file into individual layers. The printed object is the result of adding these layers of material, one on top of the other [3]. This process is different from some traditional manufacturing methods, where material is removed from an initial workpiece [3], such as machining and milling [4].

AM technology is utilized to produce prototypes, models, parts, and components using a wide range of materials including metals, ceramics, composites, plastics, glass [4], and biological systems [3]. 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 healthcare, automobile, food, and aerospace [5], industries whose companies are helping to push this technology forward [6].

The aerospace industry was one of the pioneers in the adoption of AM [7], due to the higher disposition to pay for better functionality, as the lightweight potential, mentioned previously. First used for rapid prototyping, AM has evolved into a rapid manufacturing, which creates almost finished or, in some cases, even finished parts [2].

AM may also play an important role in the spare parts sector, providing the aptitude to produce parts on demand, reducing the amount of inventory needed for parts which are rarely ordered, in addition to the time spared and the cost associated with it [4]. This may lead to a shortening of the supply chain, ultimately bringing revenue to the aerospace industry [8].

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 [9], much of which made by the aerospace industry [10].

MAM technologies have been the subject of very intensive research and there is still much study and development to be done in many areas. Understanding the material properties and the surface treatment characteristics [11], developing software solutions to take advantage of the benefits of AM in the design, with process optimization [10], creating standards for all aspects of AM materials [11] and establishing certifications are some of the work that needs to be continued in the near future [12].

Alongside the continuous research mentioned, in order to adopt any new technology, production costs have to be considered and scrutinized [13]. 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 dissertation work intends to increase the knowledge of the economical side of MAM in the aerospace industry, through a cost model and its analysis. 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, something that will also be studied in this thesis.

1.2 Objectives

The main objectives of this dissertation are:

- Develop a cost model and a time estimate model for a metal AM technology, in order to understand all types of costs inherent to this type of manufacturing and in what situations AM can be competitive;
- Apply the cost model to a case study and analyze the results obtained;
- Study the difference in fuel consumption in an aircraft for weight reduction, associated with the advantages of AM.

1.3 Thesis Outline

In order to be able to address all the objectives proposed above, the structure of this work is defined as shown in figure 1.1.

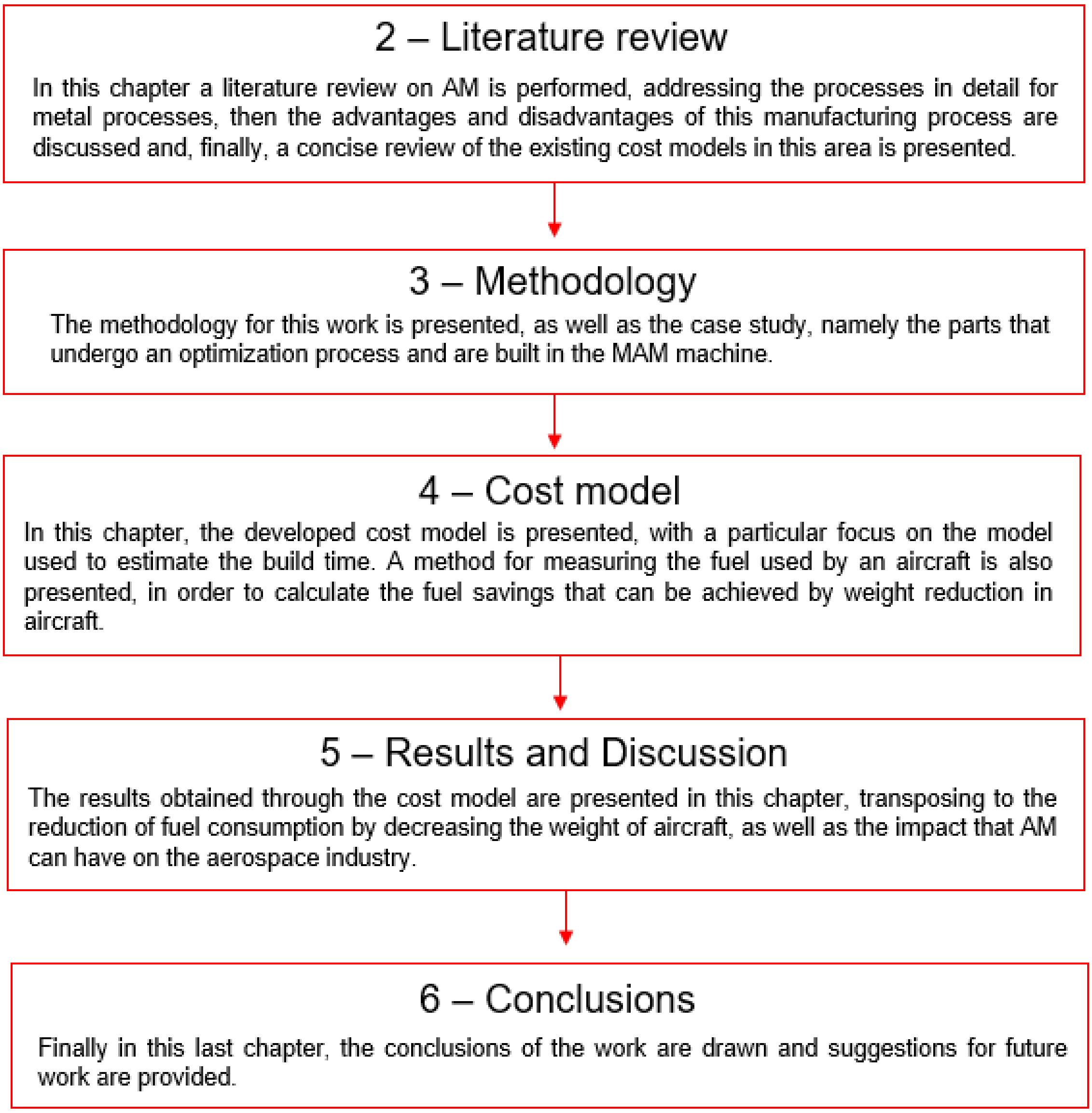


Figure 1.1: Thesis outline diagram.

Chapter 2

Literature review

This chapter lays out the grounds for this dissertation. Beginning with a brief introduction to AM, its history and the potential it may have in the future in the aerospace industry. Then the AM processes, more specifically the metal processes, are presented, followed by their advantages and disadvantages and the opportunities inherent to them. Finally, a bibliographical review of the most important cost models of the past, which will serve as a basis for the work developed in this dissertation.

2.1 Additive manufacturing

2.1.1 Background

The first ideas that anticipated this type of manufacturing go back to the 19th century. With the origin of photography in the early 1800s, inventors began to contemplate how to expand the process to a third dimension and reproduce physical objects [14]. Photo sculpture in the 1860s and topography in the 1890s were two remote ideas that gave rise to the process known today [3]. After more than fifty years without major developments in this area, it was in 1951 that Otto Munz [15] presented a system called photo-glyph recording, which has features of existing stereolithography (SLA) techniques [16]. SLA is a process in which layers of liquid polymer are solidified using a laser beam [4]. Along with Munz's patent, many photo sculpture techniques and patents are currently densely in active AM patents [14].

Two decades later, in 1971, Pierre Ciraud [17] presented a powder process that had similar features to the modern AM direct deposition techniques. The following year Ciraud proposed the first successful AM process, a powder deposition method using an energy beam [16]. Few years later, Ross Housholder, in 1979, [18] submitted a patent for a molding process for creating three dimensional objects in layers using heat and powdered feed stock [14], which was one of the predecessors of the powder laser sintering processes used nowadays [16]. A year later, Hideo Kadama developed a functional photopolymer rapid prototyping system and published about it in 1981 [19].

The first AM system commercialized was the SLA-1 by 3D Systems, in 1987 [4]. 3D Systems was co-founded by Charles Hull, who three years early filed his SLA patent [20], which was attributed in 1986, the same year as the foundation of his company [14].

In the next years a plethora of AM processes emerged. Technologies, as the desktop computer, and the accessibility of industrial lasers allowed the advance of AM [4]. Over the following twenty years, the research was continued and innovative ways to solve a variety of problems were appearing in a wide range of technical areas. Nowadays AM continues to grow academically and commercially [16]. In figure 2.1, it can be observed an increase in the number of publications on the topic of AM over the years, with an exponential growth of this number over the current decade [21].

In addition to publications, the number of AM-related patents has also increased since 1995 (in dark blue in figure 2.2), as well as the number of AM-related published patent applications since 2001 (in light purple in figure 2.2), which has skyrocketed in recent years. Most of the patents and applications are for utility patents that cover technological advances [22].

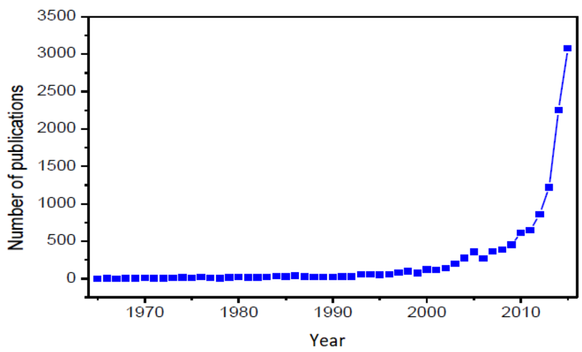


Figure 2.1: Number of AM-related publications in the last 50 years. Source: [21].

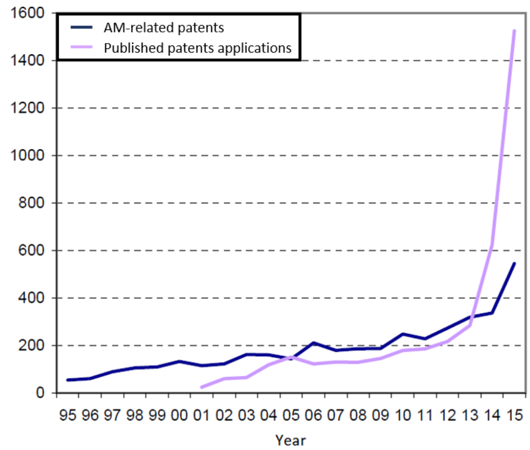


Figure 2.2: Number of AM-related patents and published patent applications in the last decades. Source: Wohlers Report 2016.

2.1.2 Potencial of AM

Taking into account all research and investment made in the last two decades, AM technology has matured very quickly and currently is used in various industries, including medical, automotive, and aerospace [23]. Although there is still a long way to go, the global AM market has followed the pace of technology and according to the Wohlers Report (WR) 2018 [24], the revenue of AM industry exceeded 7300 million dollars, with a growth of 21% over the previous year. Revenues have been increasing year after year, as can be seen in table 2.1 and this growth, according to WR 2019 [25], is expected to continue in the coming years, as presented in table 2.2, with Wohlers Associates, the AM consulting firm responsible for WR, estimating that in the long-term AM might take 5% of the total manufacturing globally [22].

Table 2.1: Revenues and growth for the AM industry from 2014 to 2017.

Wohlers Report	2015	2016	2017	2018
Revenue [million of dollars]	4100	5165	6063	7336
Growth [%]	35.2	25.9	17.4	21.0

Data sources: [26] [22] [27] [24].

Table 2.2: Expected revenues for the years of 2020, 2022, and 2024.

Year	2020	2022	2024
Estimated revenue [million of dollars]	15 800	23 900	35 600

Data source: [25].

Wohlers Associates conducts inquiries every year about the industries that use AM, receiving data from industry experts, machine and materials producers, and service providers around the world [27]. With this information, a graph with the market share is drawn up each year in each WR. In figure 2.3 and in figure 2.4, corresponding to the years 2016 and 2017, respectively, it is possible to observe that industrial/business machines are the leading industrial sector, which incorporates office equipment and industrial automation equipment. Despite having a smaller percentage than the referred sector, the aerospace sector has been showing significant growth, with an increase of 5.9% from 2013 to 2017 [27], being the fastest growing sector among the others. With the prospect of total AM revenue exceeding 100 000 million dollars over the next two decades, a large partition is attributed to the aerospace industry [28].

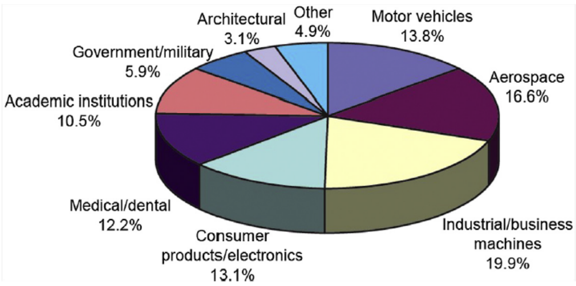


Figure 2.3: AM market share by industry in 2016. Source: Wohlers Report 2016.

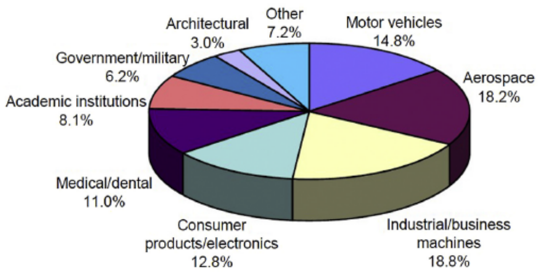


Figure 2.4: AM market share by industry in 2017. Source: Wohlers Report 2017.

The personalization capabilities are important factors for consumer products, and along with time saved and reduced environmental impact, they influence growth in the automotive industry [29]. In turn, the need to produce parts with high functionality customized to the patient's needs in the shortest time possible (e.g. implants or medical tools) helps AM to distance itself from traditional manufacturing in the medical field [30].

2.1.3 AM in the aerospace industry

The development of AM is in line with the fourth stage of industrialization, commonly identified as Industry 4.0 [31]. This influence on the manufacturing sector can be observed by the inevitable social and economic changes, such as decentralization, flexibility in product development, individualization on demand, resource efficiency, and short development periods [32]. Aerospace companies are using AM in this context, applying new designs that reduce aircraft weight, reducing their expenses for raw materials, specifically using titanium [33].

In the last years of the 20th century, companies such as Boeing and Bell Helicopter started using polymer AM parts for components that were not structural [34]. With the development of AM, it was observed that the physical and economic restrictions associated with traditional manufacturing processes could be overcome. AM brought the potential for enhancements in the part of aircraft design, which could be evident in weight reduction and performance improvement [10]. In 2003, Boeing was involved, along with the U.S. Air Force Research Laboratory, in the production of the first MAM part used on a military aircraft. To reduce the corrosion fatigue associated with aluminum parts, titanium was used in this part [35]. In 2015, Boeing had produced more than 200 unique parts for 10 diverse aircraft and more than 20 000 AM parts were mounted in numerous military and commercial airplanes [8].

In 2017, Boeing had already installed tens of thousands of AM parts in 16 different aircraft [26], and together in a program with Norsk Titanium (a MAM system manufacturer) created the first 3D printed part (present in figure 2.5) certified by the Federal Aviation Administration (FAA) for commercial flight, an additively manufactured structural titanium component to be used on the company's 787 Dreamliner aircraft [36] (illustrated in figure 2.6). Boeing had planned at the time to implement four AM titanium parts, which would translate to savings of 2 to 3 million dollars per airplane off the 265 million dollars price tag [10] and had the expectation to manufacture almost a thousand parts [36].

Figure 2.5: Part produced by Norsk Titanium, before and after final machining process. Source: The Fabricator magazine.

Figure 2.6: 787 Dreamliner aircraft on display. Source: Metal AM magazine.

In addition to Boeing, the largest corporation in the aerospace manufacturer sector, being positioned at number 64 [37] in the *Fortune* Global 500 ranking of 2017 (a ranking of the biggest companies in the world by revenue), Airbus is also a key player in the AM industry, reaching the 105th place in the same ranking [38], being the second biggest company in the aerospace and defense sector with most revenues.

In 2007, Airbus began to seriously consider MAM [39]. Seven years later, in June 2014, the first AM printed metal part, a titanium bracket, was installed in a commercial jet airliner for a test flight [40]. In 2015, the company manufactured its first space qualified 3D printed components after two years of research and development in cooperation with Innovative UK and the UK Space Agency. The AM printed parts could not be produced by conventional technology and, in these components, a structural bracket is included for Eurostar E3000 telecommunications satellites (presented in figure 2.7), which is manufactured from aluminium alloy and illustrated in figure 2.8. This single part weighs 35% less and it is 40% stiffer than the former bracket, which contained four parts and 44 rivets [41].

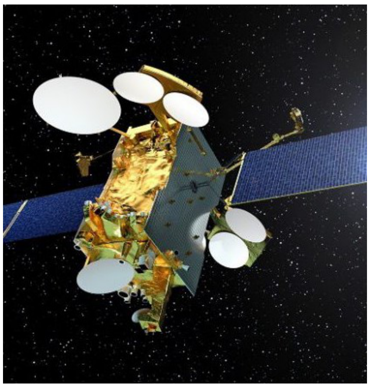


Figure 2.7: Eurostar E3000 plataform.
Source: Airbus.

Figure 2.8: Airbus first space qualified AM
printed component. Source: Airbus.

Airbus has installed metal printed cabin brackets and bleed pipes on some of Airbus A320neo and A350 XWB test aircraft [42]. The company has established a multi-year cooperative research agreement with Arconic in order to develop parameters and processes to manufacture large-scale (1 meter in length) 3D printed components [43].

The National Aeronautics and Space Administration, the European Space Agency, and SpaceX are similarly exploring the use of AM, particularly on the combustion chambers, ignitors and injectors of their rocket engines [34]. Other companies in the aerospace industry join this group, as Lockheed Martin, Honeywell Aerospace, and Northrop Grumman. In addition to the mentioned companies, many others are important in the development of AM technology. DMG Mori, EOS, SLM Solutions, Stratasys, and Trumpf are some of the companies that have driven the knowledge and technology of AM forward, trying to achieve better performances at reduced costs.

This path taken by the aerospace industry is visible, for example, in the acquisition of two leading manufacturers of metal AM technologies, Arcam AB and Concept Laser, by General Electric in 2016. General Electric, a market leading company in the adoption of AM for aerospace applications, has also invested more than 1 500 million dollars in AM technologies [44], which indicates a strong bet on the future of AM in aerospace industry and in several other industrial sectors.

2.2 AM processes

There are two main groups of components in aerospace, metallic and nonmetallic (mainly polymer). While the former is commonly related to critical aircraft parts, the latter is associated to noncritical [34]. The industry for making polymer parts is already thriving, however it is the fabrication of metal parts and systems that is of most interest for the aerospace sector, adding the fact that it is fairly easy for MAM systems to process titanium, ideal to integrate into carbon composite aircraft designs [45].

The WR 2018 estimated that 1768 MAM systems were sold in 2017, a sharp increase over previous years and a rise of approximately 80% over the previous year, as it is shown in figure 2.9. This growth in the sales of these systems is justified by the improvement of process monitoring and quality assurance measures in MAM [24]. The number of companies that produce and sold industrial AM systems worldwide also increased from 97 in 2016 to 135 in 2017 [24]. All these numbers illustrate all the investment that has been made in the last twenty years and the growing interest in this technology.

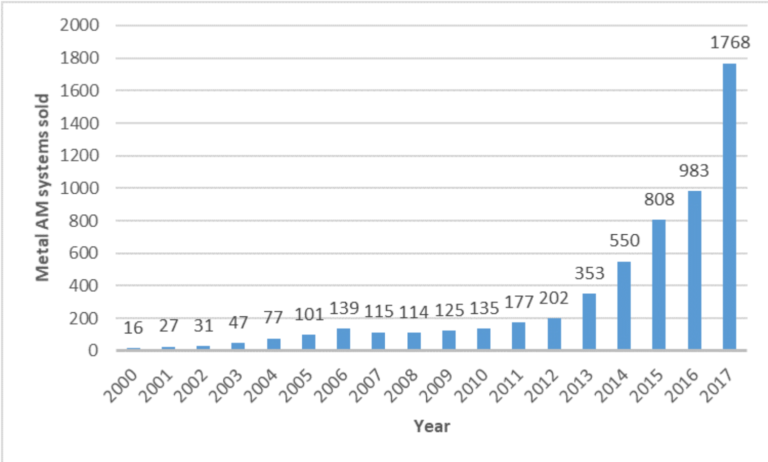


Figure 2.9: Rise in MAM systems sales from 2000 to 2017.
Data source: [24].

It is possible to distinguish all these machines by the different processes that constitute them. 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 [46]. Of these seven types of processes, only four of them use metal, in addition to other materials, as can be observed in table 2.3.

Table 2.3: AM categories, technologies and materials used.

	Category	**Technology**	**Material used**
Additive Manufacturing Processes	BJ	Binder Jetting	Ceramic
			Metal
			Polymer
	DED	Electron Beam Additive Manufacturing	Metal
		Laser Engineering Net Shape	Metal
		Wire Arc Additive Manufacturing	Metal
	MJ	Drop on Demand	Wax
		Material Jetting	Polymer
		NanoParticle Jetting	Metal
	PBF	Direct Metal Laser Sintering	Metal
		Electron Beam Melting	Metal
		Multi Jet Fusion	Polymer
		Selective Laser Melting	Metal
		Selective Laser Sintering	Polymer

Sources: adapted from [47] and [3].

Some of these four processes englobe technology compatible to being used with other materials.

The two most usual AM technologies for aerospace applications are DED and PBF. The former one includes electron beam AM, laser engineering net shape, and wire arc AM. Common PBF technologies in the aerospace industry include direct metal laser sintering (DMLS), electron beam melting (EBM), and selective laser melting (SLM). Although not so commonly used like the mentioned technologies, BJ is nonetheless relevant for aerospace applications [34].

2.2.1 Binder jetting

According to the terminology given by ASTM [46], BJ is a process in which a liquid bonding agent is selectively deposited using an inkjet-print head to join powder materials in a powder bed, forming a solid component, as is illustrated in figure 2.10. The powder material is spread over the build platform with the help of a roller. Than the print head moves over the build platform depositing binder droplets on top of the powder, according to the geometry of the part being printed [48]. After the layer is completed, the build platform is lowered by the model's layer thickness and a new layer of powder is spread onto the build area. The object is formed where the powder bounds to the liquid. Furthermore, the unbound powder remains in position around the object being formed. This process is repeated until all parts are complete [47].

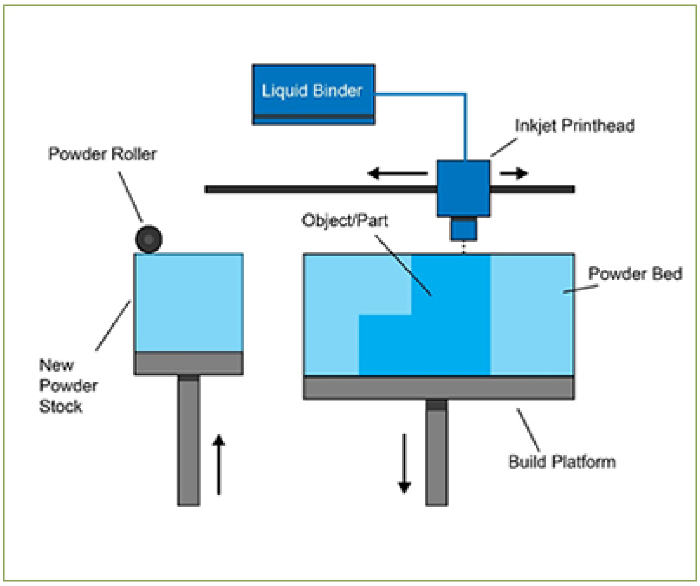


Figure 2.10: Binder jetting process.
Source: [48].

The printed parts require additional post-processing before they could be used. Since the parts are composed of bound powder, it is necessary to use infiltration during this last processing step, in order to improve the mechanical properties of the parts [3]. The infiltrant is usually cyanoacrylate adhesive, for ceramic parts, or bronze, for metal parts [47].

As shown in table 2.3, this technology is used to process a diversity of metal, ceramic, such as gypsum and foundry sand [49], and polymer materials [3]. BJ is used for rapid and reliable prototyping of metal AM parts, such as impellers and turbine blades, for rapid tooling in the fabrication of AM sand cores and molds to fabricate large metal parts [50].

When looking at other technologies, BJ presents several advantages:

- parts can be printed in a diversity of different colors [48];
- the range of materials used is large [48];
- the process is quicker than others [48];
- the process is ideal for aesthetic applications [47].

Nevertheless, BJ presents some disadvantages, which remove it from the most used technologies in the aerospace industry:

- the process is not appropriate for structural parts, due to the use of binder material [48];
- additional post-processing can add significant time to the process [48];
- the process is not indicated for functional prototypes, as the parts are very inelastic [47];
- the produced parts have inferior mechanical properties [47].

2.2.2 Direct energy deposition

DED is, as stated in the ASTM definition, a process that uses thermal energy to melt materials together as they are deposited [46], typically taking place within an inert gas atmosphere [51]. The process is shown in figure 2.11 and even though it can be utilized for nonmetal materials, it is essentially used with metals and metal alloys [52].

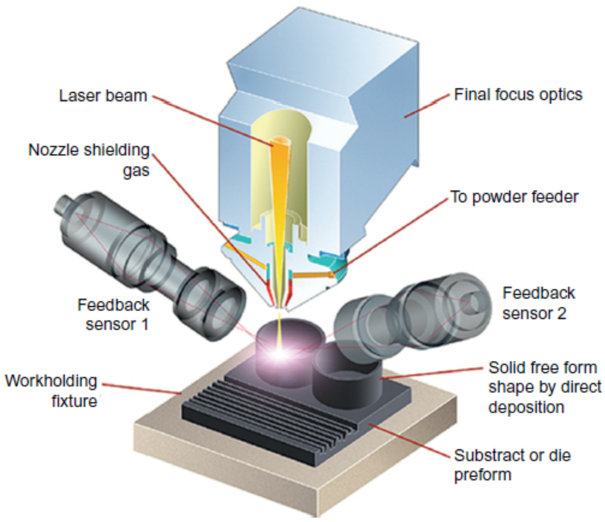


Figure 2.11: Schematic showing a DED technology.
Source: [53].

The feed stock comes in the form of powder (in the case of figure 2.11) or wire, and the source of the thermal energy may come in the form of laser beams, electron beams, or plasma arcs [54].

This process is often referred to as direct metal deposition or metal deposition. In this process, a 4 or 5 multi axis arm, with nozzle, moves around a fixed object, with material being deposited from the nozzle onto existing surfaces of the object (the nozzle can move in multiple directions and it is not fixed to a specific axis). The material is added layer by layer and solidifies, after being melting, creating or repairing new material features on the existing object [55].

As mentioned previously, these AM systems can be categorized in terms of the material feed stock.

Powder feed systems: For a powder feed system, shown in figure 2.12, the powder is conveyed through the nozzle and is melted from a laser or an electron beam on the surface of the treated part. This process is repeated until create a solid 3D component. This system can be used for freeform fabrication (creating new features onto existing parts), cladding (applying one layer of material covering another), and repair [23]. The advantages of this type of system include the ability to build in large volumes, to be used to renew worn or damaged components and the acquired geometric flexibility [12]. Nevertheless, the resolution is normally not quite as good as other systems [23] and as a powder system, there is always some wasted material [56].

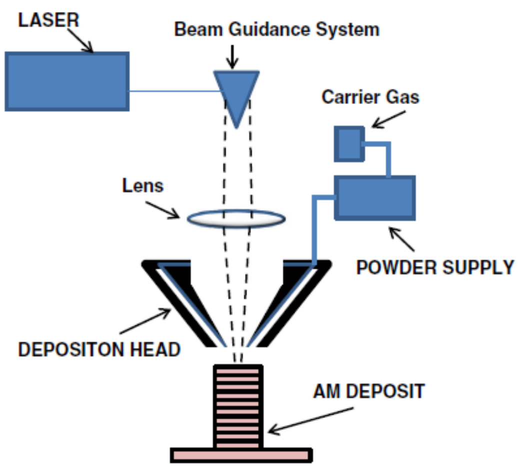


Figure 2.12: AM powder feed system.
Source: [12].

Wire feed systems: For a wire feed system, presented in figure 2.13, the energy source can be an electron beam, a laser beam of a plasma arc. For the process using this system, a single bead of material is deposited and as it comes into contact with the thermal energy, the three-dimensional structure is formed. This system is useful for high deposition rates [12], with the volume of the deposit being the volume of the wire that is fed, therefore there is no material waste [56]. Nonetheless, this system presents some disadvantages, being only adequate for simple geometries and not for more complex, large, or dense parts [56], and requiring more machining than other systems [12].

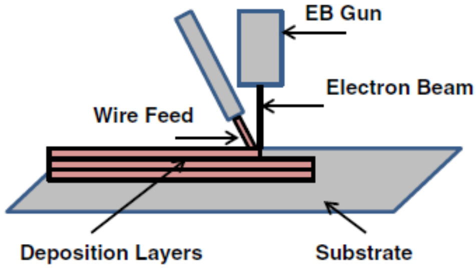


Figure 2.13: AM wire feed system.
Source: [12].

Although the mechanical properties depend on process parameters, load direction, and subsequent heat treatments, either with wire-fed laser or arc beam deposition as the source of thermal energy, both processes produced parts with properties that fit aerospace applications requirements [52].

The nature of the DED process makes it ideal for repairing or adding material to existent objects, such as airfoils, blisks, compressors, engine combustion chambers, and turbine blades [57]. Using DED technology, it was possible, for example, to repair turbine airfoils with a 0.030 mm accuracy of the original blade, and for a repair volume of 10% there was a 36% total energy savings and a 45% improvement in the carbon footprint [58].

DED, when compared to other technologies, presents the following advantages:

- the DED approach allow large build envelopes with high deposition rates [53];
- ability to control the grain structure to a high degree, allowing high quality repairing job [55];
- DED can achieve up to 99.9% theoretical density of the material [3];
- ability to add coatings to existing surfaces [3].

Despite being one of the most MAM technologies used in the aerospace industry, DED has some disadvantages:

- the process is not ideal for producing parts from scratch, due to the reliance on dense support structures [47];
- limited material use [55].

2.2.3 Powder bed fusion

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. The process, illustrated in figure 2.14, can be applied using plastic or metal powder, as seen in table 2.3. The energy source is programmed to deliver energy to the surface of the bed, by melting or sintering the powder until obtain the intended form, one layer at the time. The layers are usually composed of dense material and have a thickness of 0.1 mm. The powder is spread over the build platform using a rolling mechanism, after each cross section of the model is fused [59]. The powder that was not melted is reutilized, becoming the support for successive layers, which reduce the need for support structures [8].

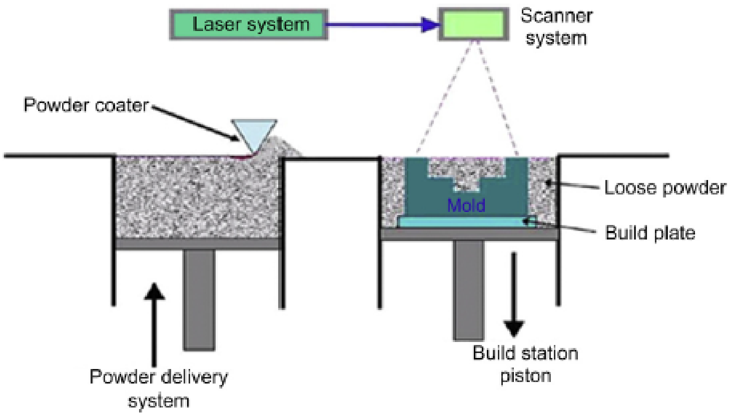


Figure 2.14: Schematic showing a PBF technology.
Source: [53].

To avoid metal oxidation, the processes DMLS and SLM, that use laser beam, occur in an inert gas atmosphere [60], while EBM, which utilizes a scanned electron beam, occurs in a vacuum [61]. DMLS and EBM printed parts present a high density, specific strength and stiffness. Post-processing requirements include removing excess powder and additional cleaning, as well as some final machining work [59].

When compared with other technologies, PBF has many advantages, such as:

- PBF processes have the ability to create complex features and internal passages [12];
- this process is relatively inexpensive [59];
- the powder works as a support structure [59];
- the process is suitable for visual models and prototypes [59];
- large range of material options [59].

This technology also presents some disadvantages when compared with other technologies:

- the process is relatively slow [59];
- the build volumes are less than $0.03m^3$ [34];
- the process requires post-processing [59]:
- high power usage [59].

For the MAM technologies presented, each type of system is dependent upon the intended applications, whether the main purpose would be repair or fabrication, and whether the process is need for a small part fabrication or a large one.

2.3 Capabilities and challenges of AM

2.3.1 Advantages of AM

AM, and in particular MAM, is a recent technology that 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 opens the possibility for companies to change the manufacturing paradigm worldwide, having the potential to become the norm in the years to come [62].

AM, when placed side by side with traditional manufacturing, presents numerous capabilities:

Better for prototyping: before AM, the process of producing a part, from its concept to the final design, required a large number of prototyping iterations [11], which would include machine reconfigurations that were expensive and time consuming. With AM, there is a acceleration that reduces the time to market, from days and weeks to just hours, and reduces the costs involved in the product development [62];

More complex designs: structurally complex geometries and internal cavities are made possible with AM [6]. These geometries characterized by nontraditional external shapes can provide high mechanical performances while limiting the necessary mass to a minimum. Some highly complex parts produced by AM cannot be made with conventional technologies [63], being this ability to produce such parts extremely important in the aerospace industry. To obtain such geometries, topology optimization algorithms are needed. With the use of these software tools, aerospace designers may reduce material and weight from the produced parts and retain or increase their mechanical performance, while reducing the costs [64];

Lighter parts: the complex structures, as mentioned above, can reduce weight without compromising the mechanical properties or increasing the surface area [11]. In the aerospace industry there is always a demand for lightweight aircraft components, with high strength-to-weight ratio to improve fuel efficiency. This improvement, in addition to being a huge cost savings for companies, will still reduce emissions, while responding to safety and reliability requirements [65];

Reduced material waste: unlike conventional subtractive manufacturing, where large amounts of material are removed in order to produce the final parts, AM creates objects by adding it [66], requiring less raw material. This change in material usage can be very important to the aerospace industry, which has components with high buy-to-fly ratio (weight ratio between the raw material and the weight of the final component), such as thin-walled structures and turbine blades [54]. For PBF processes, 95% to 98% of the material that was not fused may be recycled [67], having a significant positive effect on the environment [68];

Decentralized manufacturing: with AM, it is possible to produce multiple parts simultaneously in the same build, making it possible to produce an entire product on the spot [4]. This allows the possibility of printing parts in remote locations, on demand, consequently removing the need for transportation, which shorts the supply chain [62]. Contrasting to conventional manufacturing, where the production of parts is done at multiple locations and then stored after being shipped to a facility where they are assembled into the final product, AM replaces these steps as can be illustrated in figure 2.15, allowing the production of the entire assembly [4]. With AM there is no need for large inventories and, with the reduction of the logistical costs, AM contributes positively towards the environment [62];

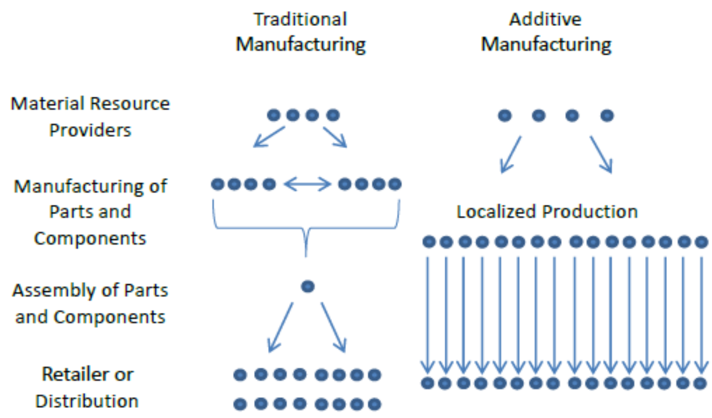


Figure 2.15: Comparison of traditional supply chain to the supply chain for AM.
Source: [4].

No tooling: unlike conventional manufacturing, that requires auxiliary resources [66], AM reduces the need for tooling, allowing the fabrication of small production runs and parts that require quick turnaround time [34]. The part is obtained directly from its CAD model, limiting human error in the process, which is an additional advantage [69];

Customization: the AM technology allows almost any complex geometric shape, as mentioned previously. Without design constraint, characteristic of conventional manufacturing [3], AM provides a complete flexibility in design and construction of a product [67];

Effectiveness in low productions: although, for large productions runs, AM tends to be more expensive, the fairly high investment cost of fixtures and tools is avoided or greatly reduced [70]. AM reveals itself to be more cost effective for small productions runs and customized parts, that are common in the aerospace industry, since maintenance, tooling and replacing parts in aircraft are very important and may comprise high inventory costs, given that aircraft have lifespans of over 30 years [71];

Production of spare parts: AM allows companies in the aerospace sector to reduce repair times, labor costs and avoid costly warehousing [62], reducing inventory as mentioned above;

Potential worker health benefits: conventional manufacturing processes, such as casting, forging and machining, generate various types of emissions, fluid spills, and produce noise, which prove to be potential health hazards for the worker, something that can be avoided by using AM processes [66].

2.3.2 Disadvantages of AM

Although the manufacturing paradigm can be changed globally in numerous sectors, AM technology, more in concrete MAM, is still an immature technology [72] and for that reason it presents some drawbacks, having some obstacles that prevent it from dethroning traditional manufacturing, at least in the short term. The challenges that AM has to overcome in the near future and the disadvantages it presents now are mentioned below:

Cost: one of the main barriers for the adoption of AM is the high cost of the printing equipment [62], with a low number of machines sold, there is a need for the machine manufacturers to recuperate the money invested in the development of this new technology, in addition to money spent in machines' expensive components [27]. Furthermore, AM material costs can similarly be fairly high when compared to traditional manufacturing, being for some technologies ten times more expensive [73]. Additionally, there are costs associated with que qualification of materials, specifically in the aerospace industry [74];

Size limitation: AM has some dimension restrictions. Parts cannot be too thin and overhanging sections require supports [6]. The size of the parts must be within the limits of the machine volume and large sized objects are impractical due to the time needed to complete the build process [66], being too expensive for technologies that require inert atmosphere or vacuum [62];

Quality issues: AM technologies present quality limitation, in terms of build resolution and consistency from build to build [56], which lead to uncertainty when measure material performance at different areas of a part [74]. Furthermore, parts produced using AM processes present a significant surface roughness and a large majority of AM systems can only process a single material at a time [66];

Post-processing: for aerospace applications, the surface roughness problem mentioned above forces post-processing to be required for most MAM processes [75]. Printed objects that use built-in support material also need post-processing to separate them. The difficulty of the methods that produce the removal depends on the type of printing process and build materials. For a support material soluble in water, it is only needed a bath with gentle scrubbing to remove it. In case of materials non soluble, it is necessary to break and remove the support from the object using pliers or conventional cutting tools. After this step, the parts often are polished using sanding or vapor smoothing [3]. Additionally, processes that use powder as feed stock produce frequently fairly porous parts [76], which is solved using hot isostatic pressing, reducing the porosity while increasing part strength and reliability [77]. It is possible to do a heat treatment process, such as an annealing post-process, in order to consolidate the grain structure and obtain the properties wanted [75]. For complex parts, it is required unconventional methods, for instance shot peening, chemical etching, or vibrahoning [75];

Regulation: the lack of consistency mentioned above makes certification quite complicated and exhausting. Although there have been approved several new AM standards for aerospace applications recently, a large amount of research remains to be done in order to qualify the AM components [78] and develop standards and certification guidelines for both materials and AM processes. As result of the lack of regulations, some manufacturers use heavier than ideal parts to reduce the possibility of failure [6];

Lack of specialized personnel, software and knowledge: the implementation of AM in the aerospace industry continues to be unfulfilled to some extent due to the lack of existing software able to fully support all phases of the AM process [10]. Moreover, there are important variances between different AM systems in terms of feed stocks, heat sources, and machine configurations, requiring a long process of learning adapted to each particular application [6]. Finally, it is necessary to train engineers to take advantage of all aspects of AM, which is very time demanding [6];

Time: AM is relatively slow when compared with traditional mass production. Until the production times of AM printers can be improved for large volume production, conventional manufacturing mechanisms will be chosen to do these manufactures [62];

Skepticism: it is necessary to change the way designers approach and think about AM [69], which with the lack of fundamental design guidelines available reveal some skepticism in the industry [1].

2.3.3 Opportunities for MAM

Understanding the weaknesses stated above may take some time [6], however, in the near future, it is anticipated that many of these mishaps can be overcome. With the development of better techniques and more manufacturers entering the industry, increasing the number of machines sold, the price of these will decrease [62]. System producers will still be able to keep prices high for some time, but when their patents expire, competition is expected to increase, causing the decrease in prices [27]. Just as the price of printers is expected to decline over the next few years, it is also expected that the cost of filaments used to print and the cost of used materials will also follow the same path, as companies find innovative ways to access or manufacture them [62].

As AM technologies develop, especially MAM technologies, it is expected that there will be an increase in system build volumes, which will eventually lead to the manufacture of larger parts, with the prospect of manufacturing large components such as an airplane wing, in the future [8].

Due to all the advantages presented above, and the potential of high revenue stream, several companies have been targeting productions in the aerospace industry, with additive factories (concept that is based on a fully integrated process, from the manufacturing of powder to finishing processes of the part) being owned by major aerospace groups. This is the case, for example, of Premium Aerotech and Avio Aero, both fully owned subsidiaries of Airbus Group and General Electric, respectively [10].

2.4 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 [79]. 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.

Cost models, or cost estimation models, are mathematical algorithms, where costs are recorded and allocated, being used to estimate the costs of certain products or projects. Even when using the same information, different costing systems could give different results as the initial data can be used in different ways, which makes the cost of a product totally context dependent [80]. There are several types of cost models techniques, of which the process-based cost model (PBCM) is one of the most suitable for efficient and cost-effective cost assessments in process modeling context [81].

A PBCM, like other engineering process models, behaves like a mathematical transformation, structuring a process hinged on its operating conditions until it obtains information that allows measuring the process performance[80].

As the name implies, PBCMs 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.

AM cost models

For cost models related to AM, the first relevant one was developed by Hopkinson and Dickens [82] 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. Hopkinson and Dickens assumed that the system would produce a single type of part for one year, that it would use maximum volume builds and that the machine would operate for 90% of the time. The total cost of the parts was defined as the sum of machine, labor and material costs, with energy and space rental costs neglected for their small contribution. The costs were calculated for two parts, a cover and a lever, using the three AM processes: stereolithography; fused deposition modeling; and selective laser sintering (SLS).

Two cost breakouts, one for each part, were made and they are illustrated in figure 2.16, the lever one, and in figure 2.17, the cover one. It is possible to observe that the IM is the most expensive process for small builds, which is due to the high cost of the mold and that the IM curve in both figures decreases with the increase of production volume, since the mold is amortized with the high number of parts produced, becoming the most convenient process. For the other processes, the line is constant because the authors allocated the indirect costs on every single part [83].

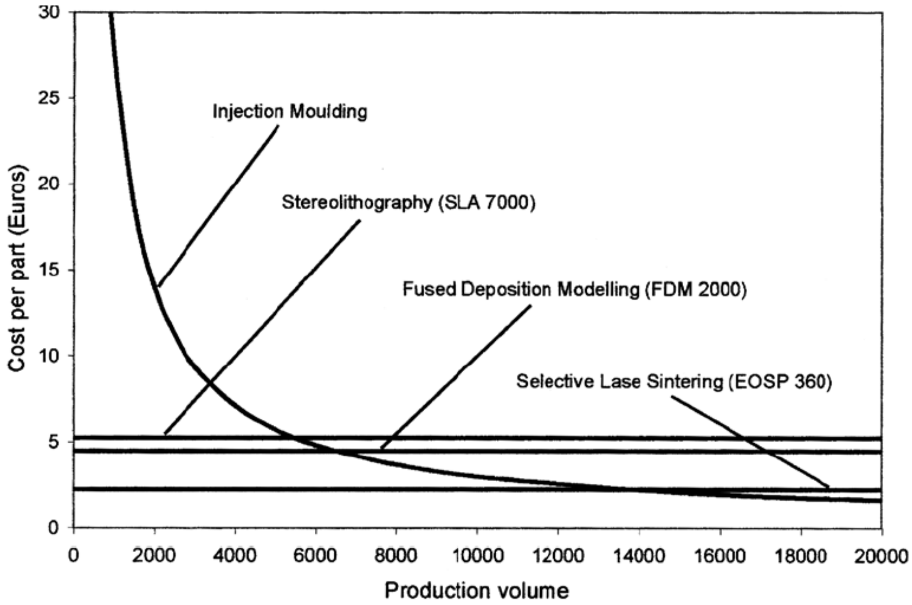


Figure 2.16: Cost comparison of the production of lever parts by different processes.
Source: [82].

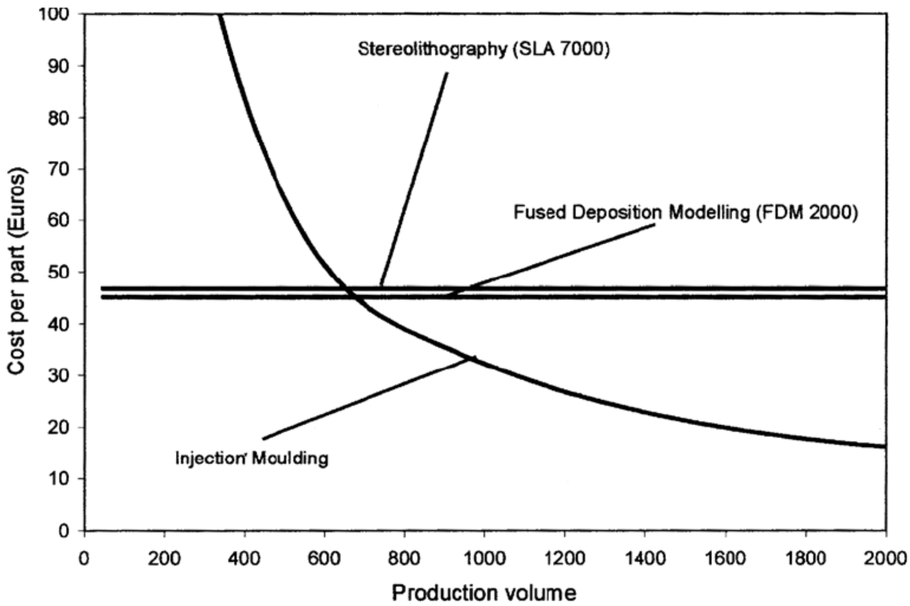


Figure 2.17: Cost comparison of the production of cover parts by different processes.
Source: [82].

This proposed model provided a first approximation for production costs, but it was developed in a moment when the technology had no matured [13] and the work was followed by the creation of other models in the following years. In 2006, Ruffo et al. [83] analyzed the production costs of the same lever 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. These activities are divided in direct and indirect costs, as shown in figure 2.18, and the sum of these costs result in the total cost of a build. The direct costs depend on the amount of material used, and the indirect costs, independent of the amount of parts produced, depend only on the process time.

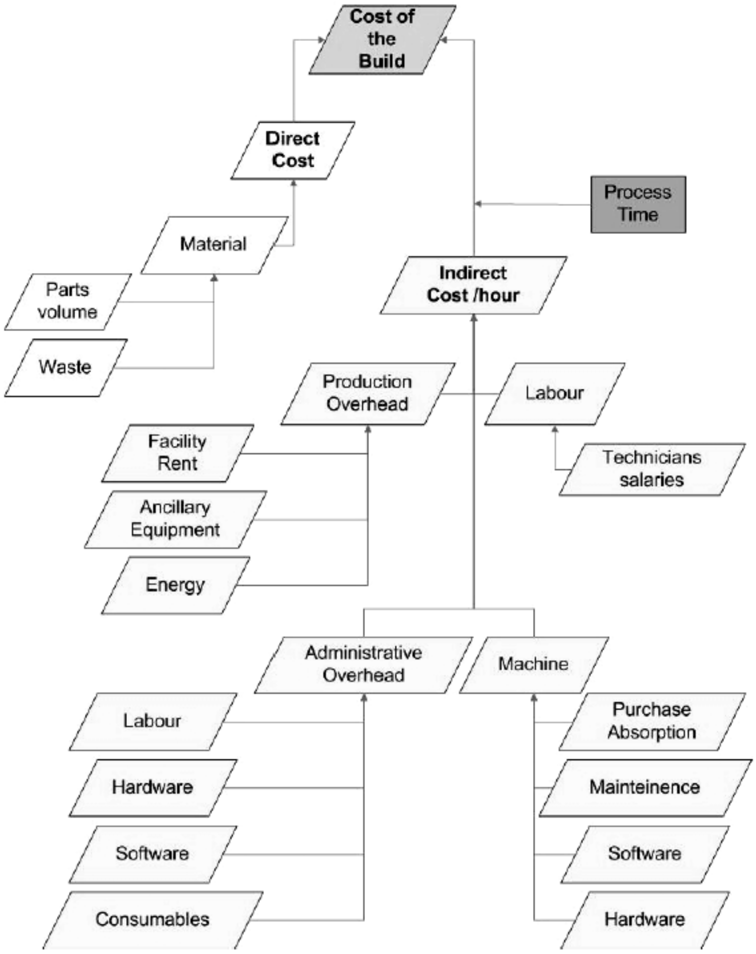


Figure 2.18: Ruffo et al. costing model structure.
Source: [83].

The process time which in turn is the sum of three different times: “time to laser scan the section and its border in order to sinter the powder”; “time to add layers of powder”; and “time to heat the bed before scanning and to cool down slowly after scanning, adding layers of powder or just waiting time to reach the correct temperature” [83].

The build time estimation was achieved using an empirical estimation algorithm and this approach is only correct for the production of numerous parts with the same geometry. In this work, it was established a comparison with the work of Hopkinson and Dickens, as illustrated in figure 2.19.

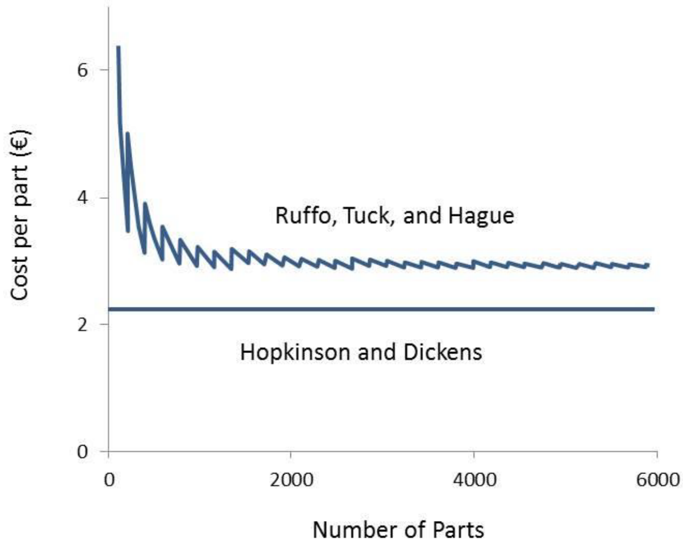


Figure 2.19: Cost Model Comparison between [83] and [82].
Source: [4].

The curve has a saw tooth shape, owing to the filling of the build space, whenever a new bed needs to be started or when a new part has to be placed on a new layer, both time and cost for the build increase.

In their following work [84], Ruffo and Hague developed a new model, including the case of mixed production of different parts in the same build chamber. They proposed three ways to calculate the unit cost of the parts: the first based on the part volume; the second based on the cost of building a single part; and the third based on the cost of a part built in high-volume production, which was, after drawing conclusions from the results, the only one appropriate, since there was a cost reduction in the production of the two different parts.

Baumers and his research group [85] were the first to examine the economic and energetic aspects, analyzing the time necessary to complete the AM building [13]. 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.

Lindemann [86] 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. With the inclusion of the last step of the process, the model takes into account the economic aspect associated with it.

In addition to the works presented, several other works were conducted in the area of cost modeling on AM [87][88][89][13]. However the review of the cost models is not within the scope of this dissertation, so it will not be detailed.

Chapter 3

Methodology

The current chapter aims to cover the methodology used to develop 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 referred methodology is presented in figure 3.1.

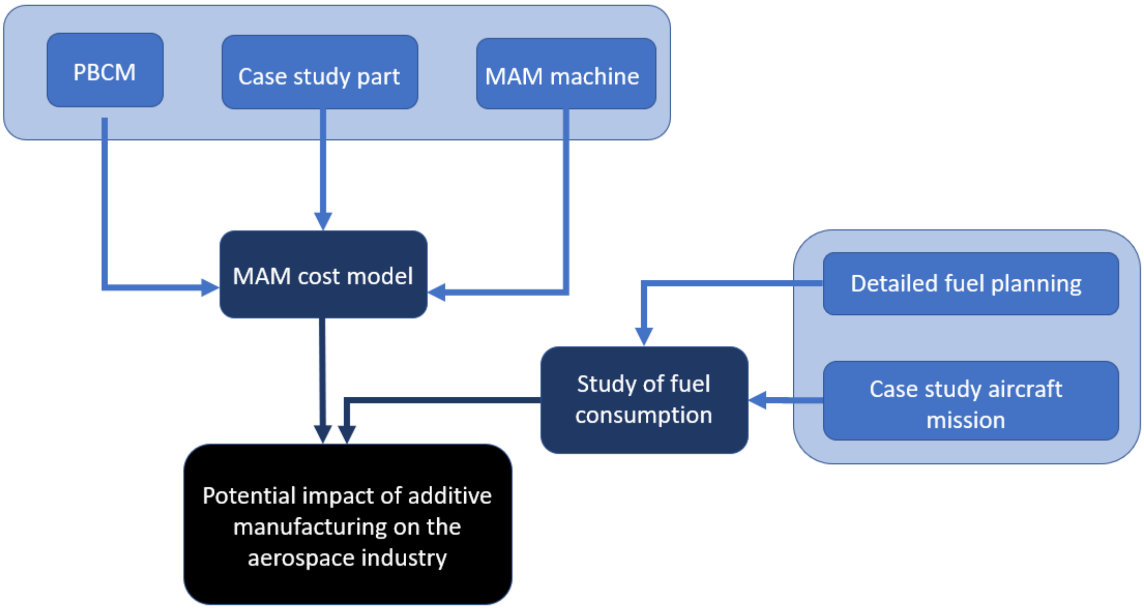


Figure 3.1: Study scope.

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 dissertation work, and was printed by a MAM machine also used in this case study. The values from this optimization 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.

3.1 Process-based cost modeling

PBCMs are constructed by making a backward decomposition, from the product cost to the physical parameters that can be controlled, finding connections between the outputs and the initial conditions. In figure 3.2, a diagram describing the work done by the modeler is presented.

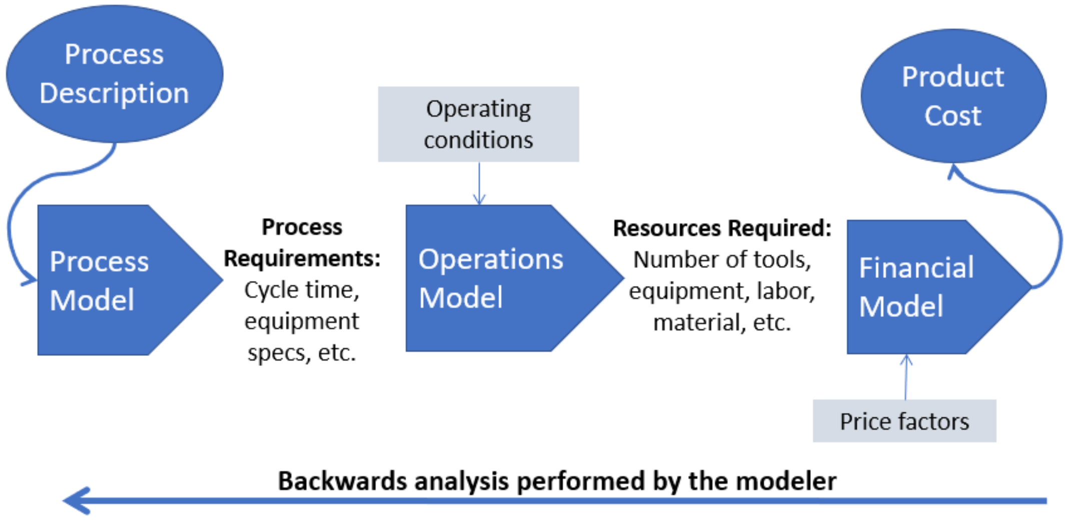


Figure 3.2: Modeler works from cost to inputs.

The process-based method derives cost from the magnitude of the factors that are directly connected to the final product, which are created from the effects of parameters that are controllable. In order to build a robust model, it is necessary to arrange and correlate a long chain of consequences between the production costs and these sets of controllable operational parameters [80].

The first step when building a PBCM is to establish the physical parameters that will influence the costs, which must be purchased or allocated to the manufacture. The most recurrent elements usually considered are material, energy, labor, primary equipment, auxiliary equipment, tools, building space and overhead. After the establishment of physical parameters, these must be related to manufacturing resource requirements (e.g., kg of material, number of laborers, building space) in order to establish a relationship between them. The foundation of a valuable cost model is predicting the required amount of each factor input. Every factor can be used to produce only a fixed and finite quantity of goods, not being possible having the production above this limit without the addition of more factor units (e.g., more machines, more tools). Capturing the connection between the consumption of factor inputs and production of process outputs reveals to be fundamental.

The cost in financial models is divided into two categories: variable cost and fixed cost, which are explained below.

Variable costs: 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. Examples of variable costs include, for example, labor costs, utility costs, and the cost of raw materials that are consumed in production;

Fixed costs: 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. While variable costs tend to remain level for different volume of production, the impact of fixed costs can change based on the number of units produced. Thus, when considering costs on a per part basis, if the production increases, the fixed cost tends to decrease because the price of a larger quantity of goods can be distributed over the same quantity of a fixed cost. The most common example of fixed cost is expenditures for equipment, rent, overhead, etc. Fixed costs can generally fall into two different groups, those which are a one-time capital expense and those which are recurrent payment with a tenuous connection with the production volume. Recurring payments, such as building rent, are annualized or converted to any appropriate time period basis. One-time payments require an allocation of the costs to the duration of production. Since capital goods can remain productive for many years, it is important to consider the time value of money in this allocation. In order to consider that, it is necessary to annualize the single expense, capturing its associated opportunity cost, by multiplying its value by the capital recovery factor (CRF):

$$CRF(r,n) = \frac{r(1+r)^n}{(1+r)^n - 1}\,, \tag{3.1}$$

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.

3.2 MAM machine

In order to elaborate a cost model, a MAM machine was observed, with the purpose of understanding its operation and how this information could be used in the development of the cost model. The machine that served as the basis for the model was the Renishaw AM 400, illustrated in the figure 3.3, which is representative of MAM machines using the same manufacturing process, PBF. The machine belongs to Hypermetal, a company located in Vila Nova de Gaia, which is dedicated to the production of metal parts by AM. As described earlier in subchapter 2.2, in table 2.3, PBF has several different technology

Figure 3.3: Renishaw AM 400.
Source: Renishaw.

types, varying depending on the type of material and the type of thermal energy. 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. The system build volume is 250 mm × 250 mm × 300 mm and this MAM machine is compatible with various materials, such as aluminum, cobalt chrome, nickel, stainless steel and titanium.

This 3D printer requires a filter to screen the particles in the circulating air to avoid contamination. Before the machine is ready for operation, an inerting cycle must be performed. This machine uses argon gas which creates an inert environment suitable for its use. It reduces oxidation of sintered parts, prevents corrosion and eliminates impurities, creating a stable printing environment, maintaining constant pressure and reducing powder accumulation to prevent part deformities.

Each machine of a given technology may have specific characteristics that differentiate it from the others, so the elaboration of a generic cost model must always take into consideration what kind of process and technology the AM machine presents.

3.3 Case study part

The methodology of process-based cost modeling is generally used to estimate product fabrication, assembly, and development costs. In order to investigate the consequences of MAM in the aerospace industry a case study is presented. The part illustrated in figure 3.4 is a bracket and it is a representative part of the aerospace industry. This part was optimized outside the scope of this dissertation work, and its optimization is used to demonstrate the impacts of reducing the weight of aircraft parts in terms of costs savings, either through less material use or reduced fuel consumption.

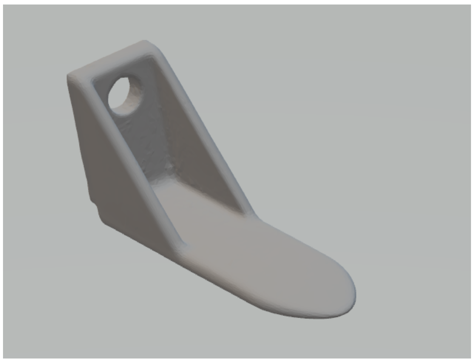


Figure 3.4: Case study original part.

With the optimization process, it is possible to present more than one alternative, which happens in this case and is shown in figures 3.5 and 3.6. These optimized parts achieve a mass reduction of about 36%.

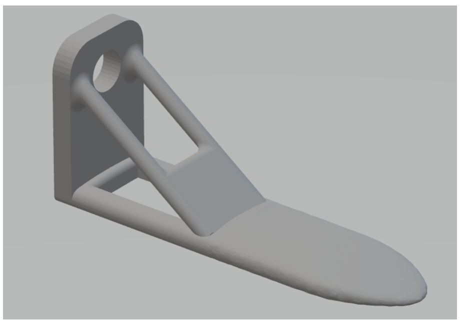


Figure 3.5: First possibility for part optimization.

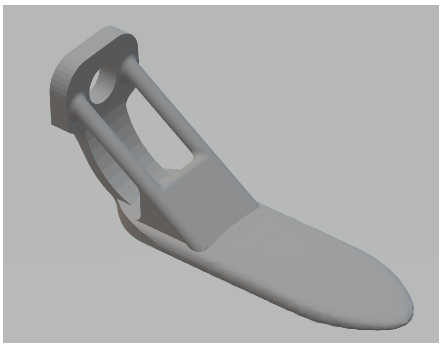


Figure 3.6: Second possibility for part optimization.

The optimized parts presented in this case study were built in the Renishaw AM 400 machine using a Maraging steel M300 powder and the values of this printing will be used afterwards.

Chapter 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 of the MAM process

With the purpose of developing a PBCM for the case study, the AM process was divided in activities, as shown in figure 4.1.

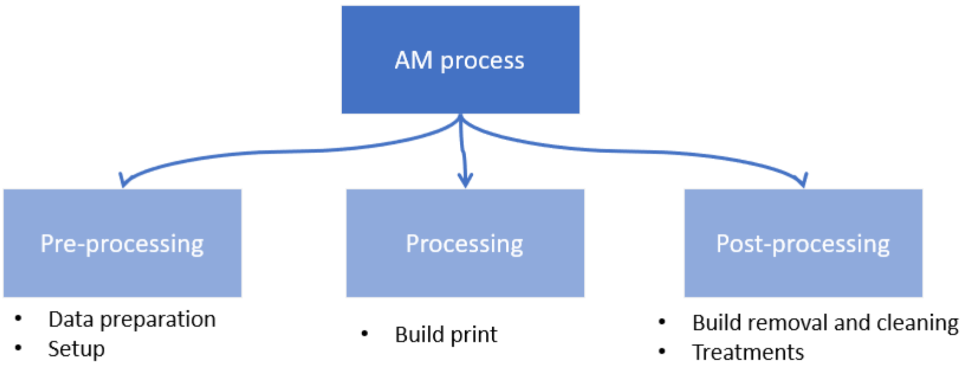


Figure 4.1: Process division into activities.

Pre-processing

Pre-processing consists in two activities: data preparation and setup.

In the first activity, the operator creates the STL file (stereolithography file used by the machine software) from the CAD file, implementing the meshes needed for the parts and generating the necessary supports to hold the parts, having in mind then the ease of their removal. Finally, the operator finds the optimal orientation for the parts on the board, in order to reduce the layer height and maximize the number of parts per batch (parts of the same or different geometry that are produced in the same run).

In the second activity, the operator prepares the machine with everything required for its operation. The powder feed stock 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.

Processing

The processing phase includes every step of the AM process. The build print divides in different steps. The first step is warming up, where the board is heated. The following step is inertization, where argon gas is used to make the environment inside the chamber inert. After that, there are two steps that intersect each other, scanning and coating. In the first, the laser scans the section area corresponding to that layer for all parts to be produced, sintering the powder. After this, for each layer, a new coat of powder is required, which is done by the machine. After all the parts are printed, it is necessary to cool down the machine, before the operator be able to remove the printed build, which corresponds to the last step.

Post-processing

After the processing phase is completed, there are still some activities that need to be performed until the parts are in their final state.

First it is necessary to remove the excess powder from the inside of the machine. Then the operator must remove the build, inspect the surface quality of the parts and verify if everything is as intended. After the build is removed, the inside of the machine should be clean and the debris such as burnt powder and filtered waste must be collected and stored 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 the parts separation, first it is necessary to remove the parts from the build board, using machining for example. Then if the parts are connected due to nesting purposes it is necessary to separate them and, finally, the parts are separated from the support structures.

In addition to the previous steps, machining may be also used to smooth surfaces, if necessary. Other processes can be performed to improve part quality, surface polishing, shot peening, and thermal post processing are usually used to relieve the residual stresses and even enhance microstructure [90].

Shot peening [91] is a surface treatment process where the local surface of the part is impacted with a flow of small spherical shots in order to improve fatigue strength and increase hardness. Heat treatment and hot isostatic pressing (HIP) [92] are processes that can also be performed to improve part characteristics. Heat treatment is used to help relieve residual stresses and HIP is used to decrease porosity. In the end, post-processing will depend on the type of material used and the application requirements of the part [93].

4.2 Activity costs

For each activity, there are different types of costs, variable and fixed, that are required for production.

Variable costs: Variable costs are divided into material, labor, energy and consumables costs.

Material costs include the powder required to produce the parts, the supports and the burnt powder that is damaged and cannot be reused. The remaining powder used in the build is reused and is not included in the costs. Labor costs include tasks the operator performs in each activity. The energy cost is the one associated with the work of the machine, having been neglected the energy cost of the data preparation in the setup [13], because the value is very small when compared to the energy cost of the build print process.

Consumables include board, gas, debris removal and filter costs. The costs of the board are related to the its thinning. The cost of the board is neglected, since one board can be used many times and the price per use turns out to be much lower than its roughing. The gas costs are associated with the use of the argon gas cylinder. Debris removal costs are associated with hiring a company to perform this task and filter costs are associated with its use.

Fixed costs: Fixed costs are divided into machine, building, maintenance and equipment costs.

Machine costs are associated with its acquisition. Building costs are related to the space required for all equipment, machines and the safety space around them. Maintenance costs are the costs reserved to keep equipment in good condition. Lastly, equipment costs are the costs associated with software and hardware purchase and their renewal.

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, $N_{required}$, in equation 4.1, either for internal use or according to market demand.

$$C_{Part} = \frac{C_{Year}}{N_{Required}}, \tag{4.1}$$

This number differs from the number of parts actually produced by the company, N_{total}, as it takes into account the number of parts rejected during the activities, in particular when separating the parts from the board and between them, and when carrying out post-processing treatments, as shown in equation 4.2.

$$N_{Total} = N_{Required} \times (1 + \frac{RR_{BRC}}{100}) \times (1 + \frac{RR_{Treatments}}{100}). \tag{4.2}$$

where C_{part} and C_{year} represent the cost per part and the total cost of all the parts produced by year, respectively. N_{total} is a value rounded up to the units. RR_{BRC} and $RR_{Treatments}$ represent the rejection rate of the build removal and treatment activities, respectively, with no rejection in the cleaning phase.

The total yearly production cost is then computed by adding the costs of each one of the activities as can be seen in equation 4.3.

$$C_{Year} = C_{DP} + C_{Setup} + C_{BP} + C_{BRC} + C_{Treatments}, \tag{4.3}$$

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

4.3 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. The table 4.1 presents factors accounted for data preparation labor costs.

Table 4.1: Variables regarding data preparation labor costs

Variable	Cost model element	Units
$t_{DP\,1}$	DP time for the first batch	[h]
$t_{DP\,n}$	DP time for the next batches	[h]
t_{DP}	Total DP time	[h]
$N_{parts\,per\,batch}$	Number of parts per batch	[-]
N_{total}	Number of parts produced per year	[-/year]
$N_{batches}$	Number of batches per year	[-/year]
$C_{Operator}$	Operator hourly cost	[€/h]

Equation 4.4 presents the calculation of the number of batches produced per year, $N_{batches}$, which is a value rounded up to the nearest integer, since even if a production does not have a batch full of parts, it is still carried out in order to meet the demands on the number of parts required.

$$N_{Batches} = \frac{N_{Total}}{N_{Parts\,per\,batch}}. \tag{4.4}$$

The data preparation time, equation 4.5, is the sum of the times for the first production plus the time required for the following productions. The first production is more time consuming than the others since it is necessary to do the whole process described above, while in the following ones most of the process is already done, thus taking less time. It is possible, however, in the cost model to always assume the same time for each batch.

$$t_{DP} = t_{DP_1} + (N_{Batches} - 1) \times t_{DP_n}. \tag{4.5}$$

Finally, in order to obtain the labor cost, the time is multiplied by the hourly cost of the operator, equation 4.6.

$$C_{DP\,Labor} = t_{DP} \times C_{Operator}. \tag{4.6}$$

For fixed costs, the costs of the building, the purchase of equipment (software and hardware) and the cost of renovation per year of the same equipment are calculated. In table 4.2 the variables required for calculating the fixed costs for this activity are represented.

Table 4.2: Variables regarding data preparation fixed costs

Variable	Cost model element	Units
$Days$	Working days per year	[-]
$Uptime$	Working hours per day	[h]
$A_{Building\,DP}$	Building space	[m^2]
$Pr_{Building}$	Building square meter price	[€/m^2]
C_{Soft}	Software cost	[€]
C_{Hard}	Hardware cost	[€]
$C_{Ren\,Soft}$	Software renewal cost	[€/year]
$C_{Ren\,Hard}$	Hardware renewal cost	[€/year]

As mentioned above, single payments require an allocation of costs to the duration of production. To do this, it is necessary to calculate the annual production time (annual uptime), equation 4.7, 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.

$$t_{Production\,line} = Days \times Uptime. \tag{4.7}$$

In relation to the cost of the building, the investment made is first calculated, in equation 4.8, taking into account the allocation of time corresponding to this activity in relation to the total production time, multiplying this value by the value of the area, the number of batches and the value of the price per square meter.

$$Inv_{Building\,DP} = A_{Building\,DP} \times Pr_{Building} \times N_{Batches} \times \frac{t_{DP}}{t_{Production\,line}}. \tag{4.8}$$

The costs of the building are therefore calculated by multiplying the investment by the CRF, with the corresponding r and n, in equation 4.9.

$$C_{DP\,Building} = Inv_{Building\,DP} \times CRF. \tag{4.9}$$

For the equipment, hardware and software, the investment is calculated in a similar way. Multiplying the cost of each equipment to the allocation time of the activity, in the following equations:

$$Inv_{Soft} = C_{Soft} \times \frac{t_{DP}}{t_{Production\,line}}, \tag{4.10}$$

$$Inv_{Hard} = C_{Hard} \times \frac{t_{DP}}{t_{Production\,line}}. \tag{4.11}$$

The cost of the equipment is obtained by multiplying the different investment costs by the respective CRFs, equation 4.12.

$$C_{DP\,Equipment} = Inv_{Soft} \times CRF + Inv_{Hard} \times CRF. \tag{4.12}$$

The hardware and software may have to be renewed every year, and this cost is represented in equation 4.13.

$$C_{DP\,Ren} = (C_{Ren\,Hard} + C_{Ren\,Soft}) \times \frac{t_{DP}}{t_{Production\,line}}. \tag{4.13}$$

The total cost of data preparation is calculated by adding the different costs, in equation 4.14.

$$C_{DP} = C_{DP\,Labor} + C_{DP\,Building} + C_{DP\,Equipment} + C_{DP\,Ren}. \tag{4.14}$$

4.4 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 costs are calculated in a similar way to the previous activity, in equation 4.15, in which case the time of this activity is used, t_{Setup}.

$$C_{Setup\,Labor} = t_{Setup} \times C_{Operator} \times N_{Batches}. \tag{4.15}$$

In relation to the costs of the 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, $C_{Rough\,Board}$, as follow:

$$C_{Setup\,Board} = C_{Rough\,Board} \times N_{Batches}. \tag{4.16}$$

The total cost of this activity is obtained by adding the previous costs, in equation 4.17.

$$C_{Setup} = C_{Setup\,Labor} + C_{Setup\,Board}. \tag{4.17}$$

4.5 Build print

4.5.1 Background for the build print time process model

As previously mentioned, some articles have addressed in the past the topic of additive manufacturing cost models. Some of these articles studied the build time and developed methods to estimate this time. Articles such as Ruffo et al. [94] studied this subject for PBF technology that worked with polymers, while other articles such as Rickenbacher et al. [87] and Baumers et al. [85] studied the build time also for PBM, but this time for metals [4].

Since different articles have studied different processes on different machines, many particularities that have been considered in their estimates cannot be transposed to other machines and technologies.

The coating time for the machine considered by the work of Ruffo et al. varied according to the position of the laser at the end of the scanning of a layer, because this laser would have to move to a corner of the machine after the end of the production of each layer [94]. This is not always the case. In the Renishaw AM400 machine, this time is always constant and does not depend on the position of the laser, since it remains in the same place for this machine. In the work of Ruffo et al., an empirical algorithm was used to estimate the time, which was suitable only for productions of parts with the same geometry [94].

In the work of Rickenbacher et al. the build time was estimated using linear regression with distinct parameters, not taking into account neither the heating time nor the cooling time [87], times that can influence the total production time and should be taken into consideration.

Meanwhile, in the work of Baumers et al., these times have already been considered, and only the time of inertization remains to be taken into account. In this work, an algorithm is used to make voxel approximations of the geometry of the parts, that is, to approximate the geometry of the part by cubes of very small volume, a size that will be much smaller if the accuracy of the approximation is to be increased [85]. For a technological cost model, this computational approach becomes unfeasible because it is not practical to use the computational algorithm when estimating the build time for parts with different geometries to those already used.

Thus, in order to estimate the build time, all present times, heating time, inertization time, coating time, scanning time and cooling time were taken into account and an analysis was performed to understand how the different parameters influenced the times.

It was found 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.

4.5.2 Estimated build print time

The build time is then the sum of the times of each production phase, equation 4.18.

$$t_{BP} = t_{Warm} + t_{Inert} + t_{Coat} + t_{Scan} + t_{Cool}. \tag{4.18}$$

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, calculated in equation 4.19, 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.

$$\bar{A}_{surface} = \frac{V_{production}}{h_{max}}. \tag{4.19}$$

The total coating time is calculated by multiplying the coating time of each layer by the number of production layers, N_{Layers}. This value is obtained by dividing the maximum height by the thickness, d, of each layer in equation 4.20. This thickness will vary depending on the material to be used.

$$N_{Layers} = \frac{h_{max}}{d}. \tag{4.20}$$

The scanning time is therefore calculated by removing the individual times of the process phases from the total build time, equation 4.21.

$$t_{Scan} = t_{BP} - t_{Warm} - (N_{Layers} \times t_{Coat\,layer}) - t_{Cool}. \tag{4.21}$$

It was then assumed that the scanning time for each layer was constant, since the layers to be produced would have the same area, thus taking the same scanning time. This average time is present in equation 4.22. Then this average time to scan a layer was divided by the average section area, obtaining in equation 4.23 an average scanning time per unit area [s/mm^2], for the simplifications made.

$$\bar{t}_{Scan\,layer} = \frac{t_{Scan}}{N_{Layers}}, \tag{4.22}$$

$$\bar{t}_{Scan} = \frac{\bar{t}_{Scan\,layer}}{\bar{A}_{surface}}. \tag{4.23}$$

In the tables 4.3 and 4.4 there are represented values of parts that were produced in the machine of this case study, using different materials, Maraging steel M300 and aluminum, respectively.

In the production of the M300 steel and aluminium maraging parts a layer thickness (d) of 0.04 mm and 0.03 mm were used, respectively.

Table 4.3: Production values of parts using Maraging steel M300

Time [h]	**Maximum height [mm]**	**Total volume [mm^3]**	**Number of layers [-]**
33,5	100,15	272259	2504
6,75	61,65	37298	1542
29	61,65	261090	1542
81,25	132,19	745969	3305
6,5	61,65	35274	1542
27,5	61,65	246916	1542
77,5	132,19	705474	3305

Table 4.4: Production values of parts using aluminum

Time [h]	**Maximum height [mm]**	**Total volume [mm^3]**	**Number of layers [-]**
70	153	628571	5100
25,5	81,62	207845	2721
9,5	50,6	67852	1687
15,7	50,6	135704	1687
13,1	43,02	98366	1434
3,1	28	14610	934
32	28	321422	934

The previous tables show only the time the machine is working on the parts, i.e. the sum of the scanning time and the total coating time. The tables also show the maximum height of each production and the total volume, which includes the total volume of the parts and the volume of the supports used.

In figures 4.2 and 4.3, for productions that used Maraging steel M300, it is observed that the average scanning time per unit area does not vary significantly with the average surface area of each production, nor 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.

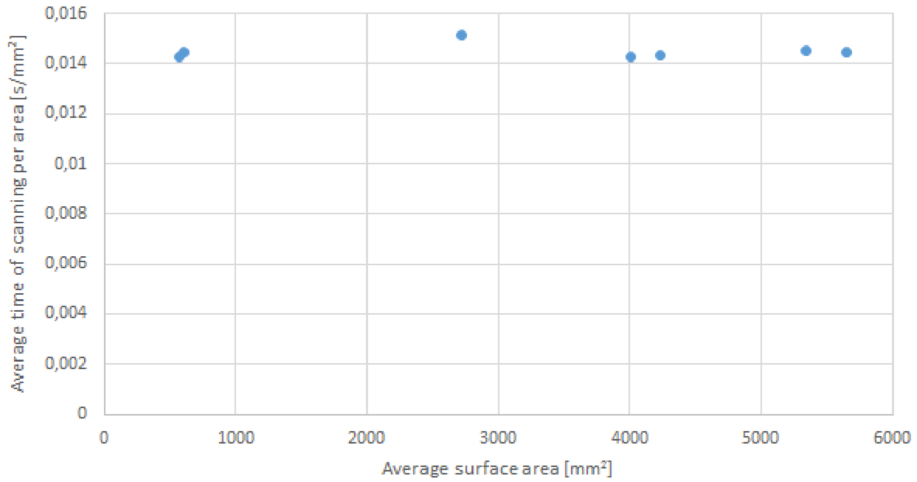


Figure 4.2: Average scanning time per unit area for different average surface areas for Maraging steel M300 productions.

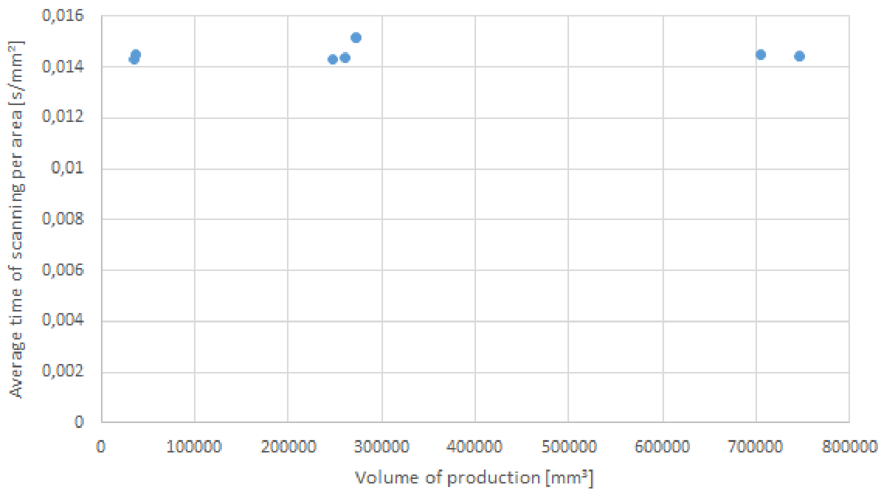


Figure 4.3: Average scanning time per area unit for different production volumes for Maraging steel M300 productions.

The same analysis was performed for the parts produced with aluminum and the values are similar to the previous ones, with a difference of less than two thousandths of a second per mm^2 between the lowest and the highest value obtained. This value also remains practically constant regardless of the average surface area, figure 4.4, or the production volume, figure 4.5.

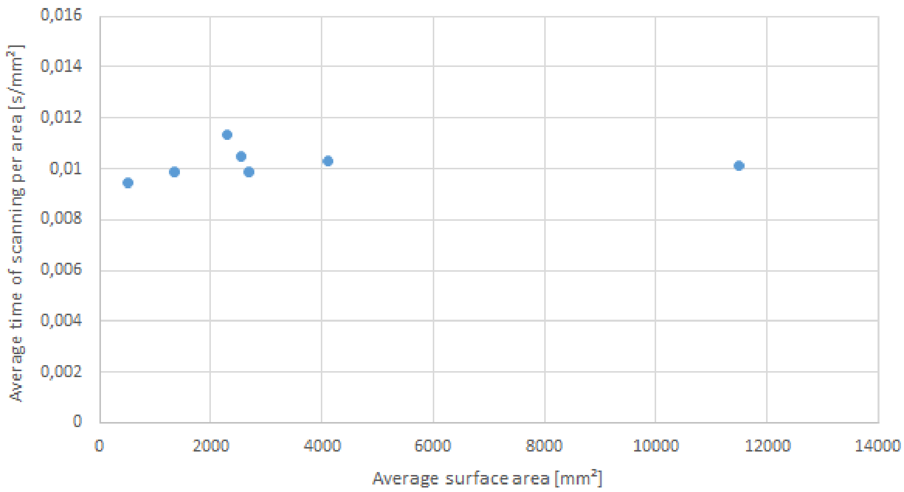


Figure 4.4: Average scanning time per unit area for different average surface areas for aluminum productions.

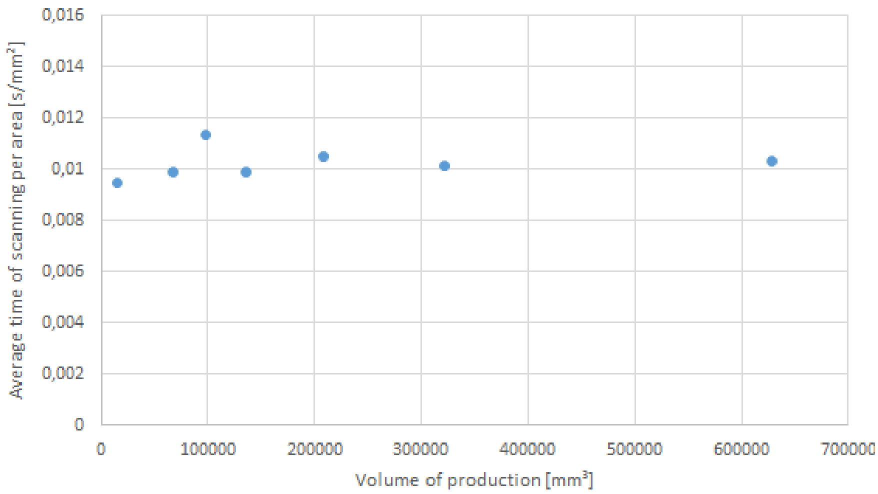


Figure 4.5: Average scanning time per unit area for different production volumes for aluminum productions.

Assuming the hypothesis that the value of the average scanning time per unit area is independent of both the average surface area and the volume of production, the average value for the production data is calculated for each material and $Average(\bar{t}_{Scan})$ is obtained. The estimated time for the total scanning time, $t_{estimated\,scan}$, is then calculated in equation 4.24.

$$t_{estimated\,scan} = Average(\bar{t}_{Scan}) \times \bar{A}_{surface} \times \frac{h_{max}}{d}. \tag{4.24}$$

4.5.3 Build print costs

For the activity corresponding to printing the parts, both variable and fixed costs are present. In the former there are costs related to material, energy, gas and filters. In table 4.5, the variables required for calculating the fixed costs for this activity are represented.

Table 4.5: Variables regarding build print variable costs

Variable	Cost model element	Units
m_{part}	Part mass	[kg]
$X_{material\,loss}$	Material loss factor	[$\%$]
$Pr_{material}$	Price of the material	[€/kg]
$P_{Machine}$	Power of the machine	[kW]
$Pr_{Electricity}$	Price of electricity	[€/kWh]
t_{BP}	Build print time	[h]
Pr_{Gas}	Price of a gas cylinder	[€]
$N_{Gas\,uses}$	Number of uses per cylinder	[-]
Pr_{Filter}	Price of a filter	[€]
t_{Filter}	Hours of use of a filter	[h]

In each production, there is usually a percentage of powder that is burned in the process and cannot be reused in subsequent production. This percentage is the material loss factor, $X_{material\,loss}$. The cost of the material is then calculated taking into account all the powder that is used (both for the part and for the supports), the price of the powder and the number of parts that are produced, as shown in equation 4.25.

$$C_{BP\,Material} = m_{Part} \times (1 + X_{Material\,loss}) \times Pr_{Material} \times N_{Total}. \tag{4.25}$$

The cost of energy was based on the work performed by Yang & Li, 2018 [5] and Baumers et al., 2012 [85]. 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 according to equation 4.26.

$$C_{BP\,Energy} = P_{Machine} \times t_{Annual\,production} \times Pr_{Electricity}, \tag{4.26}$$

where $t_{Annual\,production}$ represents the total number of hours the machine work per year for the parts analyzed and it is obtained, in equation 4.27, by multiplying the time of a production, t_{BP}, by the number of productions per year, $N_{Batches}$.

$$t_{Annual\,production} = t_{BP} \times N_{Batches}. \tag{4.27}$$

This cost model, as previously seen, provides an estimate for the build print time, which was the time used here.

In relation to the gas used in production, the vast majority is used at the beginning of production, to inert the chamber, being only a superficial quantity used in the course of the process. Thus, only the use at the beginning of the process is considered, which will be the same for any production. Thus, the gas cost is calculated as shown in equation 4.28.

$$C_{BP\,Gas} = \frac{Pr_{Gas}}{N_{Gas\,uses}} \times N_{Batches}. \tag{4.28}$$

Each filter normally works for a certain number of hours, t_{Filter}, and must be replaced at the end of this period. The cost associated with the filter is calculated, in the equation 4.29, by multiplying the percentage of the filter used for each print by the cost of the filter and the number of batches.

$$C_{BP\,Filter} = \frac{t_{BP}}{t_{Filter}} \times Pr_{Filter} \times N_{Batches}. \tag{4.29}$$

In table 4.6, the variables required for calculating the fixed costs for this activity are represented.

Table 4.6: Variables regarding build print fixed costs

Variable	**Cost model element**	**Units**
$Pr_{Machine}$	Price of the AM Machine	[€]
$A_{Machine}$	Area occupied by the machine	$[m^2]$
A_{Safety}	Safety area around the machine	$[m^2]$
$C_{Maintenance}$	Maintenance cost	[€]
$X_{Maintenance}$	Percentage of maintenance cost	[%]

The investment of the machine is calculated, in equation 4.30, by multiplying the price of the machine by the percentage of use for a particular part, taking into account the number of productions that are made per year.

$$Inv_{Machine\,BP} = Pr_{machine} \times N_{Batches} \times \frac{t_{BP}}{t_{Production\,line}}. \tag{4.30}$$

The cost of the machine is then obtained in equation 4.31, by multiplying the investment by the corresponding CRF.

$$C_{BP\,Machine} = Inv_{Machine\,BP} \times CRF. \tag{4.31}$$

The building cost is obtained for this activity in the same way as it was obtained for data processing activity. First, the investment is calculated, in equation 4.32, this time taking into account the total printing time, multiplying this value by the price per square meter and by the area corresponding to the space of the machine. This area also involves the surrounding space for safety reasons. The value of the investment is then multiplied by the CRF and the building cost for this activity is obtained, in equation 4.33.

$$Inv_{Building\,BP} = (A_{Machine} + A_{Safety}) \times Pr_{Building} \times N_{Batches} \times \frac{t_{BP}}{t_{Production\,line}}, \tag{4.32}$$

$$C_{BP\,Building} = Inv_{Building\,BP} \times CRF. \tag{4.33}$$

In the present cost model, there are two possibilities for obtaining the maintenance cost, as shown in equation 4.34. If the cost is known, it is multiplied by the allocation of time to the production of a given part. If the value is not known, a percentage of the machine cost is used as a reference.

$$\begin{cases} C_{BP\,Maintenance} = C_{Maintenance} \times N_{Batches} \times \frac{t_{BP}}{t_{Production\,line}} \\ C_{BP\,Maintenance} = X_{Maintenance} \times C_{BP\,Machine} \end{cases}. \tag{4.34}$$

The total cost of this activity is then obtained by adding the previous individual costs in equation 4.35.

$$C_{BP} = C_{BP\,Material} + C_{BP\,Energy} + C_{BP\,Gas} + C_{BP\,Filter} + C_{BP\,Machine} + C_{BP\,Building} + C_{BP\,Maintenance}, \tag{4.35}$$

4.6 Build removal and cleaning

In this activity there are only labor costs, debris removal costs and building costs. In table 4.7, the variables required for calculating the costs for this activity are represented.

Table 4.7: Variables regarding build removal and cleaning costs

Variable	Cost model element	Units
$t_{removal}$	Part removal time	[h]
$t_{cleaning}$	Machine cleaning time	[h]
$C_{Debris\,removal}$	Cost of removing debris	[€]
$N_{Filters}$	Number of filters used until removal is required	[-]
A_{Debris}	Area reserved for waste disposal	[m^2]

The labor cost is calculated, in equation 4.36, 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.

$$C_{BRC\,Labor} = C_{Operator} \times (t_{Removal} \times N_{total} + t_{Cleaning} \times N_{Batches}). \tag{4.36}$$

The cost of debris removal is calculated, in equation 4.37, taking into account the number of times it is necessary to remove debris per year, considering the annual production of a particular part.

$$C_{BRC\,Debris\,removal} = C_{Debris\,removal} \times \frac{N_{Batches} \times t_{BP}}{N_{Filters} \times t_{Filter}}. \tag{4.37}$$

The only fixed cost of this activity, 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 investment for this cost is then calculated in equation 4.38 and the building cost is obtained through equation 4.39.

$$Inv_{Building\,BRC} = A_{Debris} \times Pr_{Building}, \tag{4.38}$$

$$C_{BRC\,Building} = Inv_{Building\,BRC} \times CRF. \tag{4.39}$$

The total cost for this activity is again the sum of the previous costs, as shown in equation 4.40.

$$C_{BRC} = C_{BRC\,Labor} + C_{BRC\,Debris\,removal} + C_{BRC\,Building}. \tag{4.40}$$

4.7 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. If the treatment is subcontracted, the cost enters the model as a per part price for each process, otherwise the cost is calculated as shown below.

In table 4.8, the variables required to calculate the costs of a treatment process are represented. The calculation performed is similar for each treatment process, so only the cost of one treatment, the machining cost, is detailed, while the remaining costs are calculated in the same way.

Table 4.8: Variables regarding machining costs

Variable	**Cost model element**	**Units**
$t_{Machining}$	Total machining time	[h]
$A_{Building\,Machining}$	Space required for the process	$[m^2]$
$X_{Line\,allocated}$	Percentage of process utilization	$[\%]$
$Pr_{Machining\,Equipment}$	Price of process equipment	[€]

The only variable costs considered are labor costs, which are calculated in equation 4.41 by multiplying the hourly cost of the operator by the number of annual hours used for the process.

$$C_{Machining\,Labor} = C_{Operator} \times t_{Machining}. \tag{4.41}$$

The fixed costs considered for the treatment activities are the costs of the building and the costs of the equipment. The building costs are calculated as seen previously, first obtaining the value of the investment, in equation 4.42, where $X_{Line\,allocated}$ represents the percentage of time used for the machining of a certain part in relation to all the work this process can do in a year and then, in equation 4.43, multiplying this value of the investment by CRF.

$$Inv_{Building\,Machining} = A_{Building\,Machining} \times Pr_{Building} \times X_{Line\,allocated}, \tag{4.42}$$

$$C_{Machining\,Building} = Inv_{Building\,Machining} \times CRF. \tag{4.43}$$

For the equipment cost, i.e. all the necessary tools to perform the treatment process, the investment value is obtained first, as shown in equation 4.44 and then multiplied by CRF, in equation 4.45.

$$Inv_{Equipment\,Machining} = Pr_{Machining\,Equipment} \times X_{Line\,allocated}, \tag{4.44}$$

$$C_{Machining\,Equipment} = Inv_{Equipment\,Machining} \times CRF. \tag{4.45}$$

To obtain the total cost of the treatment process, in this case machining, the previous costs are added, in equation 4.46.

$$C_{Machining} = C_{Machining\,Labor} + C_{Machining\,Building} + C_{Machining\,Equipment}. \tag{4.46}$$

To obtain the total cost of all the treatment processes used, $C_{Treatments}$, all the costs of the individual treatment processes are added together. These can be calculated individually if they are carried out by the company or obtained at the price per part provided by the subcontractor for this purpose.

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

4.8 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, this subchapter aims to present the methodology of the study of the impact that this mass reduction can have on aircraft fuel consumption.

To perform this study, several assumptions were made, based on values present in publications and values present in the aircraft characteristics, data obtained from the aircraft manufacturer.

For the base case, an aircraft was assumed without any reduction in mass and a certain mission present on one of TAP's routes, the Portuguese airline, as shown in table 4.9.

Table 4.9: Characteristics of the mission and aircraft considered.

Mission	Lisbon - Berlin
Aircraft	A319
Time [h]	3,5
Distance [NAM]	1249
Annual Flight Hours [h]	4800
Airport altitude [ft]	374

Source: TAP website, correct as of September 2019.

In addition to the considerations made above, it was necessary to take into account the limitations of the aircraft considered when assuming the values used in the analysis, which are present in table 4.10.

Table 4.10: Values assumed for the mission under consideration.

Aircraft weight $[kg]$	62 000
ISA deviation [℃]	-5 to 5
Cruise speed $[kt]$	424
Cruise altitude $[ft]$	37000

Values according to aircraft limitations in [95] and [96].

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 [97] for the aircraft under consideration. Using these data, fuel consumption was calculated for each of the flight phases described in figure 4.6.

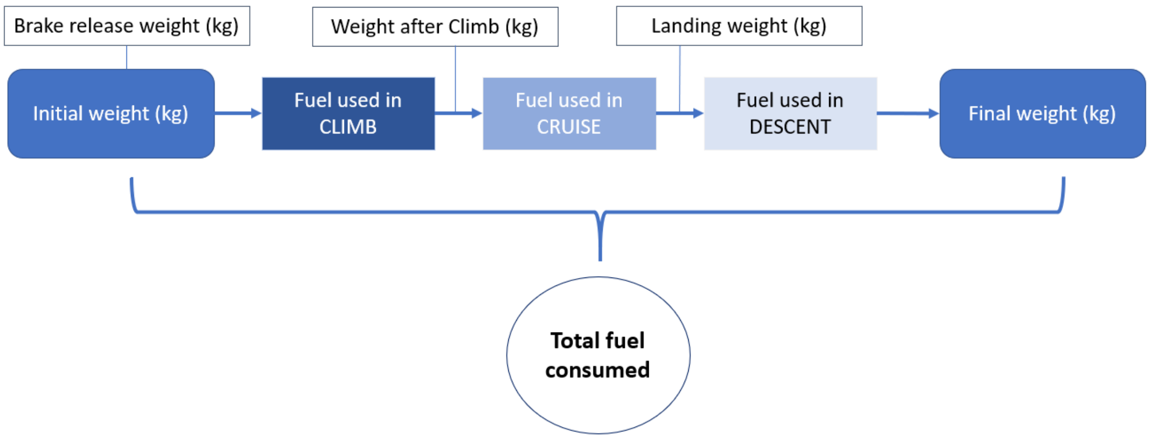


Figure 4.6: Fuel consumption calculation scheme.

In this analysis, the use of fuel in the taxi phase was neglected, having been considered a simple cruise mission, indicated for the flight in question. There are three phases of flight analyzed: the ascent, until the plane reaches cruising altitude, the cruise phase, which is the phase where the large percentage of fuel is spent, and the descent, which is the phase that consumes less fuel. The final weight of the aircraft will then be calculated by subtracting all the fuel weight used during the flight from the initial weight, as shown in equation 4.47.

$$Final\,weight = Initial\,weight - Fuel\,used\,in\,Climb - Fuel\,used\,in\,Cruise - Fuel\,used\,in\,Descent. \tag{4.47}$$

Figure 4.7 shows in detail the data required to calculate the weight of the aircraft for each phase of flight, taking into account the flight conditions considered. The variables underlined represent the weight of the aircraft and the fuel used in the different phases, considering that the difference in weight is entirely related to the fuel consumption.

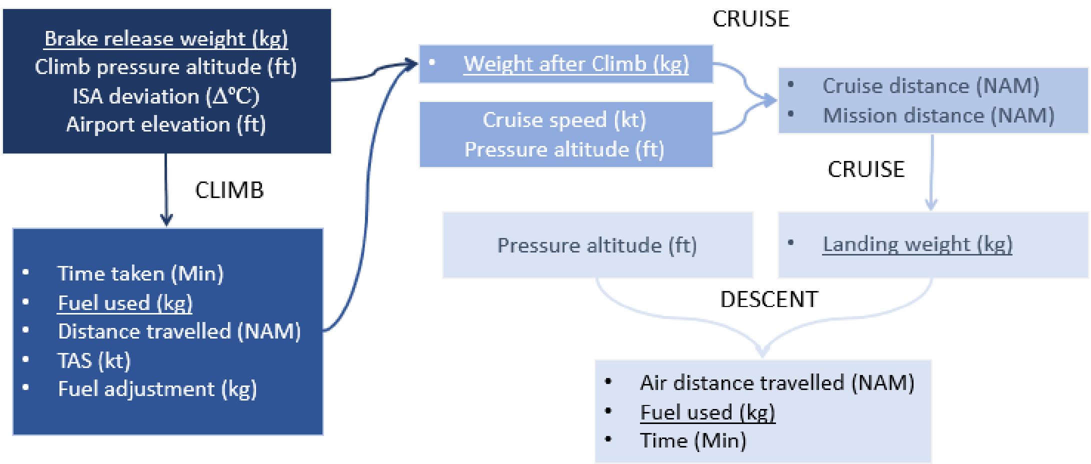


Figure 4.7: Detailed diagram of the calculation of fuel consumption.

Some values required for the calculations are interpolated from the tables of the Flight Planning Manual [97], and all the steps are explained in the following figures for each flight phase. In the table of the figure 4.8, the time $[Min]$, the fuel used $[kg]$, the distance traveled $[NAM]$ and the TAS (average ascent value) $[kt]$ are calculated for the climb of the aircraft, using the pressure altitude, the weight of the aircraft before take-off and a temperature deviation range.

ISA -5°C TO +5°C

Press. Alt. ft	Units Min/kg. NAM/Kt	BRAKE RELEASE WEIGHT KG										
		68000	66000	64000	62000	60000	58000	56000	52000	48000	44000	40000
37000	Time/Fuel				32/2250	26/1900	23/1750	21/1600	18/1400	16/1250	14/1100	12/1000
	Dist/TAS				197/400	158/396	138/393	124/392	105/389	90/388	78/386	68/385
36000	Time/Fuel			29/2150	25/1900	23/1750	21/1650	19/1550	17/1350	15/1200	13/1050	11/950
	Dist/TAS			177/397	151/393	135/391	122/390	112/388	96/386	84/385	73/384	64/383
35000	Time/Fuel	33/2450	28/2150	25/1950	22/1800	21/1650	19/1550	18/1450	16/1300	14/1150	12/1050	11/950
	Dist/TAS	209/399	169/394	148/391	133/389	121/388	112/387	104/386	90/384	78/383	69/382	601381
34000	Time/Fuel	27/2150	24/1950	22/1800	21/1700	19/1600	18/1500	17/1400	15/1250	13/1150	12/1000	11/900
	Dist/TAS	162/391	144/389	131/387	120/386	111/385	103/384	96/383	84/381	74/380	65/379	57/379
33000	Time/Fuel	24/1950	22/1850	21/1700	19/1600	18/1550	17/1450	16/1350	14/1200	13/1100	11/1000	10/900
	Dist/TAS	142/386	129/385	119/383	110/382	103/381	96/380	90/380	79/379	70/378	62/377	54/376
32000	Time/Fuel	22/1850	21/1750	19/1650	18/1550	17/1450	16/1400	15/1300	14/1200	12/1050	11/950	10/850
	Dist/TAS	128/382	118/381	110/380	102/379	96/378	90/377	84/377	74/376	66/375	58/374	51/374

Figure 4.8: Detailed fuel planning for en-route climbs.
Source: [97].

Together with the previous table there is a sub-table in the Flight Planning Manual [97], shown in the figure 4.9, which shows the correction values of the fuel used if the aerodrome has a high altitude. In the present case this does not happen, since the airport considered has an altitude close to sea level, therefore this adjustment is neglected.

Fuel Adjustment for high elevation airports	Airport Elevation	2000	4000	6000	8000	10000	12000
Effect on time and distance is negligible	Fuel Adjustment	-50	-100	-200	-250	-300	-400

Figure 4.9: Fuel adjustment for en-route climbs.
Source: [97].

After ascent, the flight is analyzed during the cruise phase. With the weight of the aircraft to be, at the beginning of this phase, the difference between the brake release weight and the weight of fuel spent on the climb. With this value the interpolation is made, illustrated in the figure 4.10, where the possible cruising distance is taken for the present specifications.

All Engines Maximum Cruise Thrust Limits A/C Auto

PRESSURE ALTITUDE 37,000 ft MACH 0.74 CRUISE TAS 424 kt

GROSS WT. kg	0	100	200	300	400	500	600	700	800	900
	CRUISE DISTANCE NAUTICAL AIR MILES									
35000	0	24	49	73	98	123	147	172	197	221
36000	246	270	295	319	344	368	392	417	441	465
37000	490	514	538	562	586	610	634	658	682	706
38000	730	754	778	801	825	849	873	896	920	944
39000	968	991	1014	1038	1061	1085	1108	1131	1155	1178
40000	1202	1225	1248	1271	1294	1317	1340	1363	1386	1409
41000	1433	1455	1478	1501	1524	1546	1569	1592	1615	1637
42000	1660	1682	1705	1727	1750	1772	1795	1817	1839	1862
43000	1884	1906	1928	1950	1973	1995	2017	2039	2061	2083
44000	2105	2127	2148	2170	2192	2214	2235	2257	2279	2301
45000	2322	2344	2365	2386	2408	2429	2451	2472	2493	2515
46000	2536	2557	2578	2599	2620	2641	2662	2683	2704	2725
47000	2746	2767	2788	2808	2829	2850	2870	2891	2912	2932
48000	2953	2973	2994	3014	3035	3055	3075	3096	3116	3136
49000	3157	3177	3197	3217	3237	3257	3277	3297	3317	3336
50000	3356	3376	3396	3415	3435	3455	3474	3494	3514	3533
51000	3553	3572	3591	3611	3630	3649	3668	3688	3707	3726
52000	3746	3764	3783	3802	3821	3840	3859	3878	3897	3916
53000	3934	3953	3971	3990	4008	4027	4045	4064	4082	4101
54000	4119	4138	4156	4174	4192	4210	4228	4246	4264	4282
55000	4300	4318	4335	4353	4371	4388	4406	4424	4441	4459
56000	4477	4494	4511	4528	4545	4562	4579	4597	4614	4631
57000	4648	4665	4681	4698	4715	4731	4748	4765	4781	4798
58000	4815	4831	4847	4863	4879	4895	4911	[illegible]	[illegible]	4960
59000	4970	4991	5007	5023	5038	5054	[illegible]	5085	5101	5116

Figure 4.10: Detailed fuel planning for Mach 0.74 cruise, first interpolation.
Source: [97].

This value is then subtracted from the distance of the flight that remains to be covered after the ascent, being then interpolated to obtain the weight of the aircraft after this phase of flight, as shown in the figure 4.11.

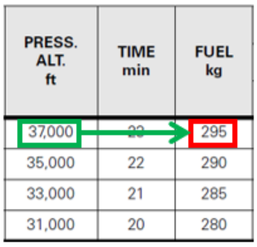
All Engines Maximum Cruise Thrust Limits A/C Auto

PRESSURE ALTITUDE 37,000 ft MACH 0.74 CRUISE TAS 424 kt

GROSS WT. kg	0	100	200	300	400	500	600	700	800	900
	CRUISE DISTANCE NAUTICAL AIR MILES									
35000	0	24	49	73	98	123	147	172	197	221
36000	246	270	295	319	344	368	392	417	441	465
37000	490	514	538	562	586	610	634	658	682	706
38000	730	754	778	801	825	849	873	896	920	944
39000	968	991	1014	1038	1061	1085	1108	1131	1155	1178
40000	1202	1225	1248	1271	1294	1317	1340	1363	1386	1409
41000	1433	1455	1478	1501	1524	1546	1569	1592	1615	1637
42000	1660	1682	1705	1727	1750	1772	1795	1817	1839	1862
43000	1884	1906	1928	1950	1973	1995	2017	2039	2061	2083
44000	2105	2127	2148	2170	2192	2214	2235	2257	2279	2301
45000	2322	2344	2365	2386	2408	2429	2451	2472	2493	2515
46000	2536	2557	2578	2599	2620	2641	2662	2683	2704	2725
47000	2746	2767	2788	2808	2829	2850	2870	2891	2912	2932
48000	2953	2973	2994	3014	3035	3055	3075	3096	3116	3136
49000	3157	3177	3197	3217	3237	3257	3277	3297	3317	3336
50000	3356	3376	3396	3415	3435	3455	3474	3494	3514	3533
51000	3553	3572	3591	3611	3630	3649	3668	3688	3707	3726
52000	3746	3764	3783	3802	3821	3840	3859	3878	3897	3916
53000	3934	3953	3971	3990	4008	4027	4045	4064	4082	4101
54000	4119	4138	4156	4174	4192	4210	4228	4246	4264	4282

Figure 4.11: Detailed fuel planning for Mach 0.74 cruise, second interpolation.
Source: [97].

After the cruise phase, the table in figure 4.12 is used to obtain the fuel used during the descent. The values in the table are for a flight idle thrust descent, with an approach and landing tolerance of 100 kg of fuel included.



PRESS. ALT. ft	TIME min	FUEL kg
37,000	23	295
35,000	22	290
33,000	21	285
31,000	20	280

Figure 4.12: Detailed fuel planning for descent.
Source: [97].

By subtracting the final weight of the aircraft from the brake release weight, the weight of fuel used during the mission is obtained. 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 can be obtained, with this analysis being performed later.

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, based on the work of Laureijs et al., 2017 [98]. These values are found in table 4.11, where they were converted from $US\,dollar/gallon$ to $US\,dollar/kg$ using $3,04\,kg/gallon$ [97]. The value of the fuel in the euro currency (for the Euro area) is also presented, having been converted using the purchasing power parities (PPP) rate of the year 2018 [99], 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.

Table 4.11: Lowest, highest and recent jet fuel prices for the last 15 years.

Case	**Lowest price**	**Recent price**	**Highest price**
Fuel price $[US\,dollar\,PPP/kg]$	0,31	0,59	1,28
Fuel price $[€\,PPP/kg]$	0,22	0,43	0,94

Data Sources: Index Mundi, "Jet Fuel Daily Price";
OECD (2019) [99].

Chapter 5

Results and Discussion

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. Sensitivity analyses will be carried out in order to better understanding the dependence that certain variables have on the calculated costs.

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 both the average surface area and 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 4.24, with the average value for the production data calculated before.

The production data of the part that was produced is shown in table 5.1.

Table 5.1: Production data of the parts produced in the case study

Time $[h]$	42,5
Maximum height $[mm]$	135,1
Total volume $[mm^3]$	351521
Layer thickness $[mm]$	0,04

The value obtained for the estimated scanning time was compared with the production scanning time in equation 5.1. The production scanning time is calculated by subtracting the total coating time from the observed production time. Therefore, an error of less than 2% was obtained.

$$Error_{Scan} = \frac{|t_{estimated\,scan} - (t_{Prod} - t_{Coat})|}{(t_{Prod} - t_{Coat})}, \tag{5.1}$$

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 5.2, an error of less than 1.3% was obtained.

$$Error_{Prod} = \frac{|(t_{estimated\,scan} + t_{Coat}) - t_{Prod}|}{t_{Prod}}. \quad (5.2)$$

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. For the present case study, for the parts produced using Maraging steel M300 in the mentioned machine, the estimated time is a good approximation. Since only one production was used to test the hypothesis that the scanning time per unit area is constant regardless of the production volume, this hypothesis needs to be proven. In this case, data from seven productions were used for the materials Maraging steel M300 and aluminium and the productions were made on the Renishaw AM 400 machine. In a future analysis, more data should be used and other machines of the same technology as the one of the case study can be used.

5.2 Data presentation

The cost model developed has several variables that can depend on each company or even on each country. For the present case study, the values needed to provide results were collected from the company Hypermetal. These values are mainly mean values or assumptions and will be described below.

The variables presented in table 5.2 were named exogenous variables in such a way as to indicate that these variables are constant and are not changed independently of the activity in question. The square meter price was estimated for the industrial zone where the company is located, in Vila Nova de Gaia. The value of the discount rate was an assumed value of 10%. The price of electricity was obtained through the EDP tariff (Portuguese energy company and main electricity supplier in the country) in 2019, for a simple hourly option and for a contracted power of 20.7 kVA. The hourly cost of the operator was assumed for a wage of 1200 €/month plus benefits and taxes.

Table 5.2: Exogenous variables

Variable	**Cost model element**	**Value**	**Units**
$Pr_{Building}$	Building square meter price	800	[€/m^2]
r	Discount rate	10	%
$Pr_{Electricity}$	Price of electricity	0,158	[€/kWh]
$C_{Operator}$	Operator hourly cost	16	[€/h]

In the agreement to purchase the machine from Hypermetal, it was established that the maintenance would be included in the price of the machine, so no value was attributed. For the hardware cost only the acquisition of a computer necessary for the data preparation activity was assumed.

The data mentioned above, as well as the other data for the data preparation and setup activity, are present in table 5.3. The depreciation time for the building was assumed to be 30 years, the hardware (computer) depreciation time was assumed to be 5 years and the software depreciation time was assumed to be 3 years, based on other software of the same type used in this activity, Renishaw QuantAM.

Table 5.3: Pre-processing costs

Variable	Cost model element	Value	Units
	Data preparation		
$t_{DP\,1}$	DP time for the first batch	3	[h]
$t_{DP\,n}$	DP time for the next batches	0,5	[h]
$A_{Building\,DP}$	Building space	3	[m^2]
C_{Soft}	Software cost	0	[€]
C_{Hard}	Hardware cost	1500	[€]
$C_{Ren\,Soft}$	Software renewal cost	0	[€/year]
$C_{Ren\,Hard}$	Hardware renewal cost	0	[€/year]
$n_{Building}$	Building depreciation time	30	[years]
$n_{Software}$	Software depreciation time	3	[years]
$n_{Hardware}$	Hardware depreciation time	5	[years]
	Setup		
t_{Setup}	Setup time	0,5	[h]
$C_{Rough\,Board}$	Cost of roughing the board	20	[€]

In the table 5.4 all the necessary values to calculate the processing costs are presented.

Table 5.4: Processing costs

Variable	Cost model element	Value	Units
	Processing		
m_{part}	Part mass	0,285	[kg]
$Pr_{material}$	Price of the material	25	[€/kg]
$X_{material\,loss}$	Material loss factor	8	[%]
Pr_{Gas}	Price of a gas cylinder	60	[€]
Pr_{Filter}	Price of a filter	30	[€]
$N_{Gas\,uses}$	Number of uses per cylinder	6	[-]
t_{Filter}	Hours of use of a filter	100	[h]
$C_{Maintenance}$	Maintenance cost	0	[€]
$P_{Machine}$	Power of the machine	0,4	[kW]
$Pr_{Machine}$	Price of the AM Machine	500 000	[€]
$n_{Machine}$	Machine depreciation time	10	[years]
$A_{Machine}$	Area occupied by the machine	4,5	[m^2]
A_{Safety}	Safety area around the machine	18	[m^2]

The mass of the part of the case study takes into account the part itself and also the necessary supports to produce it. This value was calculated as an average for the 10 parts produced. The price of the used material was assumed based on a powder steel that is used in the Renishaw SLM250 machine [100]. The material loss factor is an average value provided by Hypermetal, corresponding to the burnt powder that cannot be reused. A depreciation time of 10 years was assumed for the machine and the remaining values were supplied by Hypermetal, based on average values for the company's productions.

For the calculation of post-processing costs, the treatment costs for the parts of the case study were disregarded, due to the fact that the necessary treatments vary from part to part, according to the function to be performed by each one. As the case study part is an illustrative part, no treatment costs were calculated, although the model is suitable for the calculation of any treatment process.

Therefore, it is shown in the table 5.5 the values used to calculate the costs of the build removal and cleaning activity. The times present in the table were estimated according to data provided by Hypermetal. The area reserved for waste disposal consists of a barrel where filters and debris are placed. The rejection rate after removal of parts was considered according to the information supplied by Hypermetal. The number of filters until it is necessary to resort to the removal of debris from the company's facilities was provided by Hypermetal, as well as the cost for this removal.

Table 5.5: Post-processing costs

Variable	Cost model element	Value	Units
	Build removal and cleaning		
$t_{removal}$	Part removal time	0,05	[h]
$t_{cleaning}$	Machine cleaning time	1	[h]
A_{Debris}	Area reserved for waste disposal	1	$[m^2]$
RR_{BRC}	Rejection rate of the build removal	2	$[\%]$
$N_{Filters}$	Number of filters used until removal is required	9	[-]
$C_{Debris\,removal}$	Cost of removing debris	70	[€]

whether or not it includes

5.3 Comparison between AM and Forging

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 [98]. For MAM, this means that a manufacturer with a machine certified to produce a certain set of parts is not authorized to produce a different set without re-certifying the machine for the new production, whether or not it includes parts present in the already certified set [72]. Any change to the quality system is therefore subject to review by the regulatory authorities[1]. 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 [98]. Using a cost model for the forging process [101], it was compared, in figure 5.1, the difference in cost per part for the different production volumes for the forging process and for the MAM process in the case where the

[1]Such as FAA for the United States of America and EASA for Europe.

production is dedicated and in the case where the production is non dedicated. The latter case would represent a machine that could produce any set of parts, without taking into account the certification aspect mentioned above.

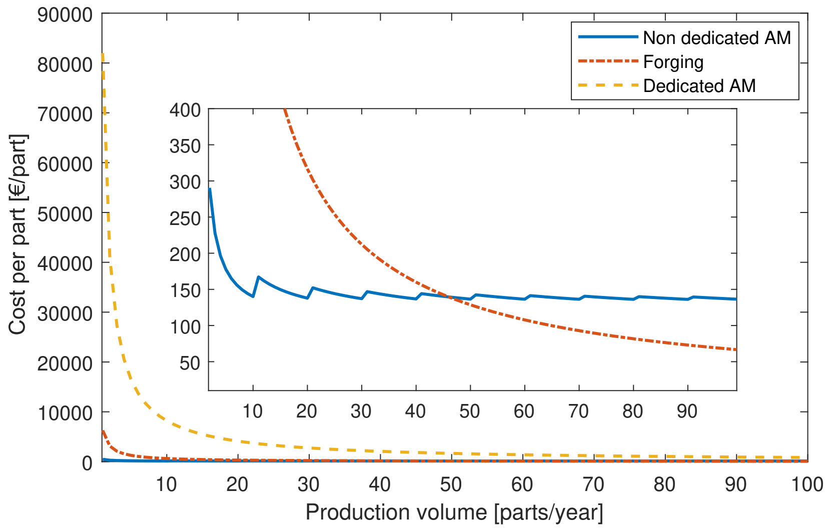


Figure 5.1: Comparison between dedicated and non dedicated MAM production and forging.

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. This path that needs to be taken will mean that, if successful, in the future it will be possible to have a non dedicated MAM process for the aerospace industry, where different parts can be produced on the same machine. This scenario is present in figure 5.1 and the following analyses for MAM will take this scenario into account.

As previously mentioned, it can be observed that non dedicated MAM has a lower cost per part for a lower production volume when compared to a traditional process, in this case forging. In the present case, MAM is advantageous for a production volume of up to about 46 parts produced per year. For this analysis an uptime of the machine of 3120 hours per year was assumed. This number is due to the capacity of the machine studied to produce almost 100 hours in a row, being able and occupying in some cases the whole weekend in addition to the night periods. These periods, which in other manufacturing processes cannot be accounted for, can be used in MAM, since the physical presence of any operator is not necessary in that space of time.

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. This is because the time to produce one part or the time to produce ten parts in the same batch is not linear. There are times that are constant, regardless of the number of parts per batch, assuming that the parts have the same height. In other words, the production of a new part will be allocated the same constant time of the machine that would be allocated to a production with more parts and therefore there is the referred increase of the cost per part.

A comparison is then made of the cost distribution for the MAM and forging processes. It can be seen in the figures 5.2 and 5.3 that the vast majority of the cost of MAM production is associated with the cost of the machine, about 84% and 85% for the cases in which the production volume is 50 and 100 parts per year. With the increase in production volume, costs remain practically constant in percentage terms. The only variations to be highlighted are the decrease in the value of the labor due to the fact that it was assumed that the operator would take less time to prepare the data for the productions that followed the first one, with most of the cost being representative of the first batch produced, and the decrease of the building cost because it is a fixed cost that is divided into a different number of parts. The energy cost present 0.2% of the total cost, which is practically insignificant in this case. The percentages of these costs will also remain practically constant for higher production volumes than those considered here.

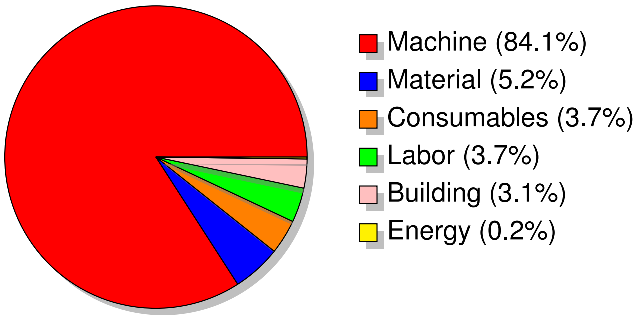


Figure 5.2: Distribution of the costs of MAM for an annual production of 50 parts.

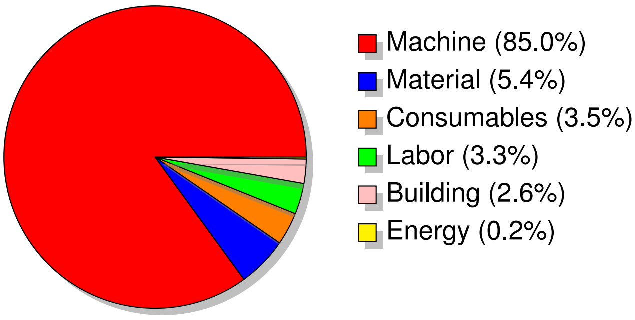


Figure 5.3: Distribution of the costs of MAM for an annual production of 100 parts.

Figures 5.4 and 5.5 show the percentages associated with each cost for the forging process [101]. The same material that was used in the calculations for MAM was considered, which is cheaper for the traditional process [100]. In this type of manufacture the cost of the machine does not have the same influence as in the previous case, because the parts spend a short time in the machine. Even with a high machine price the cost allocation to each part will be very small. In this process, the tooling cost is the most relevant, representing 96.9% and 94.4% of the total costs for the annual production of 50 and 100 parts, respectively. In this case, with the increase in production volume, the tooling capitalization is observed. The cost of the machine begins to rise due to its higher utilization with increased production.

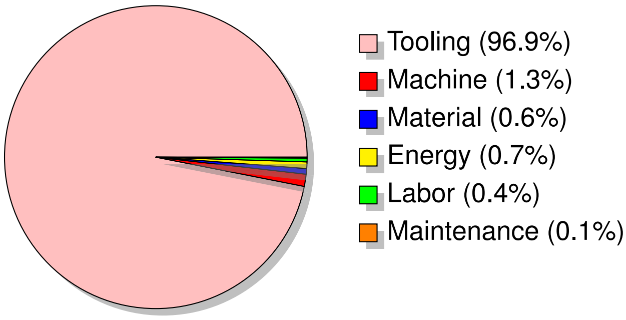


Figure 5.4: Distribution of forging costs for an annual production of 50 parts.

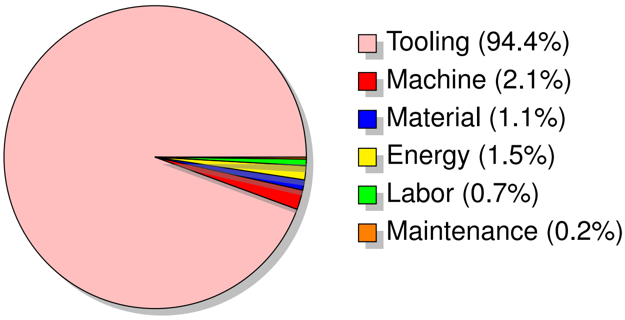


Figure 5.5: Distribution of forging costs for an annual production of 100 parts.

This tooling cost, which represents almost the total cost in forging for low production volumes, does not exist in AM, which is one of the advantages of AM, mentioned previously.

When comparing the costs of the process steps in the MAM, in figure 5.6, it can be seen that 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 [102]. As previously mentioned, the cost model developed is able to perform the calculations of the treatment activities.

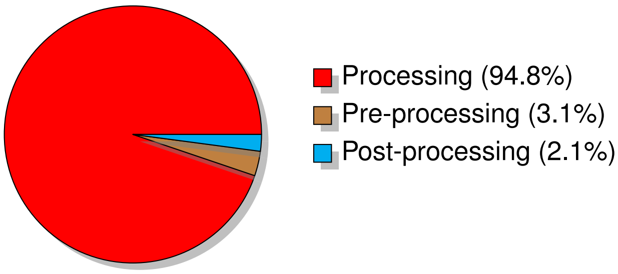


Figure 5.6: Contribution of pre-processing, processing and post-processing costs to the final cost of the part, for a annual volume of production of 100 parts.

5.4 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 results shown above, it was assumed a maximum number of parts, of the same geometry as in the case study, that can fit into a single batch. The cost model has an algorithm to give an estimate of the maximum number of parts that can be produced with the same geometry taking into account the volume of the machine chamber and assuming that no parts are produced on top of others.

In the figure 5.7 is represented the variation of the cost per part for different values of parts per batch.

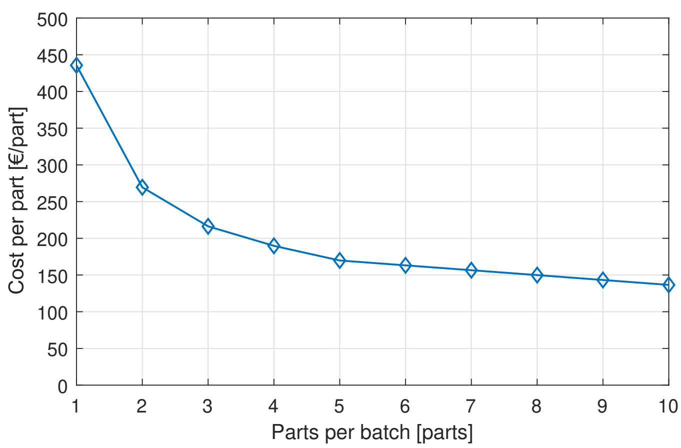


Figure 5.7: Sensitivity analysis for the number of parts produced per batch.

For this analysis it was assumed an annual production of 50 parts and a machine uptime of 3120 hours. As can be seen, the more parts produced per batch, the lower the cost per part is.

The time estimate model of the cost model was used to estimate the production time for the different part values 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.

It should be noted that for this analysis a zero rejection rate was considered. Since a production volume of 50 parts was considered, that number being a multiple of the 10 parts per batch, the consideration of a rejection rate, however small, would lead to the need to produce an extra batch, with only one part in the case of the maximum optimization of the number of parts per batch. In this case, the cost per part for 10 parts produced per batch would be higher than the cost of producing 9 parts per batch. In order for these figures not to be misleading, the zero rejection rate was assumed, as mentioned above.

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 5.8 represents the machine uptime sensitivity analysis for a production volume of 50 parts per year.

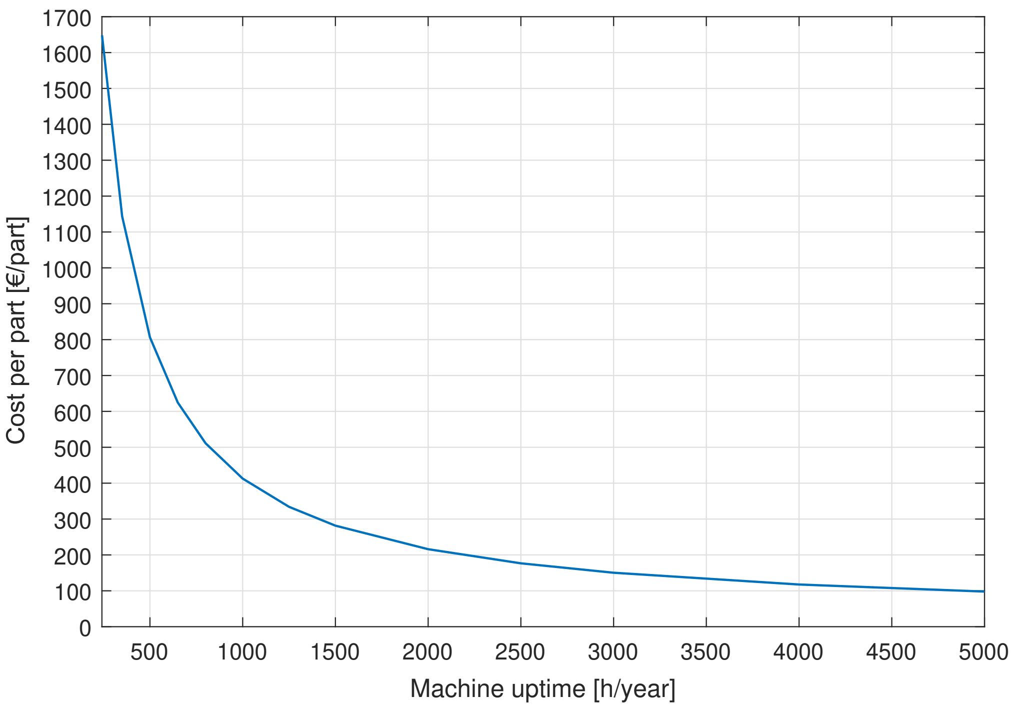


Figure 5.8: Machine uptime sensitivity analysis, for an annual production of 50 parts.

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.

With the increase in the machine uptime to values in the order of 5000 hours, the cost per part falls to less than 100 €. With a machine uptime of 4000 hours, the cost per part is already lower than the cost of forging, taking into account the annual production of 50 parts. For a larger production volume, the curve has the same shape, with the cost per part also decreasing with the increase in the annual number of parts produced. The cost per part, for each machine uptime value, is slightly lower than the one presented.

Since the curves are similar, the analysis is only illustrated for the case of a production volume of 50 parts.

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.

In the figure shown above, the machine activity time varies from the dedicated production value to the value of 5000 hours. This value may seem a very high number and even though it takes many hours or even more than a day to make the essential changes to make productions with different materials, when it is taken into account that it is possible to make productions of many consecutive hours, as mentioned previously, this value proves to be doable.

It is important to point out that even if no operator is working, during certain hours when the machine is operating, at night and at weekends, vigilance is always required to ensure that production goes as planned.

As previously observed, the cost of the machine is the cost that most influences the final cost of each part. 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 MAM powder materials is also high, although the cost of the material has less influence on the final cost of the parts. 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 [103].

Tables 5.6 and 5.7 show sensitivity analyses for cost per part according to a possible reduction in the price of the machine, for an annual production volume of 50 and 100 parts, respectively, with a machine uptime of 3120 hours being considered. The price of the machine was reduced in the analysis to 100 000 € just to see how low this price would have to be in order for the MAM to have a lower cost per part than forging.

It should be noted once again that the price of the machine includes, in this case study, also the price of the software and the price of maintenance. Therefore, the change in the price of the machine will not only correspond to the machine itself. Nevertheless, it is possible to get an idea of the difference that this change will have in the final cost of each part.

Table 5.6: Sensitivity analysis of the machine price for an annual production of 50 parts.

Machine price	Cost per part
500 000,00 €	149,82 €
450 000,00 €	137,21 €
400 000,00 €	124,61 €
350 000,00 €	112,01 €
300 000,00 €	99,41 €
250 000,00 €	86,80 €
200 000,00 €	74,20 €
150 000,00 €	61,60 €
100 000,00 €	48,99 €

Table 5.7: Sensitivity analysis of the machine price for an annual production of 100 parts.

Machine price	Cost per part
500 000,00 €	145,13 €
450 000,00 €	132,79 €
400 000,00 €	120,45 €
350 000,00 €	108,12 €
300 000,00 €	95,78 €
250 000,00 €	83,44 €
200 000,00 €	71,11 €
150 000,00 €	58,77 €
100 000,00 €	46,43 €

As can be seen, the cost per part is considerably reduced in both cases, for a decrease in the price of the machine. For an annual production volume of 50 parts there would need to be a reduction of slightly less than 100 000 € for the value of the cost per part to be lower than in forging (128.67 €). For an annual production volume of 100 parts a reduction of more than 300 000 € would be necessary for MAM to have a lower cost value than forging (66.05 €). This shows the importance of the machine price value for the final cost of the parts and how for larger production volumes a very large reduction in the price of MAM machines is required in order for this process to compete with forging in terms of cost per part.

5.5 MAM parts in the aeronautic industry

Using the considerations made in subchapter 4.8, the monetary value of the decrease in fuel use for a part reduction in an aircraft was calculated. The used fuel was calculated for the weight of the aircraft initially considered. Then, a mass reduction was assumed for a part similar to the part presented in the case study, about $0,172kg$ taken from the part with the optimization process. This value was subtracted from the total weight of the aircraft and the fuel consumption for the new weight of the aircraft was calculated using the same method presented previously. With the two values of fuel used, it was possible to obtain the difference from one case to the other, getting the value of fuel saved with the reduction of weight of the aircraft. 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.

The table 5.8 shows the amount saved for one year, taking into account the time of the mission and the number of hours of annual flights considered, with the amount saved on a one mission being multiplied by the annual number of missions. It should be noted that these figures are shown in [€PPP] so that a better comparison between the monetary value can be obtained.

Table 5.8: Annual value saved for each of the scenarios considered, for weight reduction corresponding to one part.

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

The annual savings are representative of the difference that exists with the use of an optimized part in an aircraft. The present value, PV, equation 5.3, was then calculated for savings made over a certain number of years. The savings represent the cash flows, CF, which are considered annuities and were passed to a present value using a discount rate, *r*, of 10% for the various periods, *n*, considered.

$$PV = CF \times \frac{[1-(1+r)^{-n}]}{r}. \tag{5.3}$$

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 dissertation. 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 an annual production volume of 50 parts, the difference between the cost per part of MAM and forging is 21,15 €. This value, being negative, is added to the value obtained for the PV, resulting in the present value corresponding to using the part produced by MAM, instead of the part manufactured by a traditional process, forging. The tables 5.9, 5.10 and 5.11 represent this value for a period of 5, 10 and 15 years, respectively.

Table 5.9: PV for fuel savings assuming parts with a lifetime of 5 years, for a production volume of 50 parts.

Number of parts used	**Lowest** [€ PPP]	**Recent** [€ PPP]	**Highest** [€ PPP]
1	10,65	40,39	111,85
10	106,47	403,93	1 118,52
20	212,95	807,86	2 237,03
30	319,42	1 211,79	3 355,55
40	425,89	1 615,73	4 474,06
50	532,37	2 019,66	5 592,58

Table 5.10: PV for fuel savings assuming parts with a lifetime of 10 years, for a production volume of 50 parts.

Number of parts used	**Lowest** [€ PPP]	**Recent** [€ PPP]	**Highest** [€ PPP]
1	30,39	78,61	194,44
10	303,91	786,07	1 944,35
20	607,82	1 572,13	3 888,70
30	911,73	2 358,20	5 833,05
40	1 215,64	3 144,27	7 777,41
50	1 519,55	3 930,33	9 721,76

Table 5.11: PV for fuel savings assuming parts with a lifetime of 15 years, for a production volume of 50 parts.

Number of parts used	**Lowest** [€ PPP]	**Recent** [€ PPP]	**Highest** [€ PPP]
1	42,65	102,33	245,71
10	426,50	1 023,34	2 457,13
20	853,00	2 046,68	4 914,26
30	1 279,50	3 070,03	7 371,39
40	1 706,01	4 093,37	9 828,52
50	2 132,51	5 116,71	12 285,65

It is possible to observe that for all time periods considered the change from forging production to MAM is profitable. Assuming that 1, 10, 20, 30, 30, 40 and 50 parts of the 50 produced are used, it is possible to achieve savings in the order of thousands of euros.

For the scenario where the fuel price is lower the savings are less visible, and for a lifetime of 5 years the savings are about 11 € for a part. This figure is four times higher, 40 €, for the most recent fuel price scenario and reaches 112 € for the scenario that considers the highest fuel price in the last 15 years.

For the recent scenario, it is observed that if there is a use of 50 parts in the aircraft (about 8,6 kg weight reduction), it would save about 2 000 €, 3 900 € and 5 100 € after 5, 10 and 15 years, respectively. This amount itself does not represent a large amount of money, given that it is being referred to large periods of time.

For larger production volumes, since the parts are of the same geometry, MAM even displays a negative balance, as can be seen in table 5.12, for an annual production volume of 100 parts. For this annual production volume, the difference between the cost per part of MAM and forging is 73,67 €.

Table 5.12: PV for fuel savings assuming on part with a lifetime of 5, 10 and 15 years, for a production volume of 100 parts.

Period of time [Years]	**Lowest** [€ PPP]	**Recent** [€ PPP]	**Highest** [€ PPP]
5	(41,87)	(12,12)	59,33
10	(22,13)	26,09	141,92
15	(9,87)	49,82	193,20

Since the values of fuel consumption were obtained through interpolations made with values given in the tables mentioned above, the reduction of fuel used is linear at least until a reduction in weight corresponding to more than 100 parts, so that it is not shown here again the cost for several parts to be used in the aircraft. The value obtained would then be the multiplication of the number of parts by the value of the fuel savings for one part.

It is observed that for the scenario that contemplates the lowest price of fuel there are no savings, and the result is negative. While the cost of forging varies widely between annual production of 50 and annual production of 100 parts, the cost of producing MAM remains roughly constant. The increase in the difference between the costs of the two processes is reflected in the values shown.

Although for a longer lifetime the savings amount is positive, it is a lower amount when considering the corresponding time period. Compared to the 10-year period, the savings are about three times lower than the annual volume of 50 parts and about two times lower for the 15-year period. For higher production volumes, the difference between the cost of the different manufacturing processes is even greater and there are no savings from reducing the weight of the aircraft for the time periods considered.

Nevertheless, in the future, if there is a possibility for MAM to produce parts of different geometries for the aeronautical industry and taking into account that in this study only one aircraft was considered, significant savings could be achieved. Alongside the production of different parts, part redesign allows the number of parts in an assembly to be reduced, while reducing the labor costs associated with the assemblage work. With several aircraft having their weight reduced and parts of different geometries manufactured with MAM replacing parts manufactured with traditional processes, it will be possible to obtain values that compensate this change in the manufacturing process.

Huang et al., 2016 [68], 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) [68].

Assuming then that 510 kg of metal parts suffer the same process of optimization as the part of the case study, with the same percentage of reduced mass, and assuming that, corresponding to 510 kg, all parts, not necessarily equal, have the same mass and the same cost 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.

In the table 5.13 is shown the annual value saved, for the same aircraft previously considered, in the same conditions, with a weight reduction of 202 kg. It can be observed that when considering a larger weight reduction in an aircraft, the fuel saving values begin to be much more significant.

Table 5.13: Annual value saved for each of the scenarios considered, for weight reduction of 202 kg.

Case	**Lowest fuel price**	**Recent fuel price**	**Highest fuel price**
Annual savings [€ PPP]	11 674,08	22 594,99	48 830,28

A number of parts, 1172, with the same mass was then assumed, to make a total of 510 kg. Since the cost of parts must be taken into account in order to make an analysis with the PV of savings, it was assumed an equivalent cost for all parts, corresponding to the cost of annual production for 50 parts in both processes. In table 5.14, it is then presented the values of PV for fuel savings, with a weight reduction of 202 kg.

Table 5.14: PV for fuel savings assuming an aircraft weight reduction of 202 kg, for a parts lifetime of 5, 10 and 15 years.

Period of time [Years]	**Lowest** [€ PPP]	**Recent** [€ PPP]	**Highest** [€ PPP]
5	19 481,90	60 880,74	160 333,13
10	46 960,11	114 064,37	275 268,87
15	64 021,91	147 087,23	346 634,93

It can be seen that for a 202 kg weight reduction in an aircraft, the fuel savings become more significant, with a saving of 61 000 €, 114 000 € and 147 000 € for the most recent fuel price, for 5, 10 and 15 years, respectively.

It should be noted, once again, that these values represent only the fuel savings of only one aircraft and that, although this analysis assumes that 510 kg of parts can be optimized in the same proportion as the part in the case study, 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.

Chapter 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 recently on MAM.

Given that to implement a new technology it is necessary to analyze its economic part, in this thesis a cost model was developed to calculate the costs of production of parts by a MAM process (PBF), and it was analyzed the most determinant costs for a case study. The cost model includes a process model estimation of the build time of parts in the same batch, which for the machine in question and for the materials analyzed presents values very close to the actual values.

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. This is the cause of the cost per part being so dependent on the annual machine cost and any decrease in machine price will have a direct and high impact on the cost of the part, which may prove to be competitive for an higher annual volume of productions than the one currently being registered.

In this dissertation, 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 that was not taken into consideration in this thesis, which was the certification of parts to be used in aircraft. At the moment, machines certified to produce a certain set of parts are not allowed to produce any other different set, nor to change their configurations, becoming dedicated machines for the parts in the set in question. 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 (i.e. those components that are the least critical and whose failure does not affect flight safety or aircraft performance) may require less control in terms of certification [102] and could be MAM's short-term focus on this industry.

In the future, should the necessary developments happened, the savings values considered with the reduction of fuel consumption will also increase. Given that machines may, at some point in the future, produce different parts in the same batch, the possibility of reducing the weight of aircraft in many parts of the aircraft itself, and not just in a particular location for a particular type of part, increases. This hypothesis is where MAM has the greatest potential when compared to traditional manufacturing. While the latter has a lower cost for high production volumes, it has a much higher value when it comes to a lower production volume. By being able to produce many different parts the MAM can produce fewer parts of each type and produce more different parts without increasing costs by doing so.

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, since these costs can considerably increase the cost of production of parts. The cost model developed is, however, prepared for this computation.

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.

One of the advantages related to AM is the reduction of the necessity to store parts in stock, as parts can be produced as needed. This translates into a cost reduction to which is added the time that is saved by not having to wait for the ordering of the parts. Although the time of the AM process is high when compared to traditional processes, once the supply chain is shortened, this time ends up being compensated [62]. The effects of this advantage were not explored in the analyses presented in this thesis.

Taking into account the limitations presented above, some future works are recommended that may complement the work presented in this thesis.

As the matter of parts certification for the aerospace industry has not been considered, 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.

In addition to this analysis, a study could be carried out to investigate the lifetime of parts produced by MAM compared to parts produced by conventional processes, taking into account also the lifetime of the aircraft, as well as the maintenance costs associated with the change in the used parts.

Another future work recommended here is the use of the cost model developed with values more indicated to the aerospace industry, such as the use of materials as for example titanium.

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.

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