Economic and Environmental Potential of Wire Arc Additive Manufacturing

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Thesis to obtain the Master of Science Degree in

Mechanical Engineering

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July 2021

Acknowledgements

First, I would like to sincerely thank Prof. Inês Ribeiro and Prof. Carlos Alves da Silva for the supervision given throughout the development of this thesis even in such difficult times. I would also like to thank them for the continuous support with all the research and writing pointing me towards the correct path.

Moreover, I would like to thank Eng. João Pragana whole heartedly for all the knowledge shared and specially for his availability on helping me with the troubles and the case study of the thesis.

I cannot also forget my friend, Eng. João Cravidão, who with all his support always helped me very fast and accurately.

It is also impossible to thank enough all my friends that have supported and motivated me. They have made this five-year journey for sure unforgettable, and I will take these memories for my life.

Finally, there are no words to describe how thankful I am to my parents and my sister for the unconditional love and support given and for making me a better person.

Resumo

Desde a sua origem, o fabrico aditivo tem visto um crescimento enorme, particularmente na última década. Este desenvolvimento deve-se à completa mudança de paradigma face aos métodos de fabrico subtrativos.

Esta tese explora o potencial do Fabrico Aditivo com Fio Consumível e Arco Elétrico que, utilizando máquinas comuns de soldaduras, consegue atingir altas taxas de deposição, reduzindo os tempos de produção e diminuindo o consumo de material, permitindo assim economizar nos custos de produção das peças.

O presente estudo teve como objetivos a avaliação da viabilidade económica na produção de peças por esta tecnologia, e a sua comparação com métodos tradicionais tais como a Maquinagem e a Fundição com Molde. Para isso foram desenvolvidos Modelos de Custo Baseados no Processo, que inerentemente permitem o cálculo dos custos de produção de peças com uma abordagem tecnológica. Através do inventário de recursos que foi retirado dos modelos, posteriormente foi realizada uma Análise do Ciclo de Vida de uma peça desenvolvida, com o objetivo de avaliar o impacto ambiental deste método de fabrico quando comparado a métodos subtrativos.

Com os resultados finais presentes na tese, relativos à peça do caso de estudo, foi possível inferir que, de facto, este método de fabrico aditivo pode ter uma maior viabilidade económica e menor impacto ambiental na situação apresentada. Assim, a continuação do desenvolvimento e otimização deste método de fabrico pode levar a uma mais-valia na produção de partes metálicas em certos contextos industriais.

Palavras-Chave: Fabrico Aditivo, Modelos de Custo Baseados no Processo, Análise do Ciclo de Vida, Caso de Estudo, Fabrico Aditivo com Fio Consumível e Arco Elétrico

Abstract

Since its creation, additive manufacturing has seen tremendous growth, particularly over the last decade. This progress is owed to the complete paradigm shift from subtractive manufacturing methods.

This thesis explores the potential of Wire Arc Additive Manufacturing (WAAM) which, using common welding machines, achieves high deposition rates, reduces production times, and decreases material consumption, thus saving on production costs.

The current study had as objectives the evaluation of the economic viability in the production of parts by WAAM, and its comparison with traditional methods such as Complete Machining and Die Casting. For that purpose, Process Based Cost Models were developed, since they inherently allow the cost calculation of parts using a technological approach. Through resources inventory that were obtained from the models, a Life Cycle Analysis (LCA) of a developed part was carried out, in order to assess the environmental impact of this manufacturing method when compared to subtractive methods.

With the final results presented in the thesis, associated to the case study artifact, it was possible to infer that, in fact, this additive manufacturing method may have economic viability in the presented situation. Thus, the further development and optimization of this method can lead to added value in the production of metal parts in specific industrial contexts.

Keywords: Additive Manufacturing, Process Based Cost Model, Life Cycle Assessment, Case Study, Wire and Arc Additive Manufacturing

Contents

List of Figures

Tables Index

Nomenclature

3D – Three-Dimensional

AM – Additive Manufacturing

BTF – Buy-to-Fly

CAD – Computer Aided Design

DED – Direct Energy Deposition

EU – European Union

ISO - International Organization for Standardization

LCA – Life Cycle Assessment

LCI – Life Cycle Inventory

MIG – Metal Inert Gas

PBCM – Process Based Cost Model

WAAM – Wire and Arc Additive Manufacturing

Chapter 1 – Introduction

1.1 Topic Overview and Motivation

Additive Manufacturing (AM) is comprised of several types of technologies. Over the past decades, there has been an explosion within the Additive Manufacturing (AM) market due to the increasing use by different manufacturers from multiple industries, which are able to use technologies that regard both non-metals and metals [1].

With the effects of globalization, cost, quality and the novelty of products are some of the main drivers of markets with clients always expecting higher quality with lowers costs [2]. Adding to this phenomenon's there is a progressively growing concern regarding the environmental impact of products, making the environmental impact an important criterion for new manufacturing techniques [3].

With these demanding needs, several AM technologies have been developed, including Wire Arc Additive Manufacturing. This technology, like most AM methods, allows for a significant material reduction when compared to other processes. However, due to its common type of machines, it also allows the significant reduction of machinery and tooling costs [4]. Compared to other AM processes, WAAM has a very high deposition rate which permits building bigger parts in a faster time and with good mechanical properties. However, the high heat input associated leads to a significant distortion and residual stresses which does not provide good mechanical properties to the part[5].

With this, more and more companies are using the WAAM technology to manufacture parts and therefore they need to estimate the costs related to the production of parts and compare them with the previous manufacturing methods. Even with the current models developed, there is still a need for more thorough models with different approaches to both the process and the cost [6]. As a cutting-edge manufacturing technology, it is also noteworthy that little research on WAAM environmental impact has been done.

1.2 Objectives

The aim of this thesis is thus the extensive evaluation of the WAAM method, with a focus on the economic and environmental impacts, while creating a tool that allows future assessments easier. For this, a Process Based Cost Model was developed in Microsoft Excel, to satisfy the technical needs while creating a sturdy financial tool. It was also conducted an analysis of the environmental impact of WAAM when compared with traditional manufacturing methods.

For this cost model, the scope of the study will start with the setup for the deposition process of WAAM and will finish with the finish machining process, leaving out any intermediate processes. The same scope will be applied for the environmental analysis to maintain a coherent approach. Indirect costs such as reception and storage will be left out, as quality inspections and the end-of-life treatments of the products created.

1.3 Thesis Outline

This thesis is subdivided in 6 main chapters, where the order and contents of each will be laid down as follows:

Chapter 1 – Introduction: The current chapter, where the motivation for the current work is presented, alongside with the problem statement, the scope and finishing with the structure of the thesis.

Chapter 2 - State of Art: This chapter addresses the current state of the additive manufacturing market, going into detail in the Metal Additive Manufacturing market. Then a critical review on the current economic and environmental analysis is performed. It was where the fundamental knowledge of the remaining research was obtained.

Chapter 3 - Methodology: The full methodology prepared for this thesis is shown, as well as the full methodology used to perform the case study and the Life Cycle Assessment. A detailed explanation on how to build a Process Based Cost Model and execute a Life Cycle Assessment is also presented.

Chapter 4 – Cost Model: This Chapter explains the cost model which was applied for the posterior analysis. It follows the logical order from the inputs until the final costs with an explanation for the intermediate calculations.

Chapter 5 – Results and Discussion: Everything that was explained previously is laid down in this chapter in the form of results. This stands for each analysis with a focus on WAAM cost and the subsequent environmental impact. The analysis of those results is also performed in this chapter, next to the respective results.

Chapter 6 – Conclusions and Future Work: The conclusions based on all the results from the previous chapter are drawn and suggestions for future work are provided.

Chapter 2 - State of Art

To lay the foundations for the topic of this thesis it is essential to start by a research on the existing knowledge of the topic and even its predecessors, in all the areas associated to the subject. Therefore, this chapter is sub-divided into several sub-chapters in which a brief analysis was conducted.

Hence, this literary review is constituted by an introduction to the history and development of the Additive Manufacturing (AM) proceeded by a more in-depth study of the Metal Additive Manufacturing and its different processes, focusing specially on the topic for this thesis, the WAAM technology. This is followed by an overview on the previously developed cost models focusing on the Additive Manufacturing and Metal Additive Manufacturing areas. Finally, to conclude, a review on the Life Cycle Assessment methods is done.

2.1 Additive Manufacturing

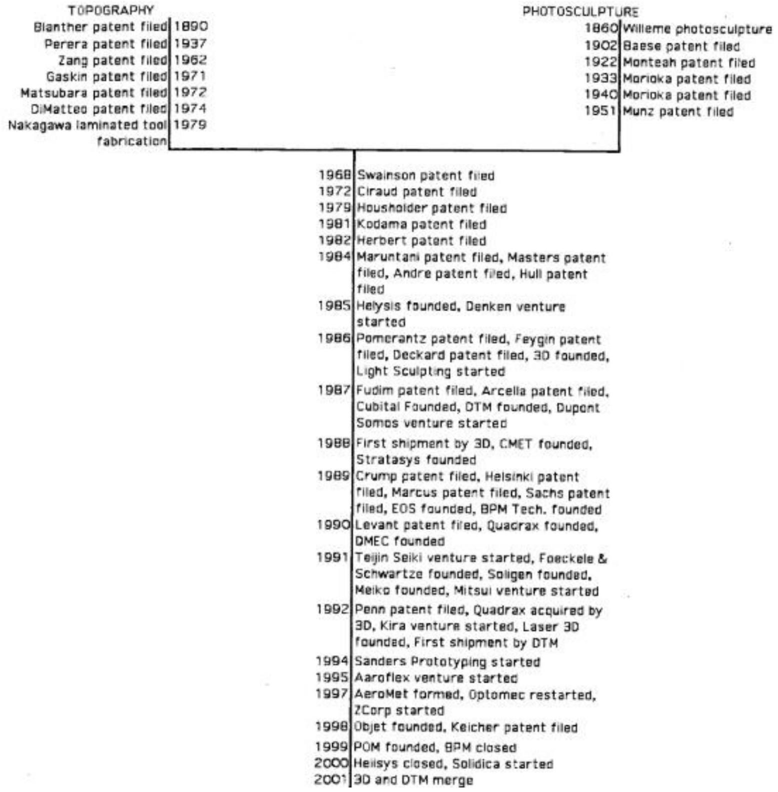
2.1.1 Background

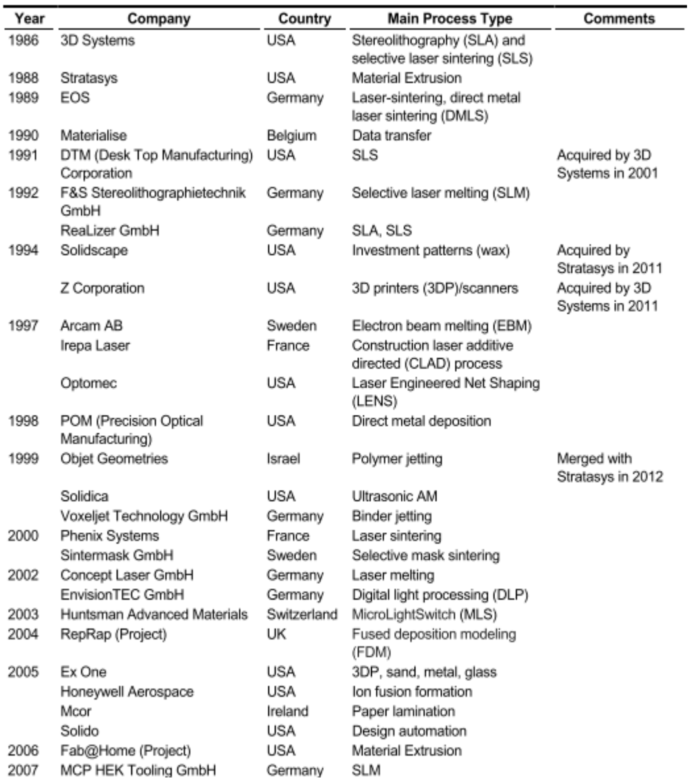
Even though additive manufacturing has, only recently, gained most of its momentum, the real origin for this method can be traced to much earlier. While it cannot be agreed when the technology began, it is commonly accepted that it traces back to the 19th century. The earliest techniques related to modern Additive Manufacturing are found in the 1860's and 1890's with photo sculpture and topography, respectively [7]. The photo sculpture technique, as the name indicates, tried to recreate copies of 3D objects obtained by photography, having the first successful attempts with François Willème between 1859 and 1868 [8]. Regarding the Topography technique, the first molds were created later, in 1892, by J. E. Blanther with his patent for the manufacturing of contour relief maps [9] .

After these first initial breakthroughs there was a slower development new technologies until in 1951, when Otto John Munz filed a patent for a system that resembles Additive Manufacturing techniques still present today [10]. This process was called Photo-Glyph Recording and it is similar to current day stereolithography. This is why, even though it is a very outdated technique, it can still be found on modern day literature [7].

About 15 years later, in 1968, Swainson first proposed a method that would allow to directly manufacture a 3D plastic pattern, but this process was not economically viable, thus not being further explored [11]. However, just 3 years later, in 1971, Ciraud present a powder process that comes strongly resembles modern day direct deposition technique [12]. In 1979, Housholder filed a patent for what is known to be the first powder laser sintering process where material is sequentially deposited and solidified [13]. Just 2 years later, Hideo Kodama of Nagoya Municipal Industrial Research Institute published the first rapid prototyping system [12].

After this between the 1980’s and 1990’s an enormous number of papers was published to solve the problems and further developed the additive manufacturing technologies. [14]





Year	Company	Country	Main Process Type	Comments
1986	3D Systems	USA	Stereolithography (SLA) and selective laser sintering (SLS)	
1988	Stratasys	USA	Material Extrusion	
1989	EOS	Germany	Laser-sintering, direct metal laser sintering (DMLS)	
1990	Materialise	Belgium	Data transfer	
1991	DTM (Desk Top Manufacturing) Corporation	USA	SLS	Acquired by 3D Systems in 2001
1992	F&S Stereolithographietechnik GmbH	Germany	Selective laser melting (SLM)	
	ReaLizer GmbH	Germany	SLA, SLS	
1994	Solidscape	USA	Investment patterns (wax)	Acquired by Stratasys in 2011
	Z Corporation	USA	3D printers (3DP)/scanners	Acquired by 3D Systems in 2011
1997	Arcam AB	Sweden	Electron beam melting (EBM)	
	Irepa Laser	France	Construction laser additive directed (CLAD) process	
	Optomec	USA	Laser Engineered Net Shaping (LENS)	
1998	POM (Precision Optical Manufacturing)	USA	Direct metal deposition	
1999	Objet Geometries	Israel	Polymer jetting	Merged with Stratasys in 2012
	Solidica	USA	Ultrasonic AM	
	Voxeljet Technology GmbH	Germany	Binder jetting	
2000	Phenix Systems	France	Laser sintering	
	Sintermask GmbH	Sweden	Selective mask sintering	
2002	Concept Laser GmbH	Germany	Laser melting	
	EnvisionTEC GmbH	Germany	Digital light processing (DLP)	
2003	Huntsman Advanced Materials	Switzerland	MicroLightSwitch (MLS)	
2004	RepRap (Project)	UK	Fused deposition modeling (FDM)	
2005	Ex One	USA	3DP, sand, metal, glass	
	Honeywell Aerospace	USA	Ion fusion formation	
	Mcor	Ireland	Paper lamination	
	Solido	USA	Design automation	
2006	Fab@Home (Project)	USA	Material Extrusion	
2007	MCP HEK Tooling GmbH	Germany	SLM	

Figure 1 - Chronology for Additive Manufacturing Processes (left) and Early-stage com AM companies(right) [14]

It is also worth noting the work of Charles Hull with his patent on the stereolithography machine in 1986, allowing the creation of many AM companies in the following decade. Finally, in the 21st century it is worth noting the project RepRap (Replication Rapid-Prototyper) for making the code for the software publicly available, giving the possibility for individuals to start using AM processes[15].

In figure 1, it is possible to see a more complete timeline of patents and innovations related to additive manufacturing and some of the first companies adopting the new manufacturing methods.

2.1.2 The Growth of AM

As it was briefly mentioned in the previous section AM has seen a large growth and has impacted several sectors, as seen in figure 2, such as the Medical/Dental, Surgical Planning, Implant and Tissue Designing, Automotive, Aerospace, Biotechnology, Electronics, and even Education and Design [12], [15].

All technologies go through a steep curve of evolution and only the successful ones survive the demands of the industry. This is what happened with AM, when in the beginning of the 2000’s wasn’t purely academic anymore and it started becoming more standardized and accepted due to the higher repeatability and reliability of the processes [17].

The additive manufacturing market is still growing exponentially (data in figure 3),however, it still has several challenges incoming. [18].

Wohlers Associates releases a report every year analyzing the whole industry of AM being a reference for the AM literature, acquiring data from experts and directly questioning the biggest companies in the sector. [1]

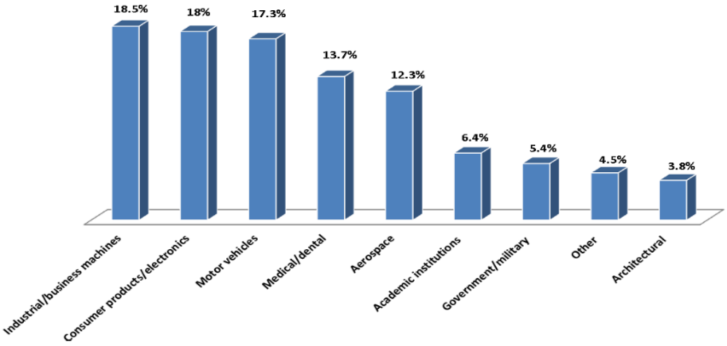


Figure 2 - Breakdown of the percentage of industrial sectors using AM in 2014 [16]

Within the EU, in 2014, a report was written to evaluate the state of AM, and to plan and predict where the technology should head to, noting the importance of AM for the economical and societal development. [3]

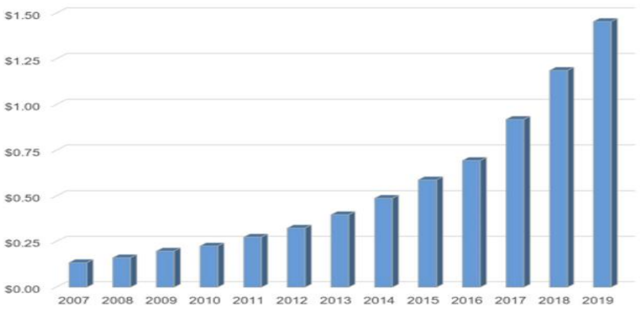


Figure 3 - Money spent annually on production of final parts by AM (Values in billions of dollars) [1]

2.1.3 Description of AM

Additive Manufacturing is a set of processes that allows building three-dimensional parts from a digital model by adding thin layers of material in a consecutive manner [19]. Synonyms also commonly utilized to describe this technique are, among others: 3-D printing, direct digital manufacturing, layer manufacturing and even rapid manufacturing or rapid prototyping [17], [19].

This process is the parallel of the ones called conventional manufacturing techniques, such as stamping or milling, that creates products carrying out the successive removal of material from a block, therefore incurring in a much more wasteful procedure [20].

Notwithstanding that Additive Manufacturing can be divided in much smaller and specific steps, all the processes have at least the same 3 basic steps [21] :

A 3D CAD model is conceptualized and developed, and finally converted to a language that the machine is familiar with, as represented on the left of figure 4.

The file is transferred to the desired machine to allow further modifications to the file and choose the best orientation and position for the part, exemplified on the second image of figure 4.

After all the desired changes are made the part is finally built by the AM machine, layer by layer, until the final desired 3D part is created, characterized on the last two images of figure 4.

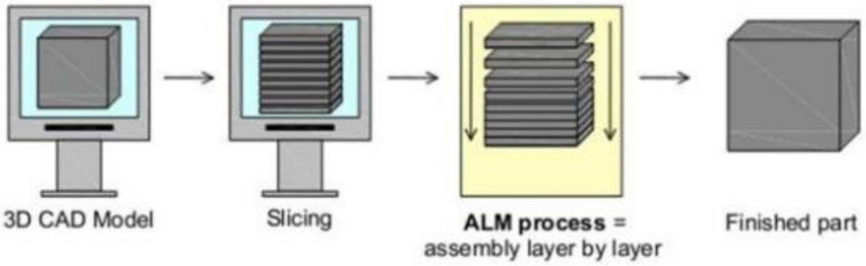


Figure 4 - Life Cycle of an AM part

AM is one of the most analyzed areas by the American Society for Testing and Materials. This institution has made the most recent division commonly accepted by the scientific community, presented in figure 5. This division allows the standardization of processes and a growth towards a common direction for the technology. Therefore, the 7 processes defined are: Vat photopolymerization, Material Extrusion, Material Jetting, Binder jetting, Powder Bed Fusion, Direct Energy Deposition and Sheet Lamination [22].

As one might infer, even though these processes are related, they are all different. When choosing one over the other there are many considerations to have in mind such has the material, the build rate, layer thickness, finishing of surfaces, machine costs, among other factors [23].

However, there are other proposed divisions such as by the state of the starting material. This will allow to separate the AM technologies into 4 different and broad categories: Liquid (where a curing period is always needed), paste/filament (depositing a thread of molten material into a substrate with a moveable head), powder (application of powder and posterior heat source to build each layer) and solid sheet (with the cutting and attaching of each of the layers) [24].

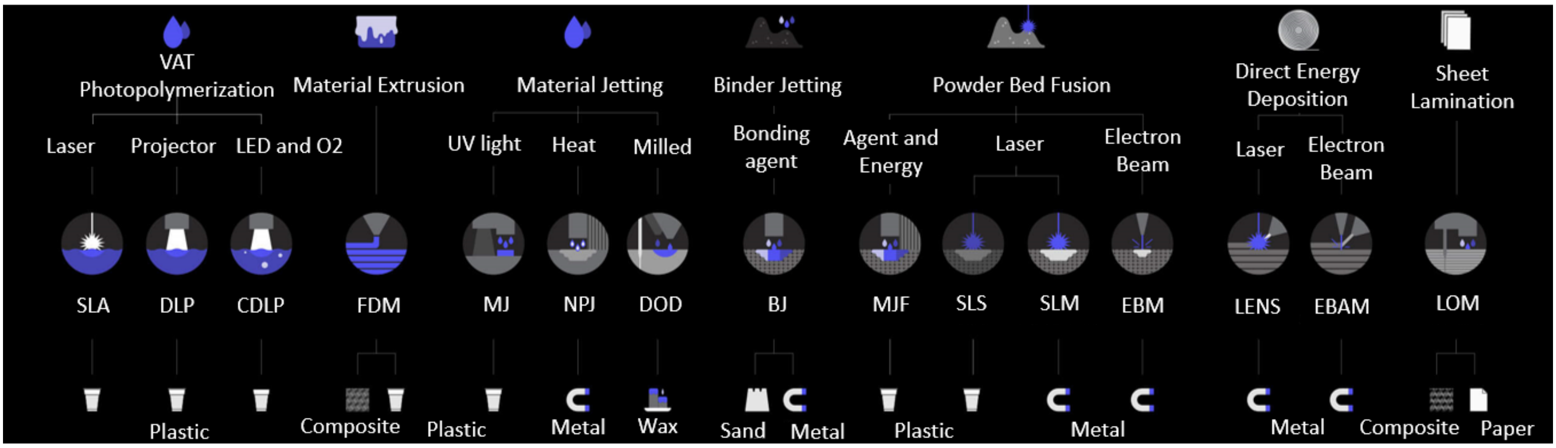


Figure 5 - Types of AM processes, adapted from [22]

2.2 Metal Additive Manufacturing

Regarding the material used in the processes AM can be divided in metallic and non-metallic categories.

It can be argued that the metal landscape within the AM community is the one which has grown the most [25]. A justification for the growth of this type is the prohibitively high costs of some metals when trying to use traditional manufacturing methods [26]. This causes the still relatively small amount of alloys used in a commercial environment [27].

2.2.1 Material Jetting

This type of technology, presented in figure 6, can be simply defined as the spraying of very small spheres of molten metal into the desired places until the part is built [28]. This technique is the analogous of the 2D printers, however in this process the material will solidify layer by layer obtaining the final part [29].

The process step by step can be defined as: first, the print head is positioned above the build platform, then the droplets of molten material are sprayed using the technology desired. When the droplets are finally solidified it is possible to re-do this process for the remaining layers until everything is built. After this, some post-processing can be done to obtain the final part [29], [30].

There are two types of solder droplet printing methods available today, continuous solder droplet, where an uniform stream of droplets are expelled from an orifice; and drop-on-demand droplets, which even though it does not have a high count of drops per second it allows to control the deposition rate.[31]

When comparing this technology to similar ones in print resolution, such as VAT polymerization, material jetting technologies offer a larger throughput of products with a less complex manufacturing process.[32]

Regarding the types of metals that can be printed using this technology, it is already possible to produce parts made of copper, aluminum, tin, mercury, between others. It is important to note that with the use of materials with a high melting, such as copper [33].

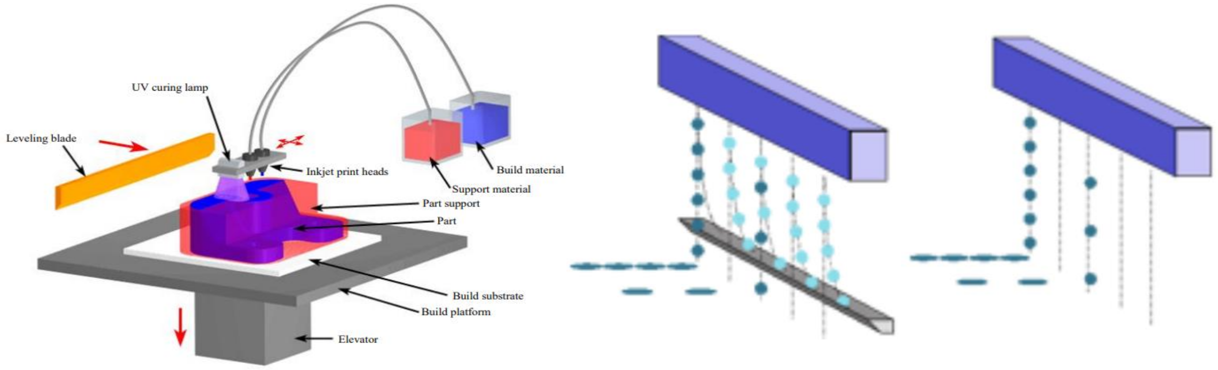


Figure 6 - Material Jetting process (left) [34], and continuous solder droplet and drop-on-demand droplets, respectively (right) [35]

2.2.2 Binder Jetting

Binder Jetting, represented in figure 7, was firstly created for educational purposes by MIT scientists in 1990, being later commercialized in 2010 [36]. This process can be divided in several steps: first, the powder is spread all over the platform using a roller to even the distribution, then the print head spays the binder over the desired area according to the 3D model, after that the build platform is lowered by one layer's thickness and a new layer of powder is deposited, binding with the previous layer in the desired areas. This process is then repeated until finishing the part. It is important to note that the unbound material stays in position surrounding the part.[37], [38]

This technology often requires a great amount of processes such as the curing, taking off the excessive powder, finishing and others [39].

The most important component for this process is the powder. The mechanism used to deposit the power will therefore be a key component to building parts with the best quality. The interactions between powder particles differs with size, composition and even humidity, being more complex than fluid behavior [40]. The binder also has extreme importance, where the minimum viscosity and highest resistance to shear stress is desired [41].

This technology has a vast array of materials that is capable of using between metals and alloys (aluminum, copper, steel, …) to ceramics (glass, sand, graphite, …) [42][43]. The printing process for this technology is extremely fast, and can be further accelerated by increasing the number of holes in the printing mechanism [43].

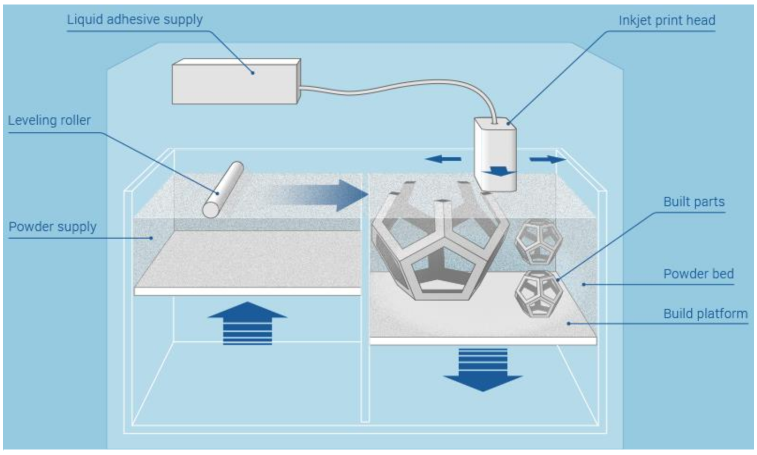


Figure 7 - Binder Jetting [44]

2.2.3 Powder Bed Fusion

As its own name implies, Powder Bed Fusion, shown in figure 8, just like the previously referenced Binder Jetting, occurs with the use of metal powders [43]. It was one of the first AM processes to be commercialized, with the most known technology being Selective Laser Sintering, developed in the University of Texas [45].

There are several stages for the manufacturing of parts with this process starting with the spreading of a thin layer of powder over the building platform, then the heat source, commonly a laser, will fuse the desired cross section. After this first layer, the following layers will be spread using a roller and subsequently fused. This process is repeated for the remaining layers until the final part is built [46]. The loose, not melted powder serves as support during the build and can be later reutilized [47].

In this technology there are 4 main binding mechanisms that are possible to use: solid state sintering (thermal process close to melting temperature), chemically induced binding (the material binds itself with chemical reactions), liquid phase sintering (binder material is fully melted) and full melting (also known as selective laser melting).[48] There are multiple decisions to be made when using this process since the way the powder is deposited, the type of atmosphere and laser can vary greatly. [49]

However, the possibility of changing so much in the process makes it very versatile, being used worldwide. It also allows to use a wide range of materials such as polymers, metals, ceramics and even composites, while not compromising too much the material properties [50], [51]. Concerning the type of atmosphere it can occur both in inert environments and vacuum environments [52].

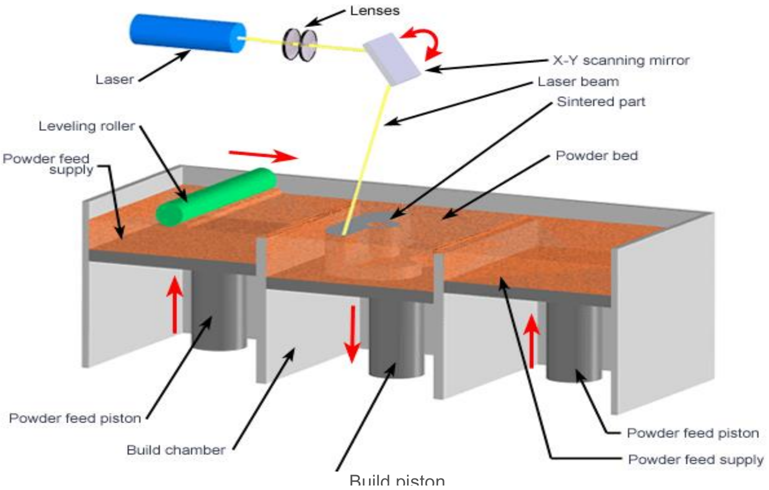


Figure 8 - Powder Bed Fusion [53]

2.2.4 Direct Energy Deposition

Direct Energy Deposition (DED) can be defined as bringing the metal, wire or powder, to a heat source, such as a laser or electron beam (shown in figure 9), which is going to make it melt into a conglomerate as more material is added [54]. It was first introduced by Frank Arcella as a powder bed fusion technique, being different enough to be considered a new sort of technology [55].

This process often starts with a moveable arm (with several movement axis) moving around the substrate. Then the material starts being deposited from the nozzle and while this happens it is melted with the use of a laser, electron beam or electric arc. This process is repeated for each layer following the cross section of the part [56]. In most cases this happens in the presence of an inert shielding gas.[57]

This method is almost exclusively used with metals, however, it can be used with a vast array of alloys such as titanium, nickel, iron based, … having a relatively high deposition rate when comparing with other additive manufacturing processes.[58]

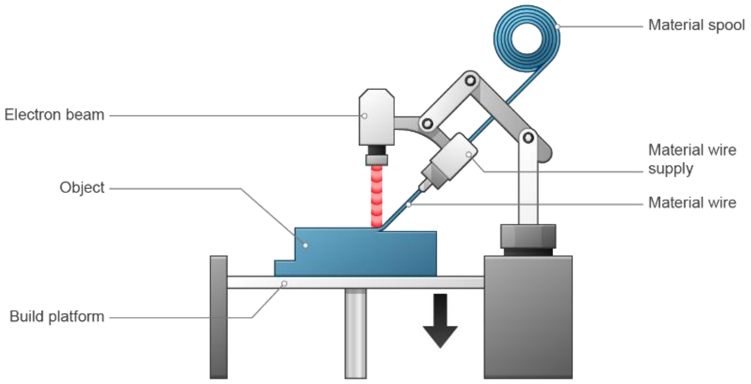


Figure 9 - Direct Energy Deposition [62]

This process always needs to have the presence of a substrate in order to be deposited to [59]. Nonetheless, it can be deposited even onto curved structures, being a viable alternative to repair damaged parts [54], [60].

Direct energy deposition has a lot of potential, being most of its processes still in a research and development phase, with most of the works being towards the optimization of parameters to improve the material qualities of the final part [61].

2.3 Wire Arc Additive Manufacturing

Even though WAAM was created much earlier, it has been mostly researched and utilized as a AM technique only from the 1990's [63]. It has been gaining a lot of reputation due to the ability of producing big metal components with a high deposition rate [5].

It is a DED process, presented previously, and can be described as the additive manufacturing of metallic parts with the resource of material in the form of a wire, by depositing the weld beads layer by layer using an arc source. It is used to produce and repair products very efficiently [4]. Comparing to other AM processes, for example SLS, its deposition rate is much higher [64].

With all the research that has been made in WAAM it was possible to find that this process can use several types of materials and can provide several types of features [5]. The materials include but are not restricted to: titanium alloys, aluminum alloys, steel alloys, nickel based super alloys and even other metals such as magnesium alloy, steel/bronze alloy, etc… [65]. There are three welding techniques that can be used in WAAM: Metal Inert Gas (MIG or GMAW), Tungsten Inert Gas (TIG or GTAW) and Plasma Arc Welding(PAW), as shown in figure 10 [66].

One of the most researched topics related to WAAM is the mechanical properties of the part when comparing to traditional manufacturing processes. While its properties are not as high as with the traditional methods it has been concluded that it has satisfactory properties.[67], [68]

However, to achieve end products using WAAM it is almost always necessary to perform heat treatments, to reduce the stresses, and finish machining, to obtain the desired final geometry [69]. Besides this post-processing, WAAM can also get other types of variation such as Interlayer Rolling, to improve the mechanical properties [70], Inter Pass active cooling, cooling the part between layers [71], or even multiple welding arcs to improve the deposition rate [72].

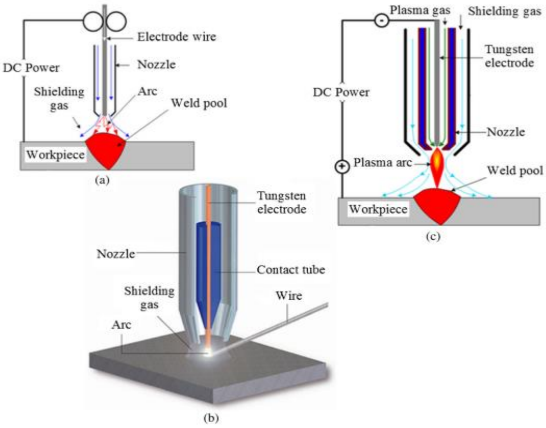


Figure 10 - Wire and Arc Additive Manufacturing using a) MIG, b) TIG and c)

Currently, a new technology called Cold Metal Transfer (CMT), presented in figure 11, which is a variant of GMAW, has been developed, and with it came great improvements for WAAM. It provides a stable arc, much lower heat input, droplet transition without splash and much better geometric dimensions. This works by the stopping of the filler wire when the system detects short circuiting. [73]

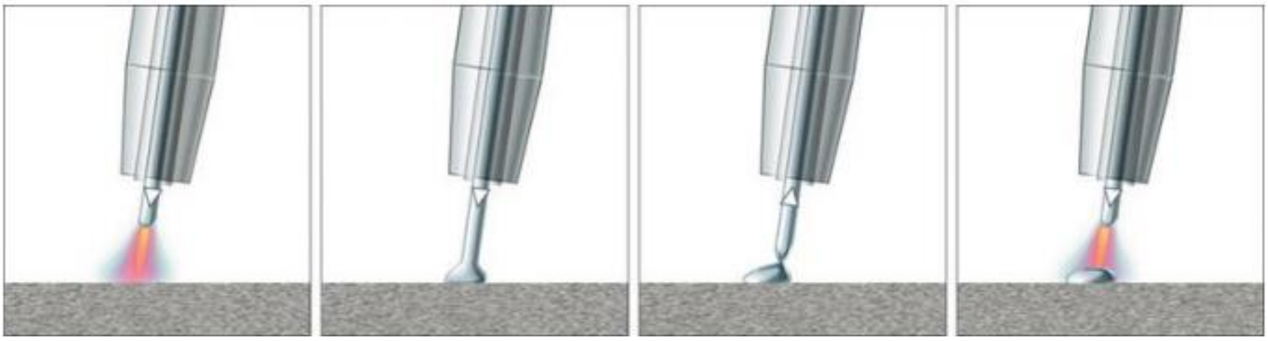


Figure 11 - Cold Metal Transfer [74]

2.3.1 Advantages, Disadvantages and Opportunities in WAAM

It is possible to see that WAAM has several advantages when comparing with PBF or even conventional manufacturing processes. Some of these advantages are:

- Possibility to build large metal parts with an extremely high deposition rate.
- With the correct process parameters high quality parts, with good density and properties.
- Suitability for repairing other parts with deposition of new material in previously damaged parts.

- Low cost of materials and machinery when comparing to other AM processes

However, as any other processes, WAAM has its own disadvantages, such as:

- A lot of residual stresses and distortions, mainly due to the high heat input of the process.
- The need of an inert atmosphere which can add up the costs
- Somewhat bad finishing, almost always requiring finish machining operations

As it was just mentioned WAAM has several major advantages when comparing to conventional manufacturing methods, being considered a viable option to replace casting, forging or complete machining is some applications [65]. With all the interest given to AM technologies recently and the clear growth of these technologies it is possible that, due to the economies of scale, the prices will decrease even further making these processes even more viable options [75].

At the same time, with the concept of Industry 4.0, WAAM robots will get even more integrated and automatized. Some even mention the integration of AI to further improve the quality of the deposited parts.[76] Therefore, continued study in this area is essential for the characterization of properties and development of the technology [65].

2.4 AM Cost Models

There were created some cost models throughout the years regarding Additive Manufacturing. In this section, the most noteworthy ones within the AM industry and posteriorly, more specifically about WAAM, will be mentioned.

One of the most notable is the work by Hopkinson and Dickens in 2003 [77]. This model was developed with the intent to perform a comparison between the traditional manufacturing route, in this case injection molding, and AM processes such as Stereolithography, Fused deposition modelling and laser sintering. For the cost estimation the authors divided the process in 3 types: material costs, machine costs and labor costs, with all the other costs such as finish machining, energy, powder recycling, rental, being ignored considering their smaller impact on the final cost. Even though the model is prepared for several components and batch sizes, it was assumed that the machine would be in full capacity and working 90% of the time.

For the results, presented in figure 12, two case studies were analyzed: one lever and one cover. It was then concluded that depending on the geometry it can be more economical to use AM processes rather than traditional methods, until a certain level of production (that can be in the order of thousands).

A few years later Ruffo, Tuck and Hague developed what can be considered an extension of the previously described model, only using selective laser sintering this time [78]. This cost model was designed to predict the cost for low and medium production volumes. The researchers used the same lever that was used in the work of Hopkinson and Dickens, but here the costs were divided into direct costs and indirect costs, resulting the sum of all costs to the final cost of the part. After that, the activities that had impact on the cost were identified as shown on the left part of figure 13. It was concluded that one of the main factors is the ability to fill the bed to the maximum. After this conclusion, and just one year later, Ruffo published another research [79], this time with just Hague, trying to incorporate several types of parts in just one bed to get the packing ratio as high as possible, with the results presented in figure 13 on the right. With this it was concluded that in fact the packing ratio has a critical role in the final costs.

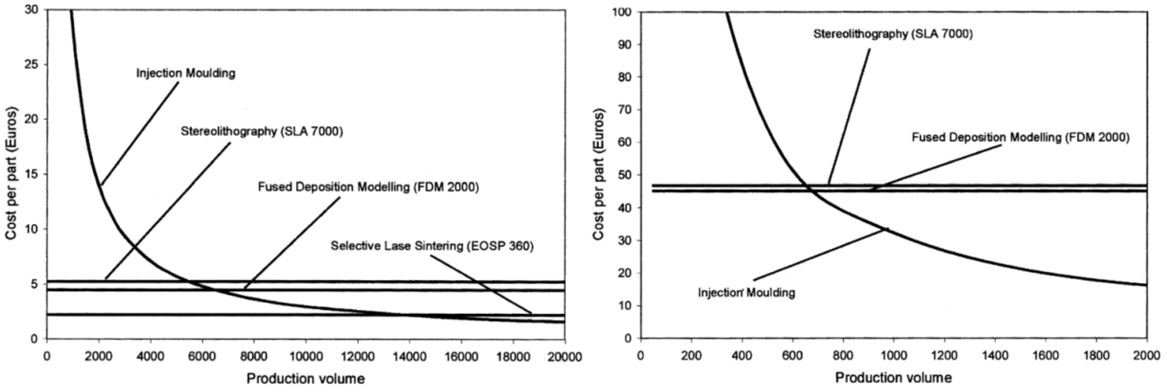
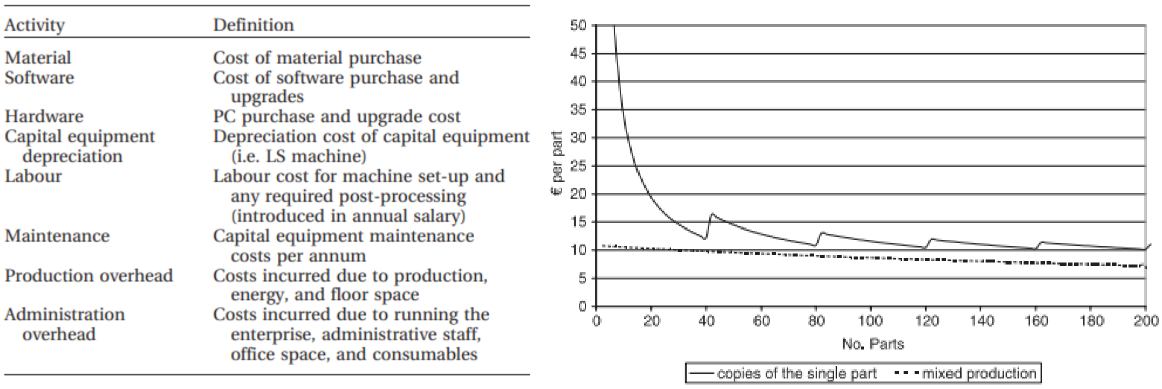


Figure 12 - Results from Hopkinson and Dickens Cost model [77]

Although the first cost models for AM were created more than 15 years ago, there are not many studies regarding the viability of WAAM, with most of the research being developed by the University of Cranfield.



Activity	Definition
Material	Cost of material purchase
Software	Cost of software purchase and upgrades
Hardware	PC purchase and upgrade cost
Capital equipment depreciation	Depreciation cost of capital equipment (i.e. LS machine)
Labour	Labour cost for machine set-up and any required post-processing (introduced in annual salary)
Maintenance	Capital equipment maintenance costs per annum
Production overhead	Costs incurred due to production, energy, and floor space
Administration overhead	Costs incurred due to running the enterprise, administrative staff, office space, and consumables

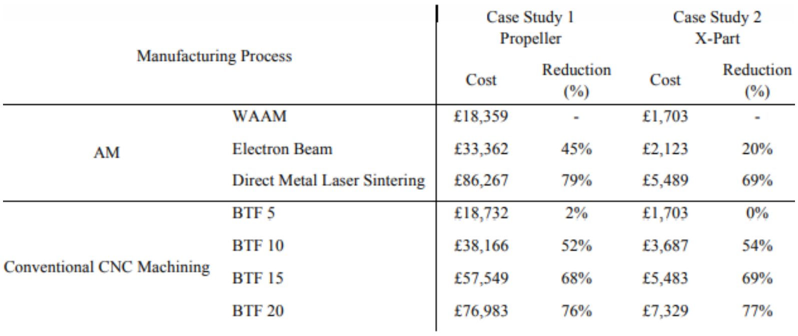
Figure 13 - Ruffo, Tuck and Hague activities considered (left) [78] and Ruffo and Hague results [79]

One of the first WAAM cost models was developed by Martina and Williams [6], where a comparison between this method and traditional machining from solid was performed. The researchers decided to estimate each variable as a specific cost in function of the time and after that tried to estimate the deposition time based on the BTF ratio desired.

Although this cost model is a bit simplistic it already offers a strong early-stage cost estimate tool. While most of the equipment related to WAAM was thoroughly considered there were some costs left out. The results of this cost model were then compared to the estimations made for complete machining in a big diversity of BFT, deposition rates, material removal rate, wire costs… It was then concluded that WAAM is viable when compared with complete machining with savings ranging from 7-69% depending on the process parameters for each one of the processes.

Two years later, also from the United Kingdom but this time from the University of Bath, it was published a more robust cost model [80]. This cost model started by identifying the most relevant activities in the process and considering each one of them as individual. Then each of the costs were divided between direct and indirect. This model is much more robust than the previous one taking in consideration most of the process variables with a posterior sensitivity analysis to account for changes in the process. This process, however, is too focused on only one type of material. Besides this, it does not consider changes in the consumables, overhead costs, and variable labor.

The results from the model previously mentioned [80], pointed out that WAAM outperforms both alternative AM methods and traditional methods for several geometries, as seen in figure 14. Therefore, it was concluded that WAAM has a very promising level of cost effectiveness, with savings between 20-79% comparing with other AM processes and between 0-77% when comparing to conventional CNC machining.



Manufacturing Process		Case Study 1 Propeller		Case Study 2 X-Part	
		Cost	Reduction (%)	Cost	Reduction (%)
AM	WAAM	£18,359	-	£1,703	-
	Electron Beam	£33,362	45%	£2,123	20%
	Direct Metal Laser Sintering	£86,267	79%	£5,489	69%
Conventional CNC Machining	BTF 5	£18,732	2%	£1,703	0%
	BTF 10	£38,166	52%	£3,687	54%
	BTF 15	£57,549	68%	£5,483	69%
	BTF 20	£76,983	76%	£7,329	77%

Figure 14 - Filomeno Martina cost model results [6]

2.5 Environmental Analysis

There is an ever-increasing consciousness regarding the environment and its protection, which leads to multiple research of manufacturing methods to understand the impacts on society and on the environment [81]. One of the main current goals is consequently sustainable development. It is agreed to be concerned with the future generations and with the resources that cannot be replenished, and even though well-being is provided by these damaging resources [82].

Traditional methods have a higher BTF ratio than AM, which results in a proportional bigger waste of material. The production of metal parts and products is, consequently, one of the most substantial contributors to damaging the environment [83].

As previously inferred, AM is growing progressively more each year [1], therefore being of extreme importance evaluating its environmental sustainability. Even though WAAM appears to have several advantages when compared with traditional methods (namely the creation of products with almost no waste) some of its drawbacks may cause the lack of sustainability of the process (such as a higher energy consumption) [84]. Despite this growth it can still be seen a lack of research on the environmental impact of AM techniques, namely Metal Additive Manufacturing [81].

To be able to estimate the real impact a process has on the environment it is currently accepted that Life Cycle Assessment (LCA) is the go-to methodology. LCA is an ISO- standardized method that is mostly used to assess the potential impact a certain product has on the environment throughout the entirety of its life cycle[85]. Due to international acceptance this methodology is advanced, being able not only to efficiently estimate the overall impacts but also the burden of each one of the phases of the life of the product. [86]

There is a lack of research of the sustainability of WAAM. However due to its inherent similarity to processes such as Metal Inert Gas it was possible to find more material available. Nonetheless, some environmental assessments were found related directly to WAAM [87]–[89].

The first LCA on focused on WAAM was developed in 2016 by Bekker, Verlinden and Galimberti [88]. This study mainly evaluated capabilities of the ISO methodology and provided a framework for the development of new environmental assessments for WAAM. However, it was a simplistic analysis with few results and conclusions, and it was focused only on bigger structures.

A few years later, in 2018, this time only Bekker and Verlinden [89] developed a much more complete work on the life cycle assessment of WAAM. This time there was a clearer use of the ISO methodology, providing a very strong tool for this study. The functional unit of this study was 1kg of stainless steel 308l, present in the databases. Then LCA’s for traditional methods, milling and green sand casting, were performed and finally all the results were compared. It was concluded that WAAM had a similar impact to Green Sand Casting and a smaller impact than Milling. This was mainly due to the big impact of material utilization.

In 2020, Priarone et al [87], studied the environmental and economic impact of WAAM using various criteria, but not using the ISO methodology.

The results of this analysis were then compared to the same parts produced by complete machining. This study was very complete, taking into account several types of materials (aluminium, steel and titanium), multiple criterions distributed in several categories, and multiple process parameters within the processes. It was concluded that WAAM can be a powerful manufacturing method that can have several benefits across the production process on parts.

As it was just demonstrated in this chapter, there is a lack of research related to WAAM, namely within the cost modelling and environmental impact assessment.

Chapter 3 - Methodology

This chapter is divided in four main parts: the overall methodology, the economical analysis, the environmental analysis, and the case study.

3.1 Overall Methodology

With the trend towards additive manufacturing, it is necessary to analyze the possible advantages within an economic and environmental standpoint. With this in mind, it was decided that one feasible solution to solve this problem is with the implementation of Process Based Cost Models.

This decision was based upon the fact that for a technologically complex model, such as WAAM, with many variables involved, a type of cost model that integrates the capabilities of an engineering and the expertise of economic models is the one which will follow the activities closer to the real-world values, even more when in the early stage of a project (design stage).

Therefore, and as explained previously, the main goal of this thesis is to analyze the real costs induced by the production of products using the wire and arc additive manufacturing method. Afterwards, this model should allow to make several types of analysis, including to compare WAAM to other more traditional manufacturing methods.

The preferred software to create the cost model was Microsoft Excel, due to its high availability, powerful tools, and simple mechanisms. Since other models were also developed using excel, this provides a fair comparison between all of them. The cost model integrates the WAAM process and the subsequent finish-machining process.

Before starting with the development of the cost model it is mandatory to conduct an extensive literary review, both to fully understand the process, to have an initial basis for the model and to see what is lacking within the previous analysis. Afterwards, the development of the model was done with constant feedback from experts on both the process and cost models.

The full explanation behind the cost model will be clarified in the following chapter, but to understand the line of work followed it is important to mention some of the procedures taken. The first step is to identify and separate the costs in the established categories. The most common, and the ones used for this model are the variable and the fixed costs. With all the important costs analyzed they will be decomposed in smaller and smaller activities until the process inputs are reached.

Some assumptions must be made in a cost model and consequently the boundaries, within the full life of the product, and conditions should be defined. The analysis of WAAM only starts when physically preparing the machines for production and ends with the finish machining process.

When the first draft of the model was finished the validation process begun. The earliest method of confirmation was the sensitivity analysis of most variables, in order to verify any mistakes made in the calculations or some assumption that is not correct. When the model was already theoretically finished, a case study, explained in 3.4, was built to validate all the results with a real-life scenario. This provides real data and results that will, in fact, simulate the real process.

With the case study artifact built and all the data available, the environmental viability of WAAM when compared with milling was assessed using the Life Cycle Assessment. It was developed with the databases available in IST in the SimaPro software. The results were then compared with ones obtained for milling and evaluated according to the specific impact it has on multiple categories.

With the data from all the previously mentioned analysis the results were obtained and an extensive analysis of the WAAM process was made from several viewpoints. With this it was possible to infer the viability of this process when compared to the more traditional ones, the cost drivers were identified and the way each input influences the cost of the model was discovered.

It is possible to see, in figure 15, the full tree explaining the full methodology taken when developing this thesis.

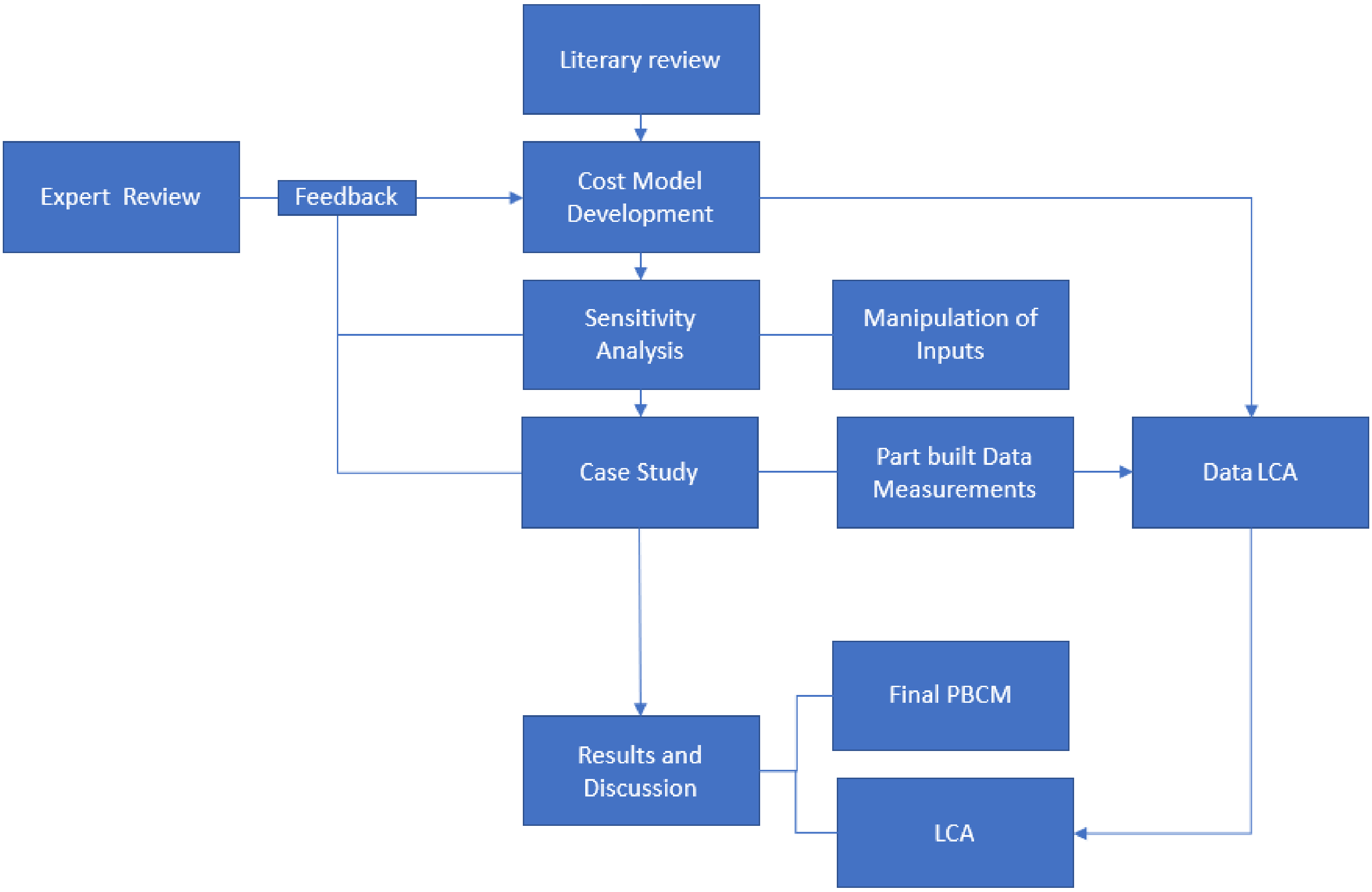


Figure 15 - Thesis Methodology

3.2 Economical Analysis

To perform the economic analysis, a Process Based Cost Model, PBCM, was used. They started as a new tool to fill in an empty gap within the cost model space. While previous cost models were either too technical oriented or financially oriented, the PBCM came to be the combination of those two types to get a technically accurate model which will estimate with good precision the financial nuances [90].

Technical models were created mostly by the people whose interest is in the technological aspect of the processes, namely mechanical engineers, and the main goal of those models is to optimize the parameters of the product, sometimes with the most cutting-edge technology, with little regard for the real-world costs of such endeavors.[90] Contrastingly, more financially oriented cost models are developed by people with economic backgrounds and as such focus more on the monetary aspect of the model with some disregard for the best technology possible for a specific product and often just reutilizing previous models of the process. Nonetheless, some cost models, especially in early design stages just like the PBCM's, need to be specific and copy the data straight out the production process.[91] As a result, in some cases, it is of major importance that the previously mentioned two types of people join forces in order to lay their strengths down and create the most financially/technologically accurate model [91].

This model will be able to react quite easily to any desired changes of the process. For example, if a machine is changed within a process, it can seem that the only difference will be the difference of the cost divided by all the parts manufactured, but it goes much further than that. The new machine will have: a different energetic consumption, which will impact the cost, a new range of motion that will allow different numbers of parts to be built, even different tax laws… In the end, the PBCM allow to somehow control the snowball effect of changing a parameter, being more useful than traditional cost models in that area. However, PBCM will still have a lot in common with other cost models, namely the way the final costs are obtained from the physical processes [90].

From this, it is important to understand that every product developed in regard with cost is very situational, therefore depending on all the conditions. That is why the product design, and the process planning are strongly tied up with the cost of the final product cost. The cost of a process is tightly linked to the design of the product and obviously the cost of the final product is a direct consequence of the processes chosen [91].

This strange entwining factor gives a very particular characteristic to this type of cost models. While from a user perspective it is only necessary to fill in the inputs and the result will appear, the whole process of creating the model is much more complex. The special attribute previously mentioned is that for the creation of such cost model, the analysis of the process needs to be done backwards, from the cost drivers until the desired product description, going through a series of complex relationships and assumptions, as seen in figure 16. This should always be accompanied with reliable data of the process.[92]

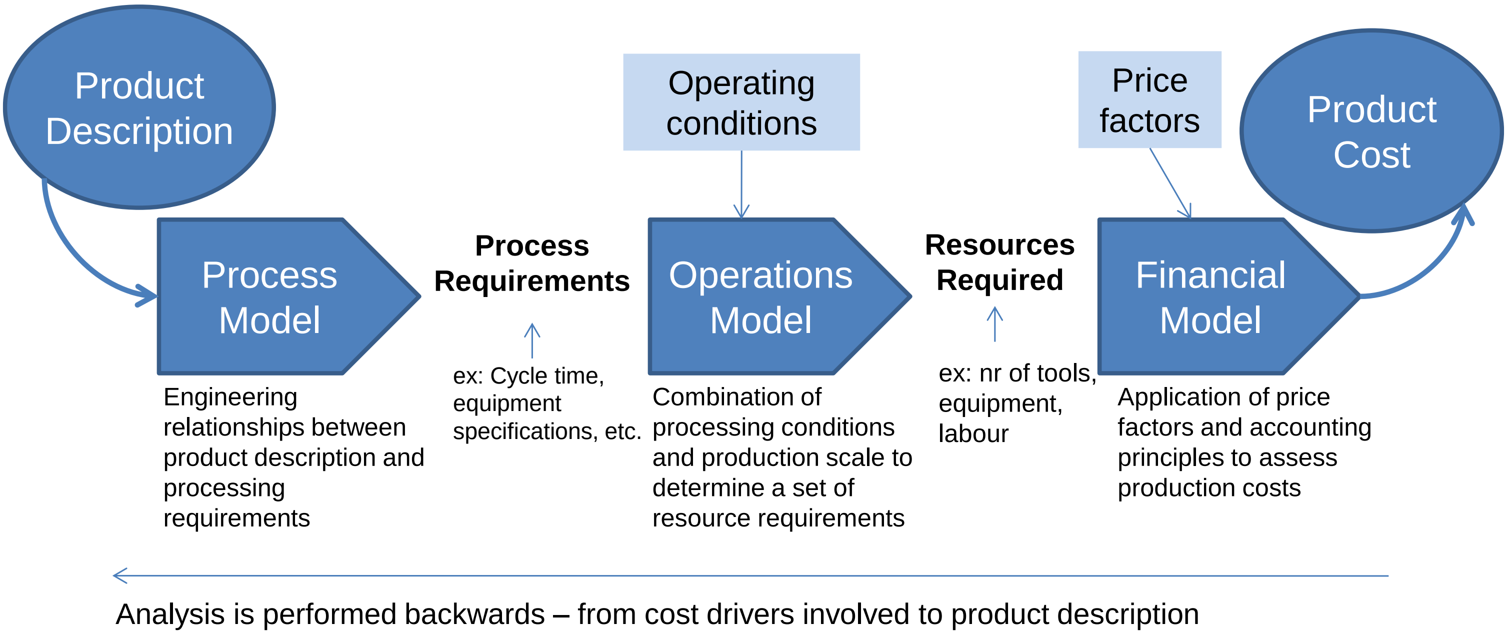


Figure 16 - Process-Based Cost Model Approach, adapted from [101]

It is important to estimate the real cost with the smallest error possible. This needs to be achieved in the most efficient way possible since modelling every possible nuance and impact is neither realistic nor practical. This is where the modeler mostly comes into play, weighting every decision, to have a simple while still reliable cost model. While some characteristics are similar to every cost model, like material, machine, energy; the remaining factors need to be calculated and implemented. The final decisions should be explicitly expressed for a better understandability for the user.

In conclusion, it should be a priority to have a cost model as soon as possible to predict the potential gains of a product. This cost model should be as complete as possible and have inputs from both technical and economic background people. All the aforementioned should be done in a simple and easy way in order to be flexible enough to sustain any changes within the production parameters of the part.

3.3 Environmental Analysis

To perform the environmental analysis the Life Cycle Assessment was used. The LCA is a method used to analyze the life cycle of a desired system from an environmental standpoint. This analysis is conducted by quantifying the impacts made on the environment and the resources utilized while the life cycle is being considered. The life cycle of a period can vary greatly, with the most common approaches being: “cradle-to-grave’, considering all the phases in a life of a product from the raw material extraction, all refinement stages to obtain the desired material to all the manufacturing stages of the production and even the end of life of the product; and, “cradle-to-gate”, only considering some parts of the life-cycle, starting in the same point (cradle) but finishing when the part is assembled and ready to go (gate) [93].

According to the International Standards Organization (ISO), from 2006, there are 4 phases in a LCA analysis: Goal and Scope definition, Inventory Analysis, Impact Assessment, and Results Interpretation, as shown in figure 17 [85].

The goal and scope definition is the most important phase since it creates the basis for the following analysis, consequently being the first one being made. Since this type of analysis represents a product or a process, a perfect model will never happen. Therefore, and similarly on how it was mentioned in the cost model methodology, the modelling decisions should be made to simplify the aspects on which the result will not depend too much on. With the correct decisions a product can be easily defined, and the boundaries of its life are relevant. It is in this step that the purpose, expected outcome, functional units and assumptions are presented.

With the inventory analysis all the inputs and outputs of the processes are identified and considered. The inputs are usually related to the raw material and to the energy input and the outputs usually include all the pollutants emissions as well as the waste streams. It is with this step that it is possible to start having a clear image on how the processes have effects on the environment.

In the impact assessment phase, it is where the environmental influences are evaluated according to the desired parameters in ways such as human health or global warming. It will take all the other steps previously made and finally give the results.

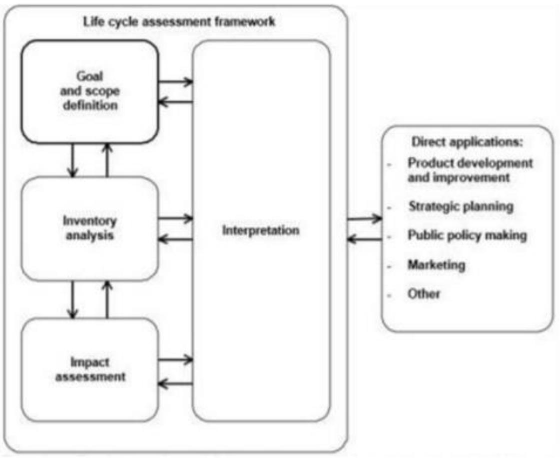


Figure 17 - LCA Methodology according to ISO

The interpretation phase will give the conclusion of the total analysis which will differ from the ones already made in terms of scope or goals. The results should then be compared and supported with existing data to comply with the ISO standard [94].

After the definition of the functional unit and the inventory, it is necessary to utilize LCA software tools to obtain and interpret the results. The software chosen for the analysis present in this thesis is SimaPro, both for its reliability [95] and having a complete database in IST.

To evaluate the impact assessment two types of indicators were taken into account, the ReCiPe midpoint and the ReCiPe endpoint. For the ReCiPe midpoint analysis, the effect for each input is assessed in 18 different categories all of them representing different impacts. These are Climate change, Ozone Depletion, Terrestrial Acidification, Freshwater eutrophication, Marine Eutrophication, Human Toxicity, Photochemical oxidant formation, Terrestrial ecotoxicity, Freshwater ecotoxicity, Marine Ecotoxicity, Ionizing radiation, Agricultural land occupation, Natural land transformation, Water depletion, Metal depletion and Fossil depletion. In the ReCiPe endpoint analysis only 3 categories are assessed: Human Health, Ecosystems and Resources [96]. It is necessary a higher level of knowledge to understand the midpoint results, however, it provides more detail on the real impacts on the environment [97].

3.4 Case Study

The first step for the case study was designing a part. The main objective with this part was producing simultaneously something simple and in conjunction with common features found in commercial parts. Using SolidWorks, the first drafts were produced and then modified until having the expert's approval. As seen in figure 18, the final part has a cuboid base with a cube with a circular blind hole on top. On the top of the cube there is a cut cone. More details about the technical drawing can be found in the Annex A.

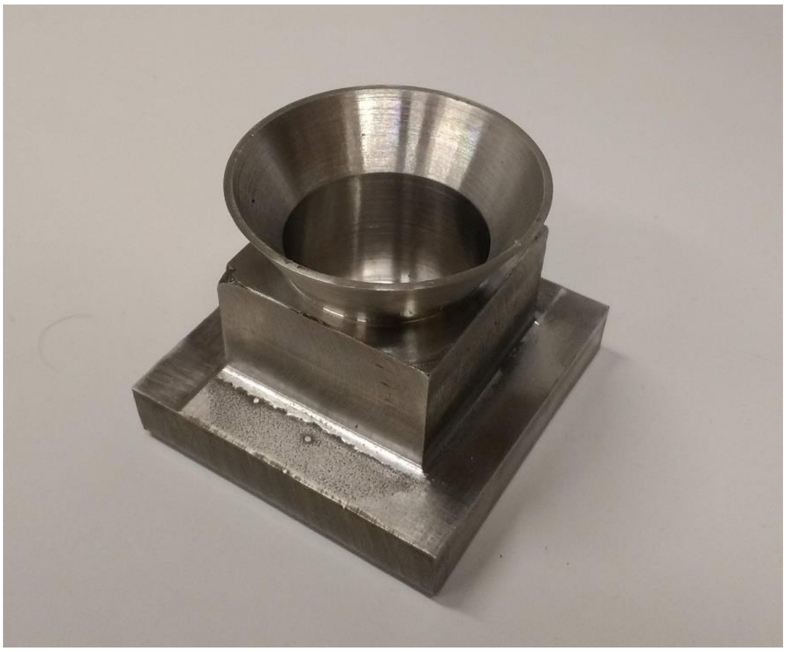


Figure 18 – Final part produced

The second step was to gather all the equipment and software. The measuring equipment used was the Power and Harmonics Analyzer Model 6830 of Prova Instruments Inc. with the 6802 probes, present in figure 20. This equipment allows the measurement of several parameters such as power, tension, current intensity, for all the three phases of the equipment. It allows to record data from 2 to 2 seconds with its highest precision setting.

After carefully analyzing the functioning of this equipment the next step was to acquire the cable equipment. For this it was necessary to have male and female plugs and cable for 3 phase machines. This was necessary because, in order to get results from the measuring equipment there are 2 options: connect the equipment directly to the electric box of the machines, which requires the presence of an experienced technician in order to prevent accidents or to build an extension. The circuit diagram used is present in figure 21.

Figure 20 - Case Study measuring Equipment

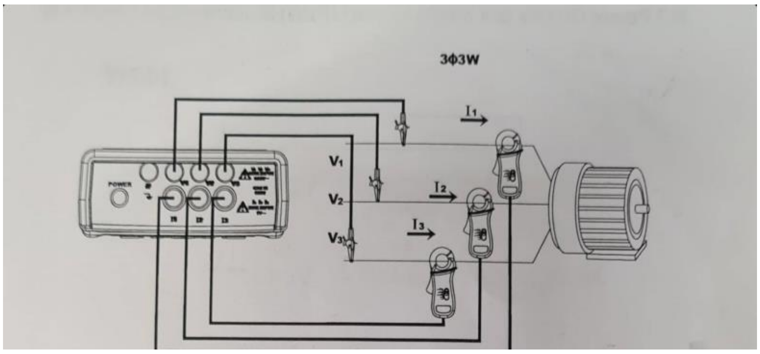


Figure 20 Circuit Diagram of Power measuring System

As for software, since the measuring equipment is a bit dated, an older version of operating systems is required. Therefore, a virtual machine with Windows XP was installed to gather all the data from the machine with the Power and Harmonics analyzer.

For the actual process of printing the part, the 316L stainless steel was used, information in table 1.

Grade		C	Mn	Si	P	S	Cr	Mo	Ni	N
316L	Min	-	-	-	-	-	16.0	2.00	10.0	-
	Max	0.03	2.0	0.75	0.045	0.03	18.0	3.00	14.0	0.10

Grade	UTS MPa	Yield Str 0.2% MPa	Elong % in 50 mm	Hardness	
				(HR B)	(HB)
316L	485	170	40	95	217

Table 1 - Material Composition and Properties

The machines used were the ones found in the Manufacturing and Process Technology Laboratory. This were the welding machine (ESAB LUC 400 Aristo 400), the CNC table (Pronum 3 axis) and the Milling machine (Deckel Maho DMC63V and Gildemeister CTX400). The welding machine is a fully programmable power source compatible with other systems, being controlled by a computer. This machine is built in such a way that it strongly facilitates the handling and accessibility in the workplace, being directly programmed and controlled by small portable cables. Concerning the AM system, it is from Pronum and it excels due to its high robustness and precision allied to a good precision in the manufacturing of medium-small parts. Regarding the CNC machines, the Deckel Maho DMC63V and Gildmeister CTX400 were the ones used. However, within the cost model a higher level of automation is assumed for the process, therefore these machines were not the ones considered, taking into consideration a more expensive and suitable machine found in databases.

3.4.1 Energy in case study

The power of the WAAM process was measured while building the case study artifact. It is shown in figure 22 the average power for each recording. Recording 14 is when the circular section of the part starts and the variation of power within these layers varies greatly compared to the square sections.

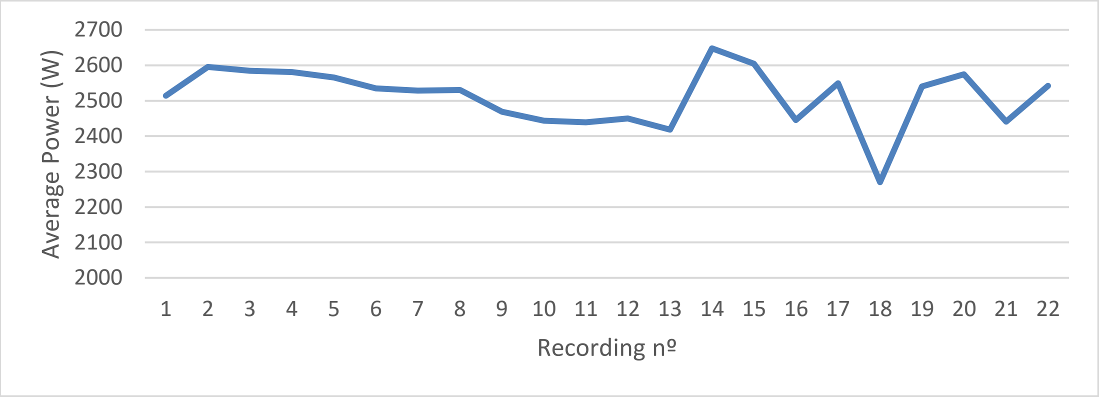


Figure 21 - Average Power of each recording

Figure 23 shows all the data captured. The power is recorded every two seconds and it was assembled from the ending of one layer to the beginning of the other. It is clear that, with the exception of some points, the energy consumption is even all across the deposition.

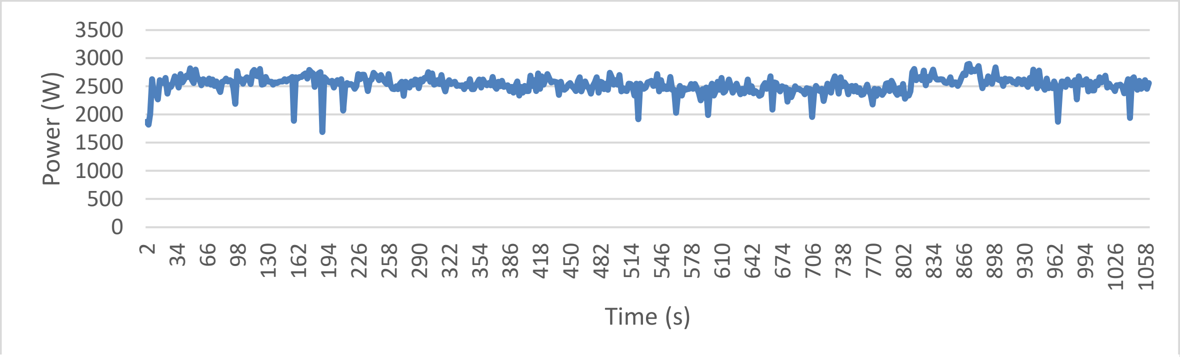


Figure 22 - Power per 2 seconds recordings

Chapter 4 - Cost Model Development

The goal of this chapter is to provide a description about the cost model development for this thesis, beginning by describing the various types of inputs. After a more detailed explanation of those inputs, in each step of the process the evolution of the model with all of its equations is carried out culminating, in the end, with the explanation of the several types of costs and where they incur.

4.1 Process Model

The first step towards the build of the cost model is to define the scope in which it will analyze the processes. By decomposing the manufacturing method into several phases, it will be easier to develop the model. With figure 24 it is possible to understand a visual representation about the scopes for the cost model developed. In blue are represented all the processes considered while in brown are the processes out of scope.

The WAAM manufacturing method was decomposed in 5 main phases, each one of them sub-divided into several other sub-phases to facilitate the understanding of the whole process, which can be confusing.

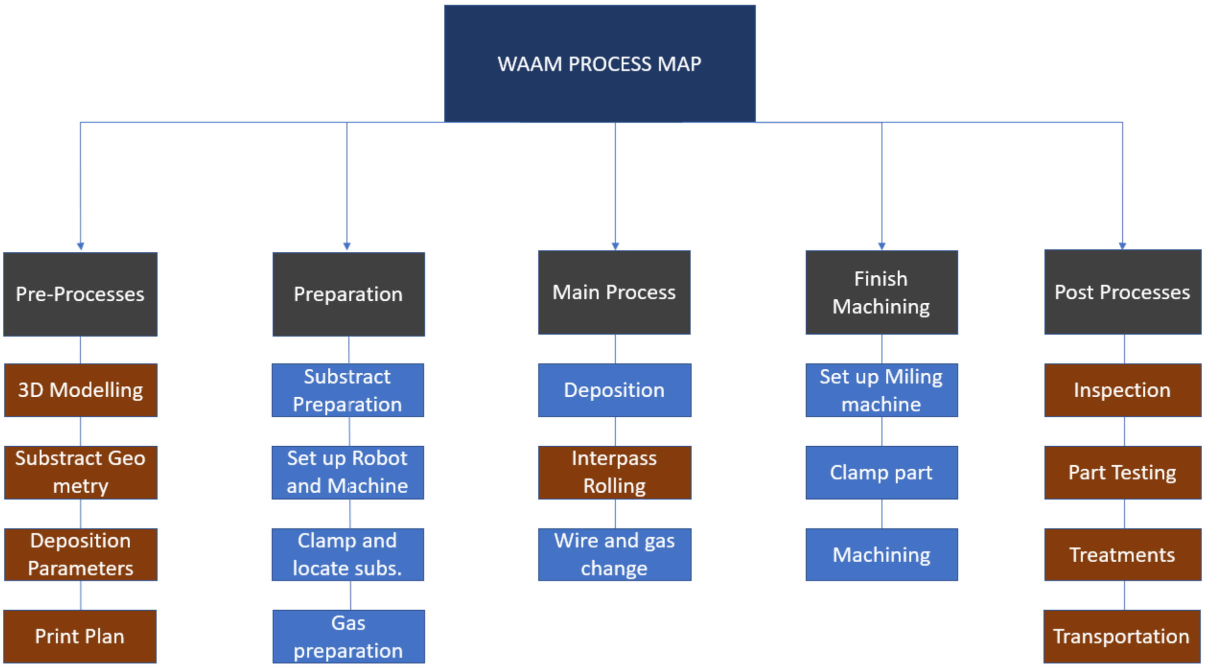


Figure 23 - WAAM process map

The phases are:

1. Pre-Processes – This is the beginning stage for WAAM. It is subdivided in 4 different stages which are: The part modelling in the 3D software, which includes, the creation and slicing into

layers. This is followed by the substrate geometry decision and all the process parameters. Finally, the deposition plan is designed with the building sequence and robot tool path in mind. None of these steps are within the scope of the cost model. Although the substrate geometry and deposition parameters are considered in the model the process of the decision is not.

2. Preparation – This stage happens in-site, therefore being fully considered in the cost model. It is also branched in 4 parts. Firstly, comes the substrate preparation, being this its pickup or recycling, then both the robot and the machine are turned on and set up, this is followed by the clamping and location of the substrate by the robot. To finish, the gas bottle is set up.
   All these steps are considered in the WAAM setup phase.
3. Main Process – This stage is the core of the whole process. It is basically defined by its deposition stage It is where the part is built with the welding process. Eventual wire or gas changes are also considered in the model.
4. Finish machining – This stage is always necessary to have a fully finished part, therefore being considered within the scope of the cost model as well. It is once again considered the setup process for this stage.
5. Post-Processes – These are the process stages happening after the main manufacturing phases. There are endless possibilities on what can happen after the process itself. Only stages related to the process were considered in the map and none of the posterior occurrences were considered within the scope of the model. Some sub-stages of post process treatments are the inspection and testing of the part as well as post-manufacturing treatments desired.

4.2 Inputs

As previously mentioned, the development of a cost model is made backwards where every cost driver is decomposed into the type of cost, and then the type of cost is divided into the final variables and so on, until the inputs for the cost model are reached.

This cost model was divided into 4 main categories of inputs: Exogenous Data, Material Information, WAAM Inputs and Milling Inputs, in which some of those main input categories have been divided into several other smaller categories.

4.2.1 Exogenous Data and Production Inputs

The Exogenous Data, in table 2, is presented in a similar fashion in every cost model following the Process Based approach. These inputs are common for all phases and its values are heavily dependent on the specific situation of the factory/company. The inputs are presented below with the corresponding physical quantities associated on the right, in Table 2, followed by a brief explanation each one of those inputs.

Regarding the quantity Inputs, these are just a prediction on some production parameters defined by the factory. All the inputs are self-explanatory being the name given for the project (or for the part), the number of parts per batch of printing and the number of batches per year.

Working Days/Yr	Days/year	**Units per Batch**	units/batch
Direct Wages (w/ benefits)	€/hr	**Batches per year**	batches/year
Price of Electricity	€/kWh		
Interest Rate	%		
Accounting Life of Machine	yrs		
Building Recovery Life	yrs		
Price, Building Space	€/m^2		
Idle Space	%		
Daily Uptime Machine	h		
Maintenance Costs	%		

Table 2 - Exogenous and Quantity Inputs

- Working Days/Yr are the number of days in a year that the factory will work.
- Direct Wages (w/ benefits) coincides with the salary per hour of the technician, already including all the benefits and bonuses.
- Price of Electricity corresponds to the agreed price of electricity with the provider.
- Interest Rate is the cost of opportunity and corresponds to the potential earnings of alternative opportunities when comparing to doing nothing with the capital.
- Accounting Life of Machine refers to the number of years on which the machine will theoretically depreciate within the accounting statements
- Building Recovery Life indicates the amount of time needed to pay the mortgage (which should coincide with the accounting value of depreciation)
- Price, Building Space indicates the cost paid per unit of area
- Idle Space is chosen concerning the amount of free space in the factory and should follow the security guidelines
- Daily Uptime Machine is the amount of time the machine is being productive every day
- Maintenance Cost relates with the cost of the equipment and is the cost of every maintenance or repair needed

4.2.2 Material Requirements

Every physical product needs at least one material in its constitution. Depending on the process and the specifications required by the user, the material inputs will greatly vary. In WAAM, two main types of material need to be acknowledged. The first one is the welding material and the second one is the substract material. For this part, the shielding gas was also considered one of the intervening materials of the process. All the material inputs utilized are present in table 3.

The welding material, arguably the core of WAAM, comes from a wire form and it mostly varies by the type of material and the diameter of the wire. Then the substrate material, a peculiarity of WAAM, is where the deposition of the welding material will occur. Finally, the shielding gas, another attribute of WAAM, is necessary to create a sterile atmosphere for the process.

Welding Material		**Substract Material**		**Shielding Gas**	
Weight Wire	Kg	**Area Sheet**	m^2	**Mixture Cost Bottle**	€/bottle
Cost per Wire	€	**Thickness Sheet**	mm	**Volume Bottle**	l/bottle
Diameter Wire	mm	**Cost Sheet**	€		
Density	g/cm^3	**Density**	g/cm^3		
Scrap Cost	€/Kg	**Scrap Cost**	€/Kg		

Table 3 - Material Inputs

Regarding the Welding material, and considering it comes in a wired form the inputs necessary are expressed on the table and are self-explanatory, where the scrap cost is the value for what the materials that cannot be used in the process anymore will be sold to a third party.

The substract material is assumed to come in a sheet of metal and all the inputs necessary are the type of material, size of the sheet (area and thickness), the cost of the same sheet its density and the scrap cost for this type of material.

Finally, the shielding gas, coming in a bottle form, the only inputs necessary are the type of gas, size of the bottle, in litters and the cost of that bottle

4.2.3 WAAM Inputs

These inputs are the core of the process and are presented in table 4. They were divided into 4 different categories: The welding machine, the AM system, the part, and the process parameters.

Welding Machine		**AM System**	
WAAM Machinery Area	m^2	**Acquisition Cost**	€
Acquisition Cost	€	**Maintenance Cost**	%
Difference Potential Machine	V	**Maximum Power**	W
Current Intensity Machine	A		
Efficiency	%		

Table 4 - WAAM Machinery Inputs

With respect to the welding machine and AM System selection, they should be carefully chosen to withstand any requirements for the process. The variables necessary to input for the welding machine:

- WAAM Machine Area represents the area the machine occupies within the factory, which should be a projection of the maximum dimensions of the machine and AM System
- Acquisition cost refers to the total cost incurred to buy the machine

- Difference Potential Machine indicates the voltage selected, within the machine, for the process of printing the part
- Current Intensity Machine symbolizes the current selected, once again within the machine, for the process of building the part
- Efficiency indicates the ratio between the previous 2 selected parameters and the real output from the electric system

And for the moveable system the parameters are similar, this time asking directly for the consumed power considering that Voltage and Current Intensity are not selected and being the final output power the only important parameter.

Finally, the inputs for the part are shown in table 5. Due to the flexibility of the method, it was decided to use a straightforward approach of not taking design fully into consideration, and the building orientation and building sequence should be pre-determined. The cooling data, contrarily, was deemed to be an important input, especially for small and compact parts. A careful analysis should be performed before the production to determine the necessary cooling time, since the model is ready for almost any decisions by its user.

Part Name	
Number of Layers	number
Volume Part	cm^3
Cooling - Linear Component (s)	*x
Cooling - Integer Component (s)	*1
How many Special divisions for cooling	[0-3]
Extra time special division Cooling	s

Table 5 - Part Inputs

The inputs necessary are therefore:

- The total number of layers that constitute the part
- The final volume of the part (after every post-process)
- The cooling function, which can be any type of function with small changes in the model and it sums the total time waited between each layer for the cooling of the metal
- How many Special divisions for cooling is a decision that allows to decide if the part is getting too hot during the deposition in some specific layer, an additional amount of time should be waited in up to 3 layers
- Extra time special division Cooling refers to the amount of time waited within the previous input variable

The cooling time is considered due to the excessive heat input and distortion, with these phenomenon’s being some of the worst enemies for the WAAM. To combat them, waiting for the part to cool is a common method. As a result, the total build time will differ from the printing time, and this should be considered when building a cost model.

To finish this section, the parameters that will guide the entire process of the cost model, the WAAM process parameters, in table 6.

Setup (turning on, cleaning, positioning, …)	s/per batch
WFS	m/min
Flux Gas	l/min
BTF (Efficiency of building)	Total Volume / Final Volume
Rejection Rate (Efficiency of process)	%
Volume Substrate	cm^3
Substrate Number of Uses	use/s
Number of workers	worker/s
Worker Dedication	%
Change wire time	s
Change gas bottle time	s
Overheads	%
Additional substrate cost (previous)	€

Table 6 - Process Parameters Inputs

- Setup is the amount of time the worker will spend between batches preparing everything for the new batch, it includes several activities such as turning on the machines, cleaning the work area, positioning the substrate and it is considered as a full attention task by the worker(s) in charge of the process
- WFS, or Wire Feed Speed, indicates the length of wire that is coming out of the roll per minute. It is one of the most important parameters of the process because this is what will determine the Amperage, so once the current intensity was already selected, this should be according to that value
- Flux gas represents the output of gas by unit of time, and it is only considered during printing times.
- BTF, also known as Buy-to-Fly ratio, represents the amount of waste material the process has. It is the ration between the volume of the total deposited material and the final volume of the part.
- Rejection Rate corresponds to the number of parts that do not have enough quality per 100 well-built parts. This can also be seen as the efficiency of the process
- Volume Substrate is the total volume of the substrate for the printing of all the batch
- Substrate Number of Uses serves to determine if the substrate will be reused after the operation (after a grinding operation) or if it is a portion of the final built part
- Number of workers refers to the amount of people working during the printing process
- Worker Dedication relates to the actual work done by the worker while the printing is happening, this is, the percentage of the time the worker is focused only on the printing
- Change wire time and Change gas bottle time are, respectively, the amount of time needed to change the wire and to change the gas bottle in the case that one of them finishes in the middle

of the printing operation. Both are considered to require full attention by the worker(s) in charge of the process.

- Overheads are the type of costs that do not correlate with the specific part built. It will be dependent on other types of costs estimated.
- Additional substrate cost (previous) represents the costs of all the operations related to the preparation of the substrate, including its cutting, grinding, …, and should also include the possible profit of selling it.

4.2.4 Milling Inputs

These are the last set of inputs for this cost model, presented in table 7. In the current state of WAAM a finish machining process is always necessary, and milling was the chosen process for this model.

However, it is out of the scope of this thesis to make a thorough analysis of the milling process and cost estimations for machined parts have been developed by different researchers. Thus, it was decided to proceed with a very straight forward analysis without compromising the rest of the cost model. The inputs necessary will be therefore:

Machine	
Finish Machine Area	m^2
Acquisition Cost	€
Power Machine	W
Tooling	%
Setup (turning on, cleaning, positioning, …)	s/per batch
Time for Milling	s/per part
Rejection Rate (Efficiency of process)	%
Number of workers	worker/s
Worker Dedication	%
Overheads	%

Table 7 - Finish Machining Inputs

- The same 3 inputs (Milling Machine Area, Acquisition Cost, Power Machine) as the ones used in the welding machine and AM System
- The tooling cost is defined as a percentage of the acquisition cost of the machine
- The setup follows the same logic as for the WAAM setup
- Time for Milling represents the total amount of time necessary to perform the full operation of the milling process
- The last 4 inputs (Rejection Rate, Number of workers, Worker Dedication, Overheads) are the same as in the WAAM process inputs

4.3 Intermediate Calculations

The functioning of the PBCM's can be compared to the way a function works. It has its specific set of inputs and, it goes through a process block that will give the desired results (which can be, afterwards, the input for the following calculation block). To reach the final cost it is necessary to combine the utilization of several of these blocks.

With all the inputs already introduced, the next logical step is to relate them and start presenting some intermediate calculations that will lead to values that are more closely related to the final costs. This section was, therefore, divided in 3 cost drivers of this cost model.

4.3.1 Material

As explained before, in WAAM there are two types of material, the deposition material and the substrate, and to simplify the understandability of the cost model the shielding gas will also be considered a material.

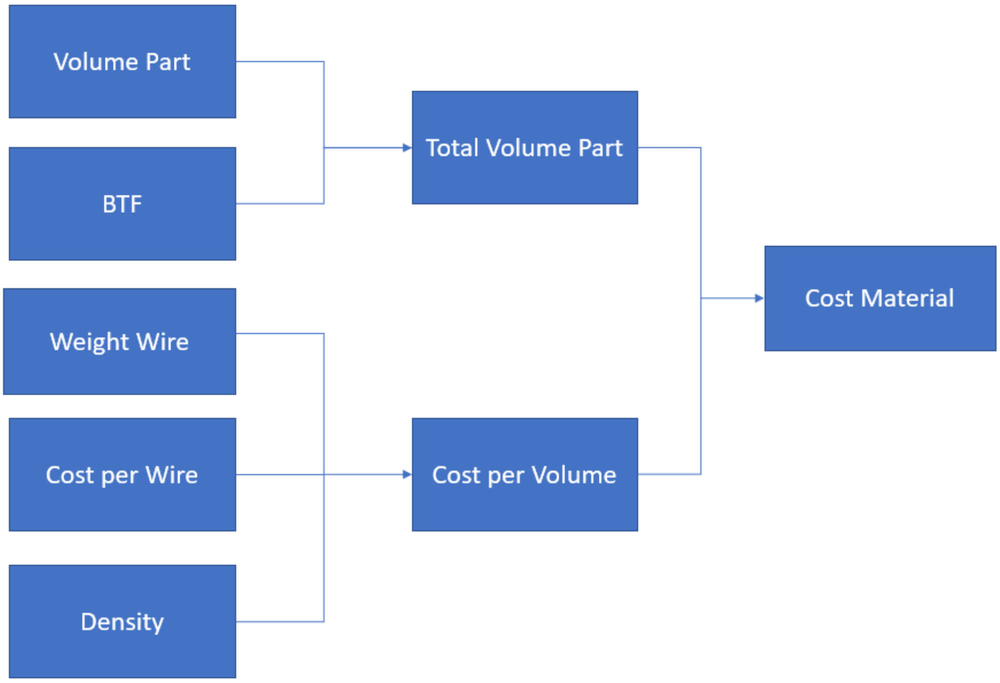


Figure 24 - Material Cost calculation

$$Cost\ Deposition\ Material = (Volume\ part\ final\ \times BTF)\ \times \frac{Cost\ wire\ \times Density\ wire}{Weight\ wire} \quad (1)$$

As it can be seen in equation 1 and figure 25, the deposition material cost will depend on the total volume of the deposited part, that is respectively the multiplication of the final volume by the Buy-to-Fly ratio. The latter will be multiplied by the cost per volume, which, by its turn, is obtained by some variable manipulation.

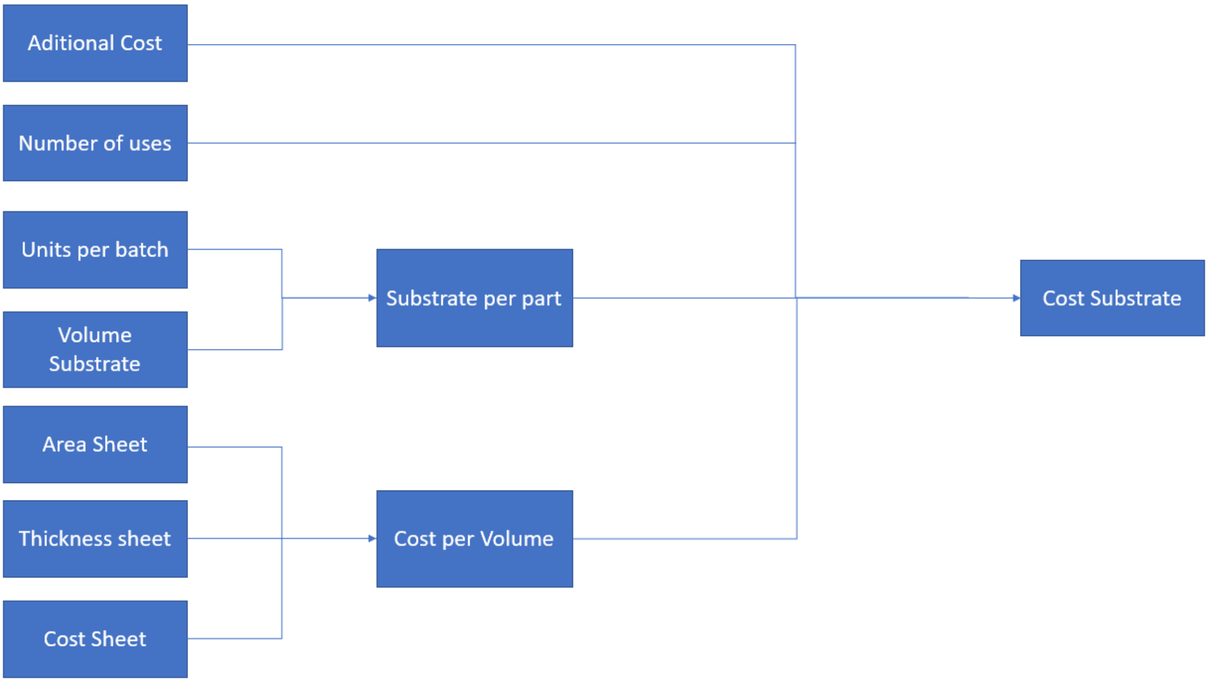


Figure 25 - Substrate Cost calculation

$$Cost\ Substrate = \frac{\frac{Volume\ Substrate}{Units\ per\ batch} \times \frac{Cost\ Sheet}{Area\ Sheet \times Thickness\ Sheet}}{Number\ of\ uses} + Aditional\ Cost \qquad (2)$$

The substrate is a very specific characteristic to WAAM, and its cost, in equation 2, can greatly vary according to the planning given to it. Generally, two main decisions must be made in relation with the substrate, the first is if the substrate is complete or partial, i.e., if the substrate will be completely used in the operation (complete) or if it will be separated from the main part, engage in cleaning and smoothening processes to be reutilized more times (partial). The second decision will be if the substrate is an integral component of the final part or if it will be removed. In the scenario of deciding the second option and if it will not be used again in posterior operations, any profits made from the sale of the material should be added within the additional cost input variable.

In regards with geometry only volume is considered, nonetheless, when planning an excess of substrate for clamping should be considered.

The calculation for the cost of the substrate is similar to the one previously made for the deposition material with some small differences previously mentioned, as seen in figure 26, just like the number of uses and the additional costs, and here the number of units per batch should be considered, assuming consequently that each part will have its ‘own substrate’.

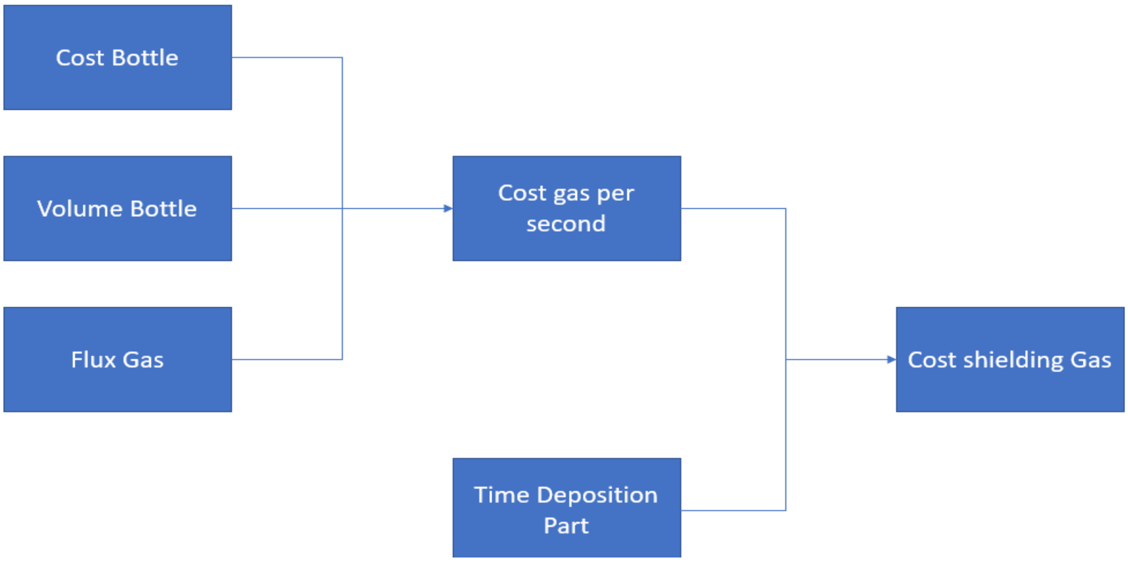


Figure 26 - Shielding Gas Cost calculation

$$Cost\ Shielding\ Gas = \frac{Cost\ Bottle\ \times Flux\ Gas}{Volume\ Bottle} \times\ Time\ Deposition\ Part \tag{3}$$

As previously mentioned, the shielding gas it is crucial for the WAAM operation because it maintains a stable deposition and prevents the beads from getting contaminated. It is mostly dependent on the characteristics of the bottle, on the desired flux and on the deposition time for the part, which will be seen on the next section. The algebraic expression for its cost is presented in equation 3 with the schematic explanation in figure 27.

4.3.2 Time

Time is one of the most important, if not the most important, variable in every cost model. As such, it was analyzed very carefully in this cost model, trying to take into consideration every important aspect of each process. The total cycle time was divided in several other important time variables, which will be calculated posteriorly.

$$Time\ Deposition = (Volume\ part \times BTF) \times \left(\frac{1}{4}\pi\ Diameter\ Wire^2\ \times WFS\right) \tag{4}$$

For the deposition time, in equation 4 and figure 28, the process planning parameters will have a lot of impact. It depends on the total volume deposited and on the rate at which material is deposited, which by its turn is a direct consequence on the diameter of the wire and the wire feed speed.

$$Total\ Coling\ Time = Polynomial\ Cooling\ Sum + (Nº\ Special\ Divisions\ \times\ Time\ Special\ division\ ) \tag{5}$$

Regarding the cooling time, in equation 5, its importance was already explained before, and to calculate it is necessary to sum the total time given by the polynomial function and the time within special layers of cooling.

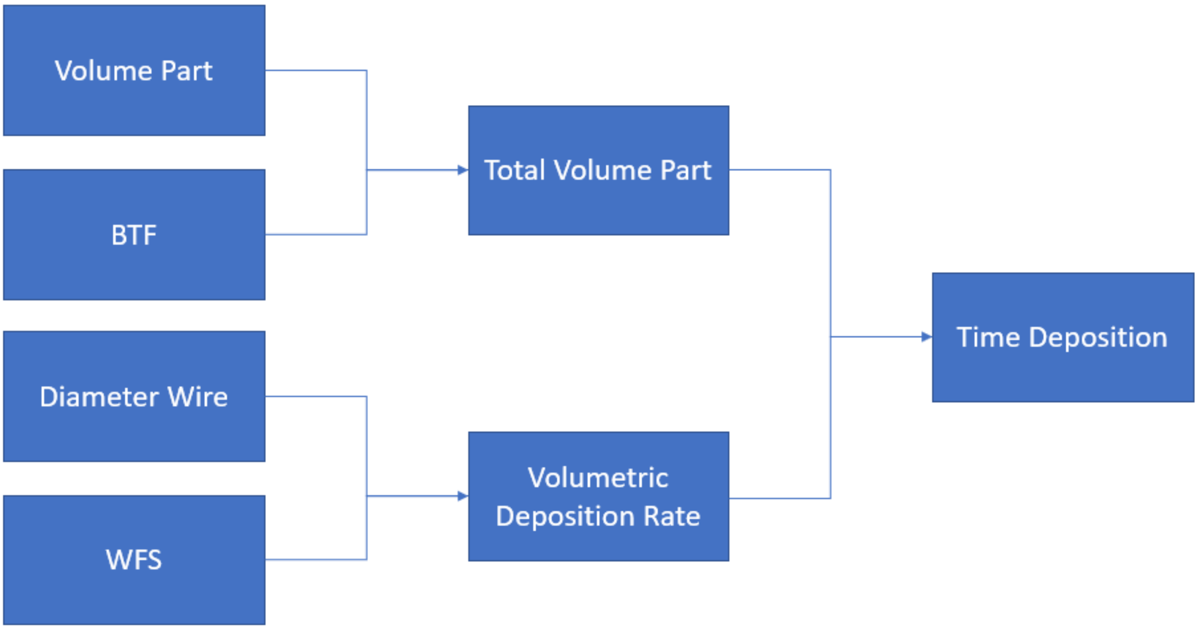


Figure 27 - Deposition Time Calculation

$$Total\ Printing\ Time = Total\ Coling\ Time + Time\ Deposition \tag{6}$$

As it is possible to easily infer, the total printing time, in equation 6, is the sum of the two previously calculated times

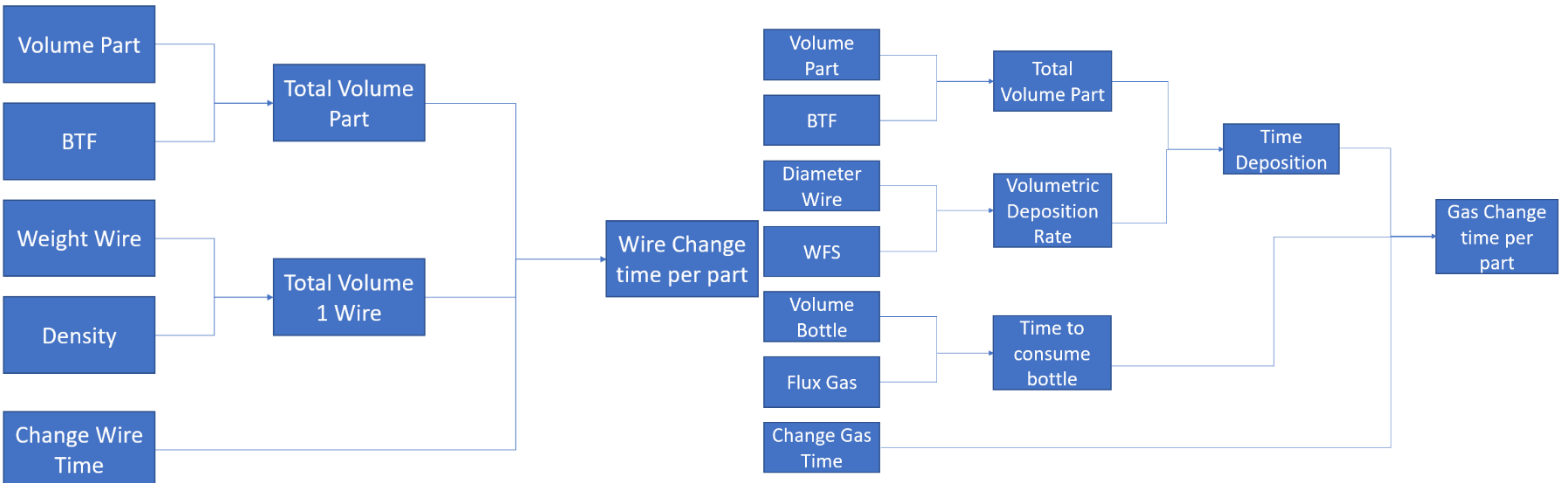


Figure 28 – Wire (left) and Gas (right) change time calculation

$$Wire\ Change\ time\ per\ part = Change\ Wire\ Time \times (Volume\ part \times BTF) \times \frac{\rho wire}{Weight\ Wire} \tag{7}$$

$$Gas\ Change\ time\ per\ part = Change\ Gas\ Time\ \times\ Time\ Deposition\ \times \frac{Flux\ Gas}{Volume\ Bottle} \tag{8}$$

The previous two diagrams, figure 29, will be treated as one due to their similarities within the cost model. These times are important to consider because they will increase the total unproductive time and the labor. To calculate the wire change time per part, equation 7, first is calculated the number of parts that are possible to build with one wire and then the total time needed the change the wire is divided by all the parts. In the case of the gas bottle change time per part, equation 8, the logic is the same, first calculating how many parts can be deposited with one bottle and consequently how much time is needed to change the bottle when the total time is distributed evenly.

$$\begin{aligned} Total\ Worker\ Time \\ &= Gas\ Change\ time\ per\ part +\ Wire\ Change\ time\ per\ part \\ &+ \frac{Setup\ WAAM}{Parts\ per\ Batch} \end{aligned} \tag{9}$$

$$Total\ Cycle\ Time = Total\ Printing\ Time +\ Total\ Worker\ Time \tag{10}$$

These final two times are just the sum of some of the previous times calculated. The total worker time, equation 9, is the total time where the worker full attention is required, and the total cycle time, equation 10, is self-explanatory.

4.3.3 Other calculations

$$Annual\ production = Units\ per\ batch\ \times Batches\ per\ year \tag{11}$$

$$Scrap\ Rate = BTF - 1 \tag{12}$$

$$Total\ Volume\ Scrap = Volume\ part\ \times Scrap\ Rate \tag{13}$$

Although these first two equations are very simple, they are essential. Both appear in the input area for an easier perception of their values. Equation 11 represents the total amount of units that need to be produced in a year and equations 12 and 13 the amount of excess material deposited within the printing stage.

$$Utilization\ Rate = \frac{Total\ Cycle\ time\ \times\ Annual\ production\ \times (1 + Rejection\ Rate)}{Working\ days\ yr\ \times Daily\ uptime\ Machine} \tag{14}$$

Equation 14 gives a very important value because in WAAM all the processes are non-dedicated due to the flexibility inherent to additive manufacturing processes. This means that all the equipment can be used to produce more than 1 type of goods. This rate will, in consequence, calculate the total amount of time, in percentage, that this specific part will take within a year.

$$Power\ Machine = \frac{Voltage\ Machine\ \times\ Amperage\ Machine}{Efficiency\ Machine} \tag{15}$$

This last intermediate, in equation 15, calculation will just give the real power used by the machine during the deposition process.

Due to the similarities between some intermediate calculations of WAAM and finish machining, the remaining intermediate calculations for the latter will not be displayed.

4.4 Costs

Even though this section is the last presented, it is in fact, as stated before, the beginning of the development of a cost model. Since it is impossible to exactly model the activities and consider every nuance of the processes some decisions need to be made with, considering all relevant costs, and excluding the ones that are not as important.

$$Annual\ Fixed\ Cost\ = Investment\ \times \frac{r\ \times (1+r)^n}{(1+r)^n - 1} \times\ Utilization\ Rate \tag{16}$$

The first assumption made with this cost model is that all costs should be calculated based on the annual production of the product desired. The total costs are comprised with the sum of two different types of costs, the variable costs, and the fixed costs. The variable costs are the ones that depend directly on the annual production. The fixed costs are calculated utilizing the equation 16, meaning that there is an investment allocated to the good (building, machine, ...) that with the cost of opportunity and years of life the annual value is calculated. For non-dedicated equipment (such as WAAM) the utilization rate should also been considered. For the present cost model, the costs were identified and separated according to table 8:

VARIABLE COSTS	FIXED COSTS
Material Cost	**Main Machine Cost**
Consumables (Gas) Cost	**AM System Cost**
Scrap cost	**Tooling Cost**
Labor Cost	**Maintenance Cost**
Energy Cost	**Fixed Overhead Cost**
	Building Cost

Table 8 - Types of Costs

With all the input and intermediate calculations already presented, the final costs do not need to the thoroughly explained. As a result, only the final equations used to calculate the costs will be explained.

4.4.1 Variable Costs

In this section the variable costs presented on the table will be specified and explained.

$$\begin{aligned} \mathit{Material\ Cost} \ &= (\mathit{Cost\ Deposition\ Material} + \mathit{Cost\ Substrate}) \times \mathit{Annual\ production} \times (1 \\ &+ \mathit{Rejection\ Rate}) \end{aligned} \tag{17}$$

The final cost of material, in equation 17, is mainly dependent on the costs of the deposition material and substrate material, with the addition of rejected parts also considered.

$$\mathit{Consumables\ (Gas)\ Cost} = \mathit{Cost\ Shielding\ Gas} \times \mathit{Annual\ production} \times (1 + \mathit{Rejection\ Rate}) \tag{18}$$

As it is possible to see in equation 18, the cost of the gas is only differing from the previous value by the number of parts that is rejected.

$$\begin{aligned} &\mathit{Scrap\ cost}_{\mathit{Milling}} \\ &\quad = -\mathit{Annual\ production} \times \mathit{Rejection\ Rate} \\ &\quad \times \Big(\mathit{Volume\ part} \times \mathit{BTF} \times \rho_{depmat} \times \mathit{Scrap\ Cost}_{depmat} \\ &\quad + \frac{\mathit{Volume\ Substrate}}{\mathit{Units\ per\ batch}} \times \rho_{subsmat} \times \mathit{Scrap\ Cost}_{subsmat}\Big) \\ &\quad - \mathit{Annual\ production} \times \mathit{Total\ Volume\ Scrap} \times \rho_{depmat} \times \mathit{Scrap\ Cost}_{depmat} \end{aligned} \tag{19}$$

Depending on the material, sometimes, the scrap from the processes can be sold to third party entities that can use it for other purposes. As a result, this is a stream of revenue for the factory, hence the negative sign. There is scrap both on the WAAM and the finish machining process, but the WAAM formula is a simpler version of the latter, therefore only the equation for the milling process is shown. The total scrap cost, in equation 19, is the value of the rejected parts (both deposited material and substrate material) and the excess of material deposited.

$$\begin{aligned} \mathit{Labor\ Cost} = \ &\mathit{Direct\ Wages} \times \mathit{Annual\ production} \times (1 + \mathit{Rejection\ Rate}) \\ &\times (\mathit{Total\ Worker\ Time} + \mathit{Total\ Printing\ Time} \times \mathit{Worker\ Dedication}) \end{aligned} \tag{20}$$

In every process it is necessary to be an operator supervising the operations. The model will only consider the costs related to people who are receiving direct wages to supervise the processes. It was considered that the workers would receive their wage on an hourly basis and therefore the total amount spent on labor, presented in equation 20, is the hourly rate multiplied by the total amount of time spent by the worker supervising the processes.

$$\begin{aligned} Energy\ Cost = {} & Annual\ production\ \times (1 + Rejection\ Rate) \times (Power\ Machine + Power\ AM\ system) \\ & \times Time\ Deposition\ Part\ \times Cost\ of\ Electricity \end{aligned} \tag{21}$$

Equation 21 demonstrates how to calculate the costs related to the use of power. It is important to notice that when inputting the variables related to this cost the values should be related to the actual amount of energy spent on the process and not the energy that was put into the process.

4.4.2 Fixed Costs

In this section the fixed costs presented on the table will be specified and explained.

$$\begin{aligned} Machine\ Cost = {} & Acquisition\ Cost\ Machine \\ & \times \frac{Interest\ Rate\ \times (1 + Interest\ Rate)^{Accounting\ Life\ of\ Machine}}{(1 + Interest\ Rate)^{Accounting\ Life\ of\ Machine} - 1} \times\ Utilization\ Rate \end{aligned} \tag{22}$$

$$\begin{aligned} & AM\ System\ Cost \\ & = Acquisition\ Cost\ AM\ System \\ & \times \frac{Interest\ Rate\ \times (1 + Interest\ Rate)^{Accounting\ Life\ of\ Equipment}}{(1 + Interest\ Rate)^{Accounting\ Life\ of\ Equipment} - 1} \times\ Utilization\ Rate \end{aligned} \tag{23}$$

Both the welding machine, in equation 22, and the moveable system, in equation 23, follow the same equation regarding cost, as previously explained. Both machines are non-dedicated, hence the utilization rate needs to be considered.

$$\begin{aligned} Tooling\ Cost = {} & Tooling\ \%\ \times Acquisition\ Cost\ Milling \\ & \times \frac{Interest\ Rate\ \times (1 + Interest\ Rate)^{Life\ tools}}{(1 + Interest\ Rate)^{Life\ Tools} - 1} \times\ Utilization\ Rate \end{aligned} \tag{24}$$

The cost for the tools of the milling machine, in equation 24, is very similar to the previous equations, with the only difference that the investment for the tools is a percentage of the total spent on the machine.

$$\begin{aligned} & Maintenence\ Costs \\ & = (Machine\ Costs +\ AM\ System\ Cost(or\ tooling) + Building\ Cost) \\ & \times Maintenence\ \% \end{aligned} \tag{25}$$

The maintenance cost, in equation 25, is a fraction of the money spent that year on machinery and building.

$$Overhead\ Costs = Overhead\ Percentage\ \times Labor\ Cost \tag{26}$$

The overhead costs, in equation 26, is also considered as a function of other cost, but this time is the labor cost. This cost considers the money that is not directly spent on the process but is necessary for the good functioning of everything else. This includes things such as office supplies (paper, writing material, duct tape, …), technical and non-technical personnel (consultants, technicians, secretaries, …), …

$$Building\ Costs = Building\ Space\ Price \times Machinery\ Area \times (1 + Idle\ Space) \times \frac{Interest\ Rate \times (1 + Interest\ Rate)^{Building\ Recovery}}{(1 + Interest\ Rate)^{Building\ Recovery} - 1} \times Utilization\ Rate \tag{27}$$

Building costs, in equation 27, are the last type of cost considered within this cost model. When referring to the building investment the variables that need to be considered are the price per area of the location and the area required (contemplating both the machine area and idle space necessary to follow the security guidelines). The rest of the formula is like the previous ones containing the building life instead.

Chapter 5 - Results and Discussion

5.1 Test Case

The part used for the results was explained in chapter 3. This section clarifies the inputs that were used within the cost model.

5.1.1 Exogenous Variables

The values of the table 9 are the exogenous variables. These represent the values estimated from real life industrial settings for this type of process.

Working Days/Year	240	days
Direct Wages (w/ benefits)	10	€/h
Price of Electricity	0,1	€/kWh
Interest Rate	15,00%	%
Accounting Life of Machine	15	yrs
Building Recovery Life	30	yrs
Price, Building Space	1500	€/m^2
Idle Space	25,00%	%
Daily Uptime Machine	8	h
Maintenance Costs	10,00%	%

Table 9 - Case Study Exogenous Inputs

5.1.2 Material Requirements

All the costs considered in table 10 are based on the purchase price paid by IST Manufacturing and industrial management unit, providing a real-life value of the cost for an enterprise.

Welding Material	**Inox Steel 316L - 1 mm**	
Weight Wire	15	Kg
Cost per Wire	258	€
Diameter Wire	1	mm
Density	8	g/cm^3
Scrap Cost	0,5	€/Kg

Substract Material	Steel 316L	
Area Sheet	0,1	m^2
Thickness Sheet	20	mm
Cost Sheet	80	€
Density	8	g/cm^3
Scrap Cost	0,5	€/Kg
Shielding Gas	Ar (99,9%)	
Mixture Cost Bottle	120	€/bottle
Volume Bottle	10700	l/bottle

Table 10 - Case Study Material Inputs

5.1.3 WAAM Inputs

All the inputs presented in table 11 were based and adapted from the real values of IST production [68].

Welding Machine	**Machine 1**	
WAAM Machinery Area	5	m^2
Acquisition Cost	15000	€
Difference Potential Machine	16,5	V
Current Intensity Machine	100	A
Power Machine	1650	W
Efficiency	66,00%	%
Moveable System	3 Axis	
Acquisition Cost	5000	€
Maintenance Cost	15,00%	%
Ave. Power	170	W
Part Name	Part 1	
Number of Layers	30	number
Volume Part	94	cm^3
Cooling - Linear Component (s)	0	*x
Cooling - Integer Component (s)	40	*1
How many Special divisions for cooling	1	[0-3]
Extra time special division Cooling	300	s

Process Parameters		
Setup (turning on, cleaning, positioning, …)	300	s/per batch
WFS	6	m/min
Flux Gas	10	l/min
BTF (Efficiency of building)	1,20	TotalVolume/Final Volume
Rejection Rate (Efficiency of process)	5,00%	%
Volume Substract	62	cm^3
Substract Number of Uses	1	use/s
Number of workers	1	worker/s
Worker Dedication	5,00%	%
Change wire time	300	s
Change gas bottle time	300	s
Overheads	160,00%	%
Additional substract cost (previous)	0	€

Table 11 - Case Study WAAM Inputs

5.1.4 Cost per process

Figure 30 represents the data for the combination of processes, representing the values from the beginning to the end. It is still possible to see that the material costs are the most significative on the process. However, the second and third biggest costs, machine and overhead costs, respectively, are both fixed. The labor cost also arises as one important cost, being present in both stages of production. The gas cost, even though just used in WAAM, still has an important contribute to the cost. The variable costs rule over the fixed costs, with a total value of 26,52€ for the variable costs and 19,70€ for the fixed costs.

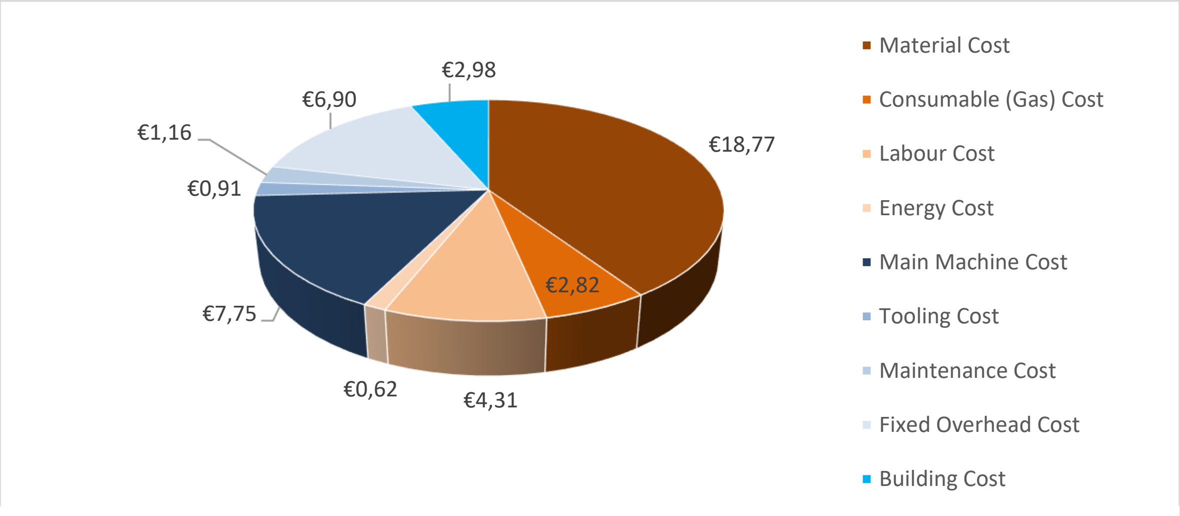


Figure 29 - Full processes cost in €

After the results from the full processes a more detailed analysis was carried out for each process.

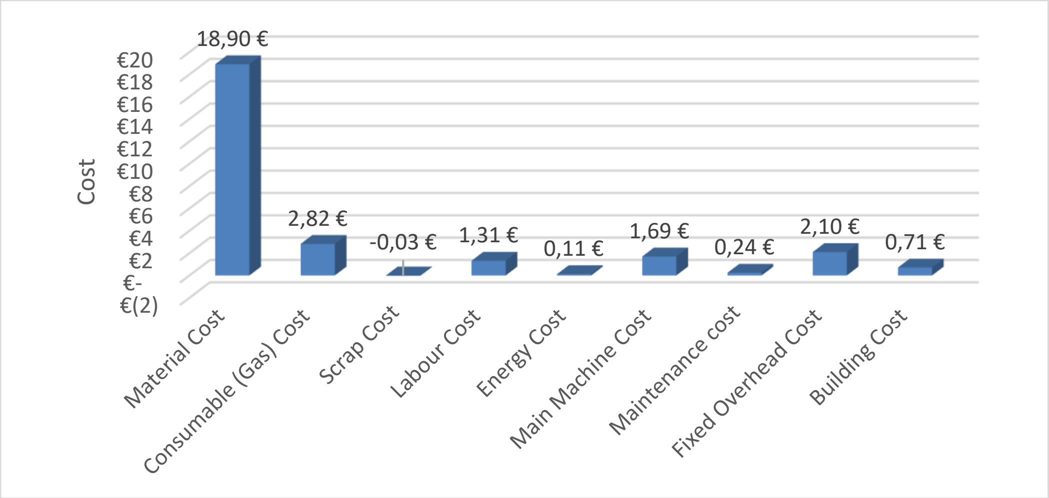


Figure 30 - WAAM deposition process costs

As observed in figure 31 the costs are subdivided into several categories. As expected, the cost with the main impact on the WAAM stage is the material cost. This occurs due to the high cost of the wire. The second main cost is the cost of the gas, which was also expected due to the lengthy processes with constant volumetric flux. This value can vary a lot depending on the cost of the bottle. The scrap value for this process is so low because only the faulty parts are considered. The labor cost is also not very high due to the high automatization of the process giving opportunity for the technician to oversee other machines or work on different things. The cost of energy is also low since the current price of energy is low. Then, regarding the fixed costs, the main machine cost is low, which is one of the main advantages of WAAM. The building cost is equally low due to the compact machinery space. The overhead cost is to simulate all the structure behind the industrial production of parts.

It is possible to see that in the WAAM phase the direct costs have much more impact than the fixed costs, showing once again the advantages AM has within small production volumes.

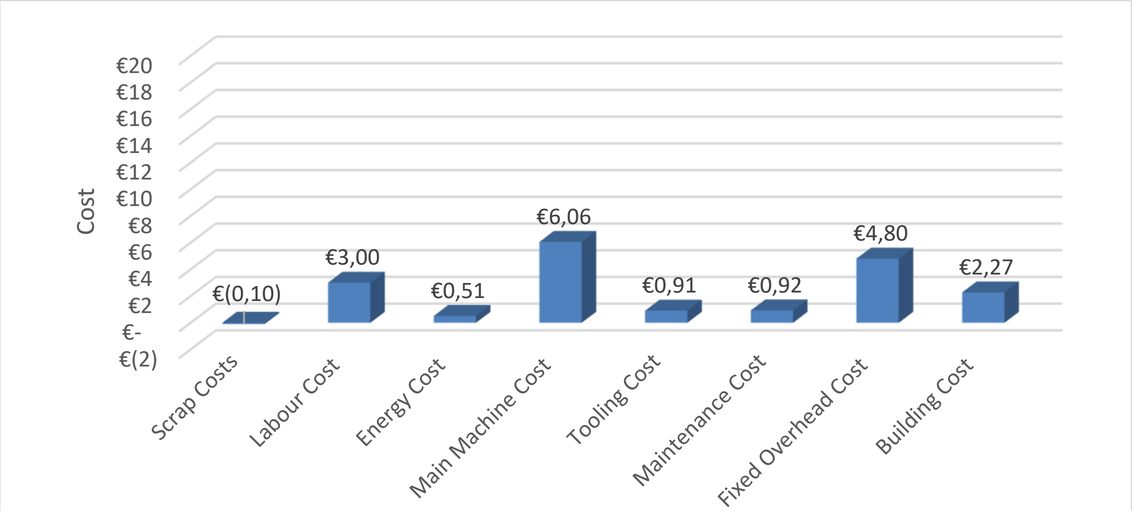


Figure 31 - Finish Machining process costs

Figure 32 demonstrates the discriminated costs for the second process, the machining part. The machine considered on this stage is based on real industry machines, therefore, having a big cost. In this part the fixed costs largely outweigh the direct costs. This type of process also requires a more detailed attention of the worker, which translates in higher labor costs. The size of this machine is also greater than the welding machines, which also translates into a bigger building cost per part.

5.1.5 Cost with Integrated machines

Another important type of analysis is with an integrated machine. In certain circumstances this is seen as the end goal since it allows a fully automated process. However, it is necessary to analyze the viability of the process.

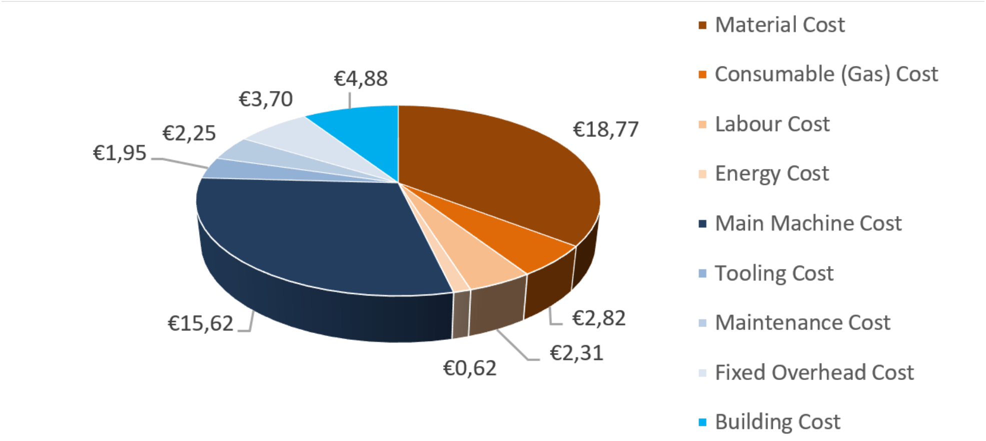


Figure 32 - Costs in a part for integrated machinery

In a first look at the figure 33 it is clear that it is not worth it to utilize an integrated machine when comparing to separated machines, since the cost is increased to 52,91€. This change is mainly due to the increase in the machine price which will need to be fully accounted in all the processes going from 7.75€ to 15,62€. Even with the reduction of the setup times and the total space required the final cost is higher.

Amid to these results, all the posterior analysis, except one figure, will be done regarding 2 different machines.

5.2 Sensitivity Analysis

The sensitivity analysis is a crucial part of a cost model. Even though all the calculations and assumptions were explained the model still needs to be validated. This validation is done by varying each one of the inputs and analyzing how it influences the cost, checking for any unexpected values and confirming all the equations. This analysis is also important to understand how each one of the variables influences the cost and can steer into the right direction for new developments changing the most cost influencing areas.

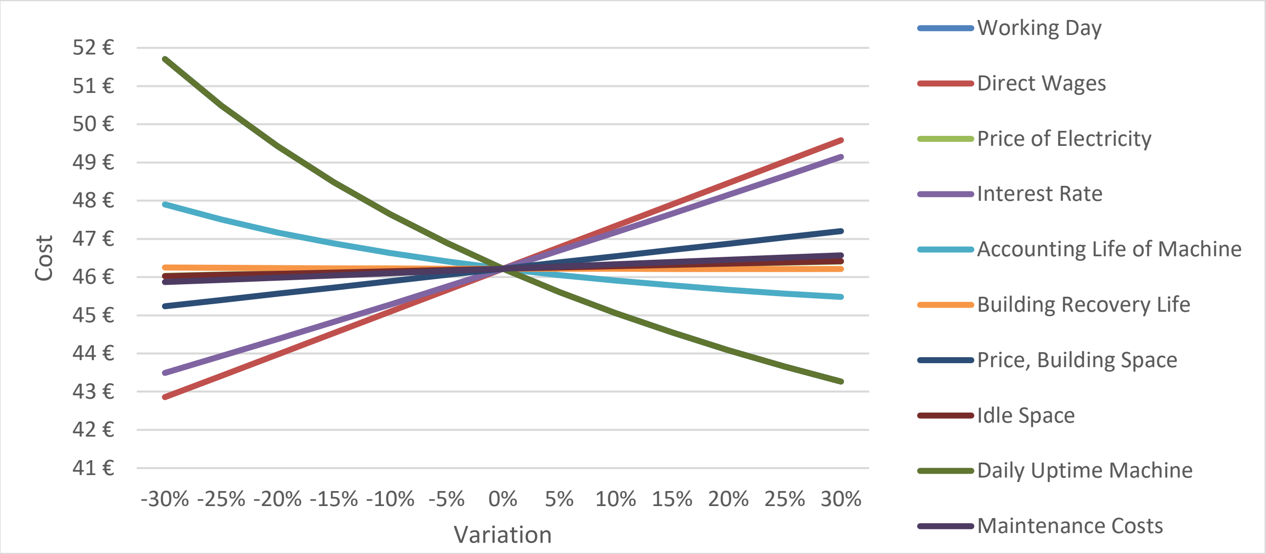


Figure 33 - Sensitivity Analysis of Exogenous Inputs

In figure 34 a sensitivity analysis is done to the Exogenous Inputs. Since these inputs are very specific to the industrial setting in question it is necessary to carefully analyze the ones with the biggest impact on the overall cost. The most impactful input is the daily uptime of the machines, with a negative slope, showing that when the machine is active less hours per day the cost of the machine per hour will increase and therefore the cost of the part will increase. With the -30% variation the part changes its cost from 46,22€ to 51,71€ which translates to a variation over 10%. The second most impactful input are the direct wages. This value directly modifies the final cost since labor cost is one of the main costs analyzed. It varies mostly depending on the country of production. The third variable with the main impact is the interest rate and it is used to calculate the real annual cost of machinery and building. This also depends on the type of loan contracted or the cost of opportunity considered.

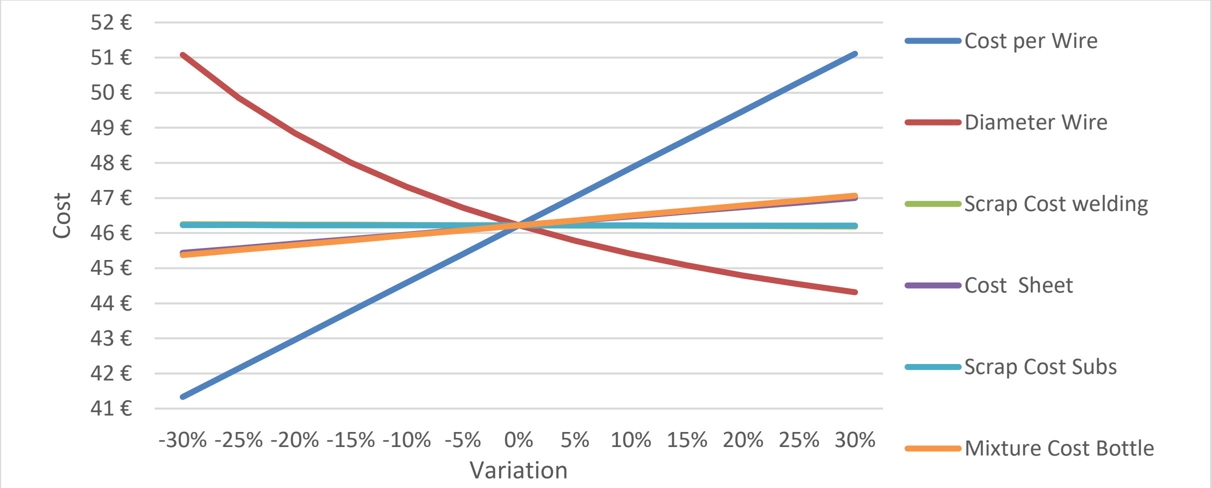


Figure 34 - Sensitivity Analysis of Material Inputs

In figure 35 a sensitivity analysis is done to some of the material inputs. The one with the biggest impact is the cost of the wire. This was a result to be expected since it was previously seen that the cost with the biggest impact on the total cost was the material costs. The second main influencer is the diameter of the wire, which has a second order influence on the cost due to its influence on the time of deposition. However, this should be balanced out with the other variables to create the most ideal parameters.

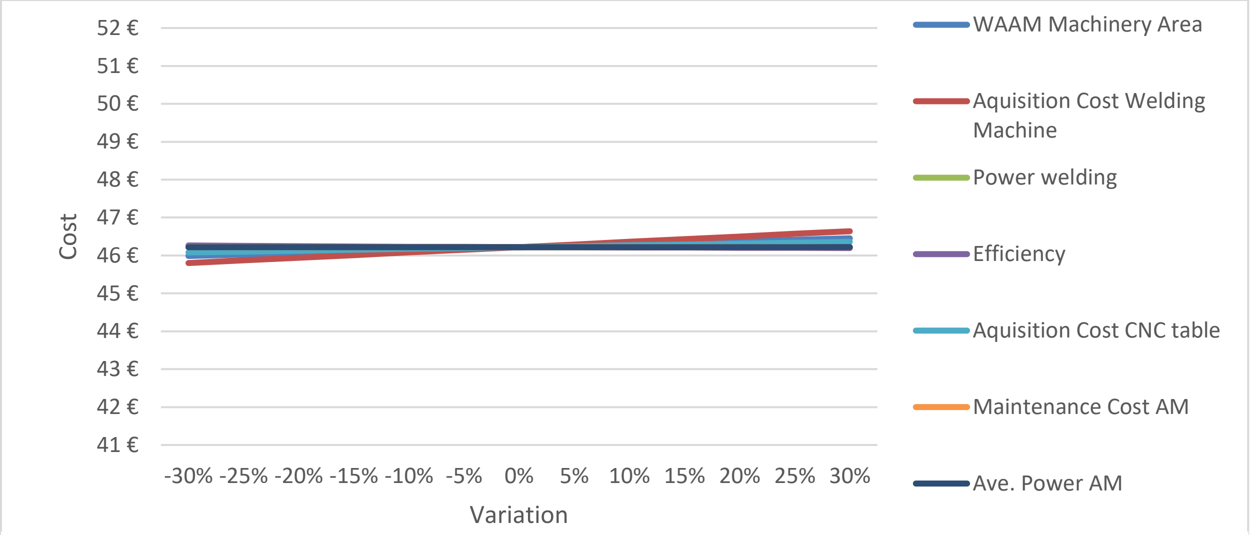


Figure 35 - Sensitivity Analysis of Machinery Inputs

Regarding the machinery inputs, in figure 36, it is possible to see that it has a much smaller influence comparing with the previously analyzed inputs. This can be explained by the extreme versatility of the AM methods which do not require dedicated machinery and the low cost of electricity. Namely for WAAM, within the AM space, the machinery required is cheaper the other processes.

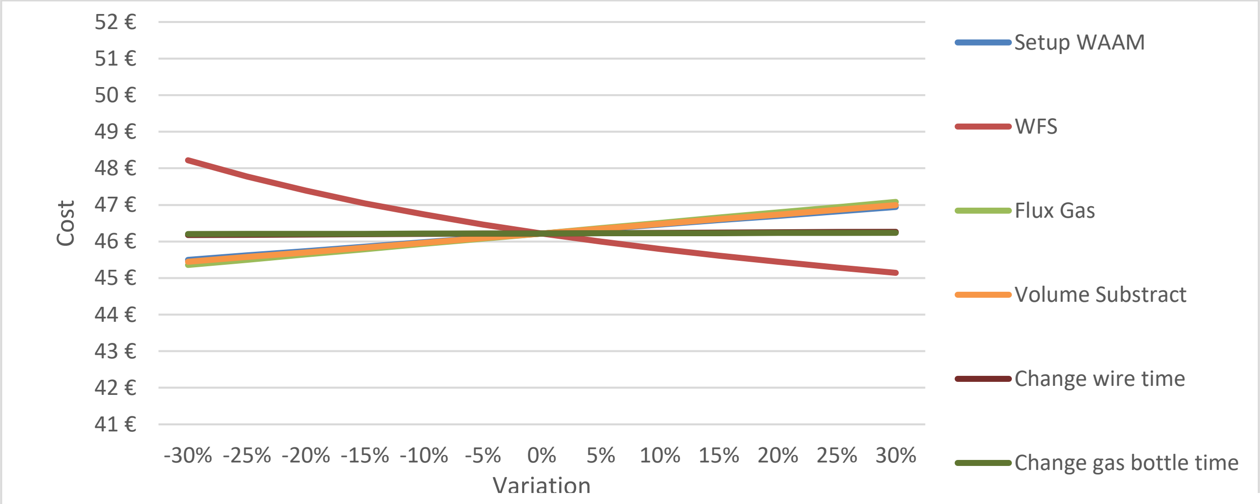


Figure 36 - Sensitivity Analysis of WAAM Deposition Parameters

Regarding the real process inputs, presented in figure 37, the ones with the main impact are the Wire Feed Speed and the Flux of the Inert Gas. The first mainly influences the cost by increasing the deposition rate therefore reducing the deposition time and all the costs around it. The second will mainly influence the amount of gas spent and with it the capital spent on the gas. Both should be carefully analyzed since they determine the good quality of the part.

Regarding the finish machining process, in figure 38, the input with the biggest impact is the time for the operation. This will dictate the material removal rate and therefore a lot of costs are determined by it. However, it should be carefully analyzed since just choosing the lowest time possible will impact a lot the operation. The second most cost-impactful operation is the setup time. It has so much impact due to the full attention of the worker and the high cost of the machine. The third cost is the acquisition cost for the machine, which is much higher than the WAAM one because milling machinery is more expensive than welding machinery.

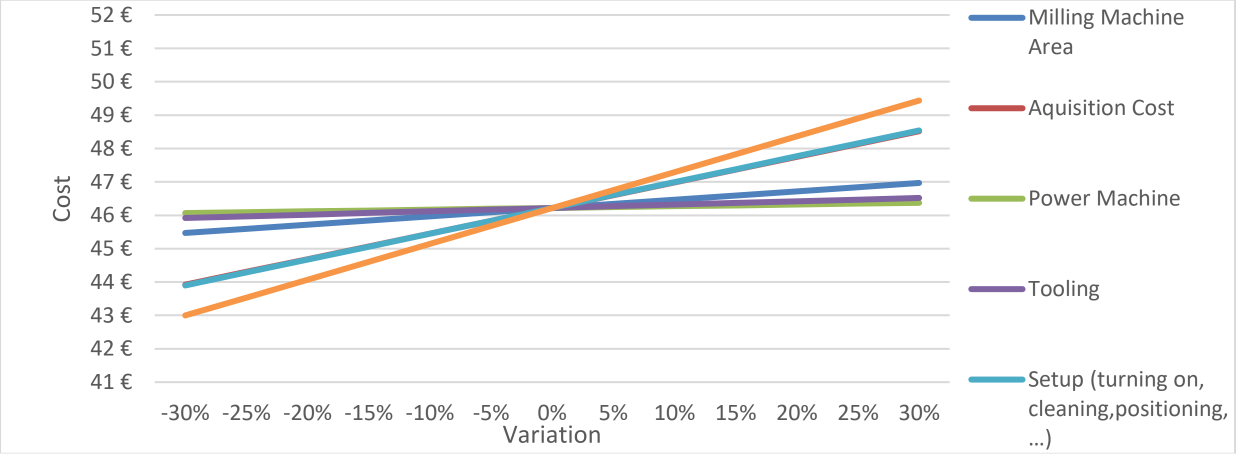


Figure 37 - Sensitivity Analysis of Finish Machining Parameters

Now, regarding the variables that do not make sense to vary from -30% to 30%.

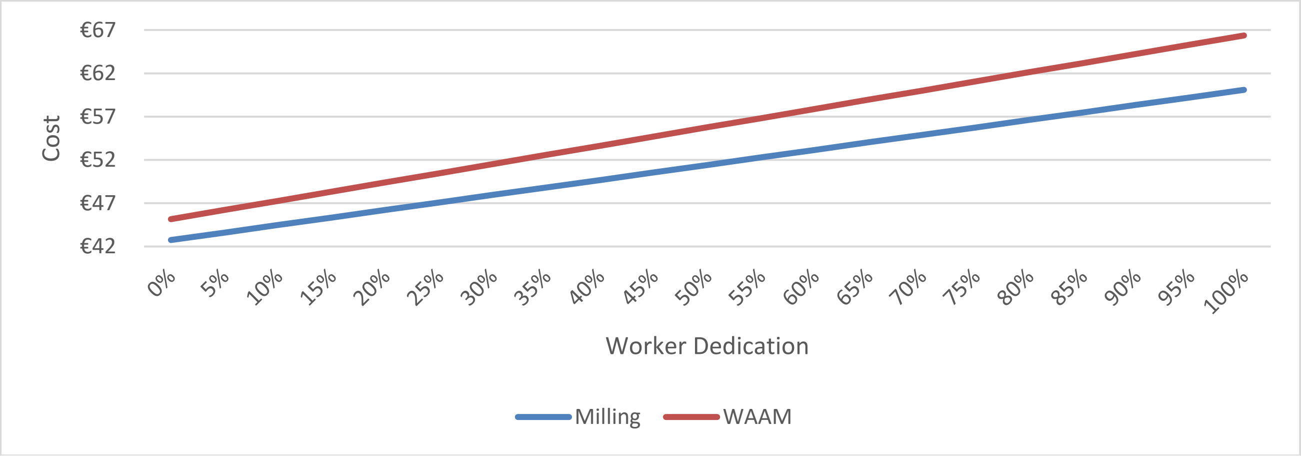


Figure 38 - Sensitivity Analysis of Worker dedication

First the worker dedication for both the WAAM and Milling in 5% increments, from 0% (no worker) to

100% (full attention of the worker), presented in figure 39. The values were measured with the case study for the WAAM and estimated for the Milling. It is possible to see that it has a lot of impact on the cost when considering 100%, however it is not realistic to assume that in such automatic processes the worker will only be focused on the production of one part.

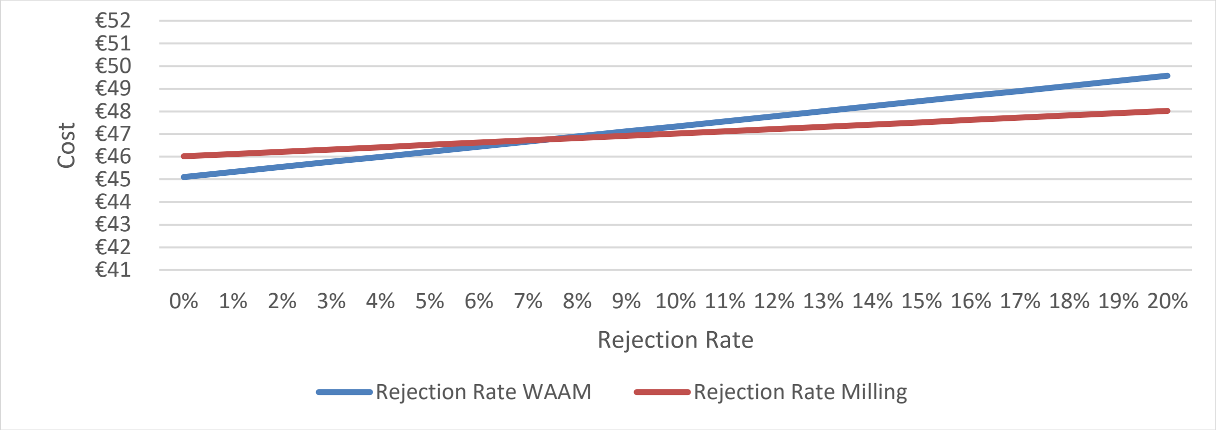


Figure 39 - Sensitivity Analysis of Rejection rate for the deposition process and the finish machining process

In figure 40 the rejection rate of each process is analyzed. It is clear that the WAAM rejection rate has a higher influence on the cost than the milling rejection rate. This was expected since, as seen before, the WAAM process has more impact than the milling.

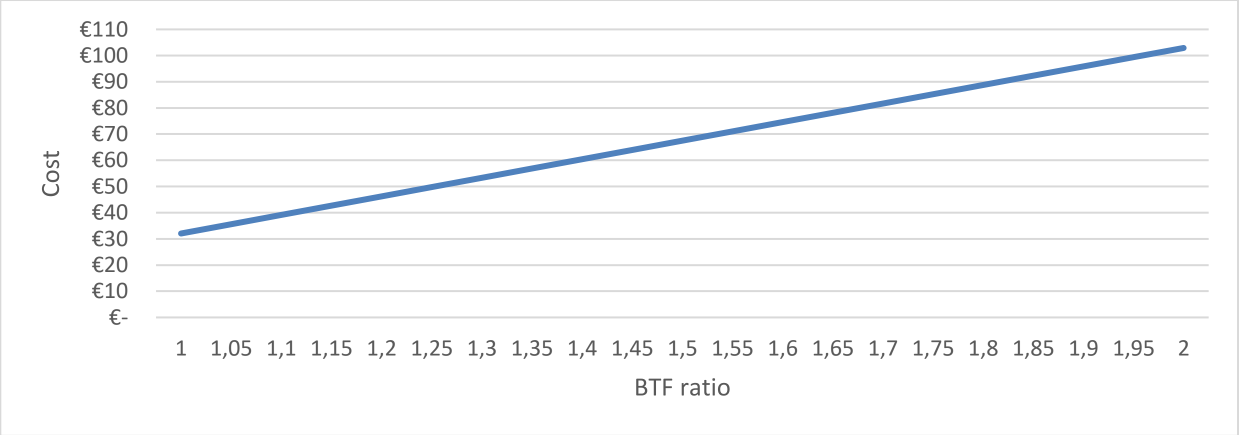


Figure 40 - BTF ratio effect on final price of machine

For the WAAM process it is not reasonable to consider BTF higher than 2. The BTF value should be planned from the 3D model and it is therefore also not reasonable to consider an ideal process of BFT=1. This parameter is a major cost driver since it influences everything, from all the sorts of time to the material quantity as seen in figure 41.

Although figure 42 looks trivial, it is at the same time it is very important. Figure 42 shows the versatility of WAAM allied with milling. None of the machines is dedicated so the price for each part remains unchanged no matter the number of parts produced.

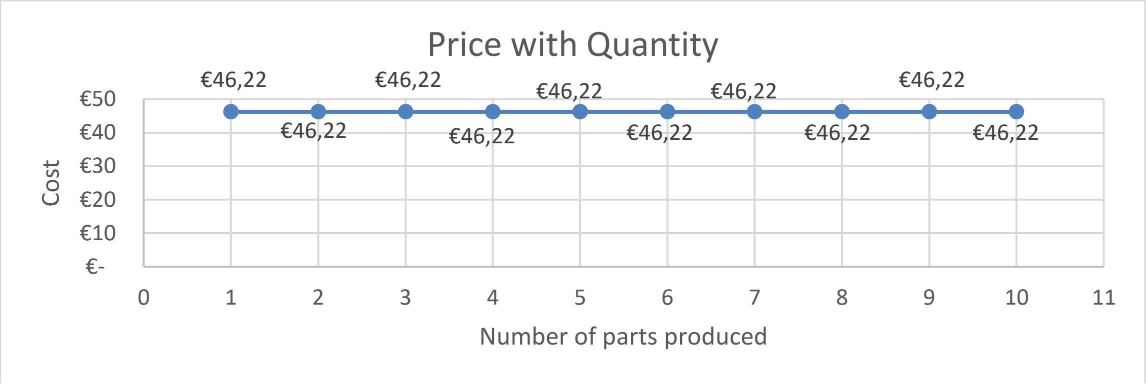


Figure 41 - Price per part with production volume

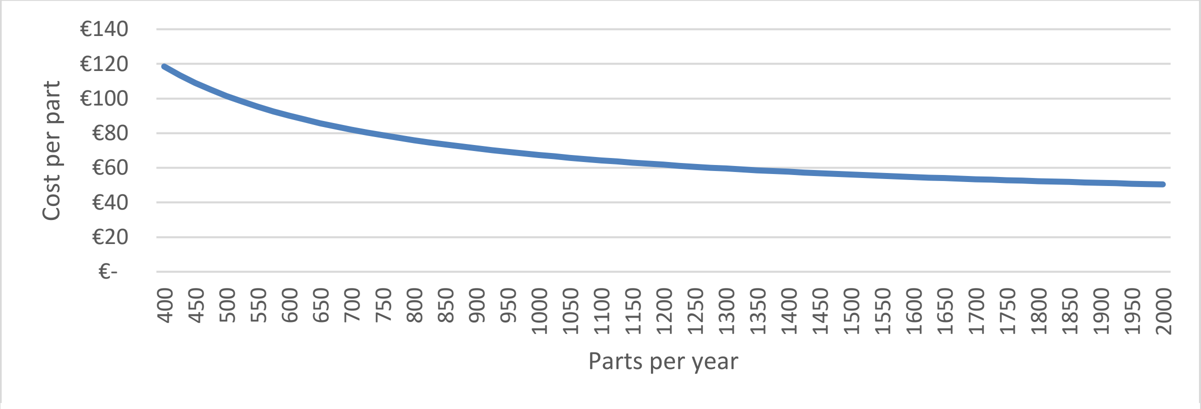


Figure 42 - Price per part with production volume for dedicated machinery

Contrasting the previous analysis, a second analysis was elaborated to see the evolution of the cost when the machinery is dedicated for the production. With this it is possible to see that with an increase on the number of produced parts, the price will decrease. Even though this could be the expected result for the previous figure, for this type of analysis with dedicated and non-dedicated machinery this result shows the power of the AM technology. This type of consideration makes more sense in industries with more rigorous standards. This analysis is also noteworthy for producers with big unused times where the machines are getting depreciated without use.

For the figure 44 the number of parts per batch is analyzed. For WAAM the number of parts per batch is now as important as in other AM methods such as PBF since there is not theoretical limit and the size of the substract is chosen by the producer. However, since the cooling time was a variable seriously considered within this cost model, the number of parts per batch will mainly influence in this regard since when one part is done depositing and it is starting to cool, the time for the deposition of the other parts is subtracted to this cooling time, therefore reducing the machine and worker time. Besides this, it will also reduce the setup for each one of the parts since one of the main time consumers in the setup is the calibration of the axis. Influences in cooling times between parts should be taken into account when deciding the cooling time for each part.

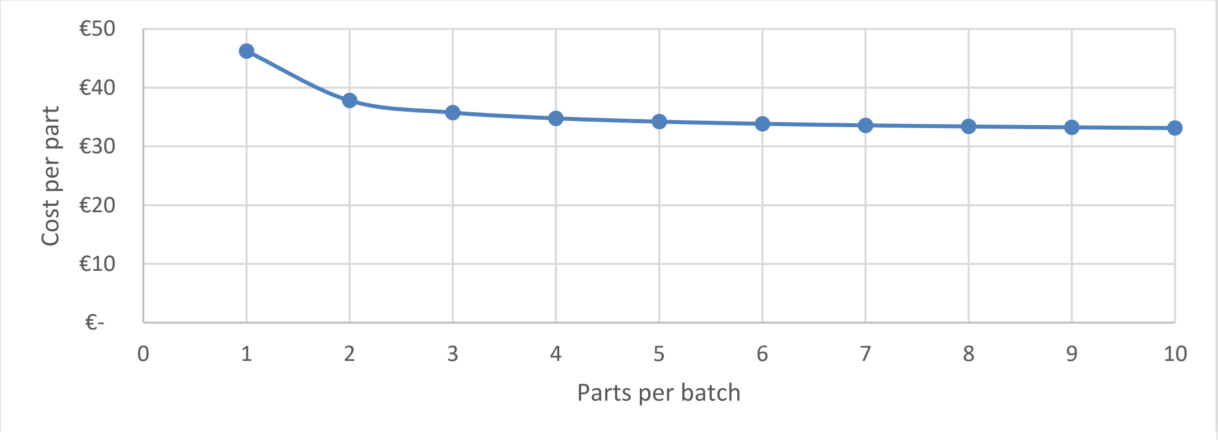


Figure 43 - Price per part variation with number of parts per batch

5.3 Comparison with traditional manufacturing methods

The next step in the analysis of the viability of WAAM is the comparison with traditional methods. The methods chosen to compare are complete machining, were the cost model applied was an adaptation from the machining part of the previous cost model and die cast, adapted from a previously developed cost model [98].

5.3.1 Milling

The complete machining process was derived from the WAAM second process. The same principles were transferred to the new cost model, but it was changed in a way to represent the fully machining processes more accurately, for example, considering two milling stages instead of one.

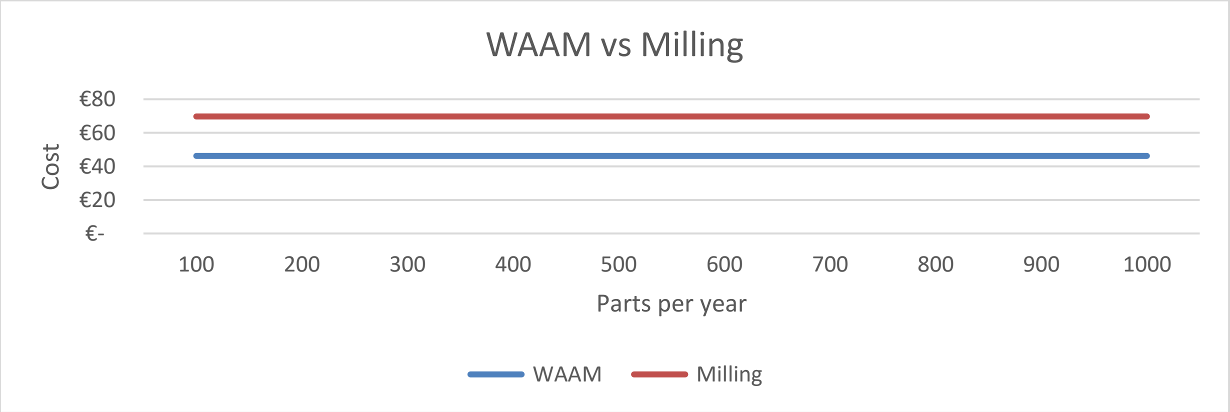


Figure 44 - Cost comparison between WAAM and Complete Machining with variable quantity

The first analysis is the quantity analysis, in figure 45, where the costs with quantity are compared between the methods. Both in WAAM and Complete Machining the processes are non-dedicated, being possible to manufacture different parts with the same machinery. It is possible to see that the total costs of the complete machining process are higher than the WAAM ones which is possible to explain with the following analysis.

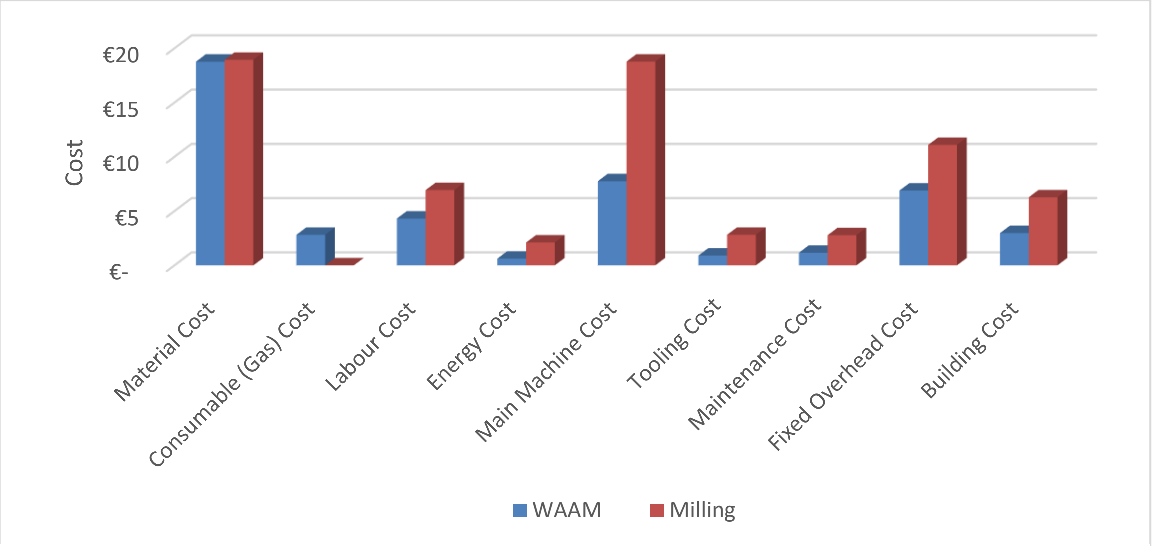


Figure 45 - Breakdown costs comparison between WAAM and Complete machining

In figure 46 each type of cost is compared between the manufacturing processes. The material costs are the highest ones in both WAAM and complete machining. Even though the wire costs are much higher than the costs of a block of material, the BTF ratio is much more advantageous in WAAM than in complete machining. The biggest disparity between costs is the machinery costs. The machines used in the WAAM finish machining process and the complete machining process were the same, however the utilization time of this machine is much higher in the complete machining process than in the WAAM finish machining process. Due to the high cost of the milling machine the difference between the costs is therefore so distinct. The remaining variables are also mainly due to the machine, since it is bigger and more expensive.

With these results it would be expected to conclude that WAAM is better than complete machining, however many other factors are not taken into consideration such as the mechanical properties of the part. Other parameters could also be optimized for the complete machining process, which would improve the overall costs of the production.

5.3.2 Die Cast

The second method to which WAAM was compared is die casting. The cost model was adapted from a PhD Thesis [98]. To make a realistic analysis the WAAM model was also altered, changing the variables to a part manufactured in Aluminum.

Once again, a quantity analysis is done but this time an important contributor for the cost in the die cast process is dedicated, the mold. Since figure 47 is not a straight line anymore and with more production the cost for each part will decrease. It is possible to see that for the case study artifact it is necessary to produce around 2300 parts in order for it to be more beneficial than WAAM process.

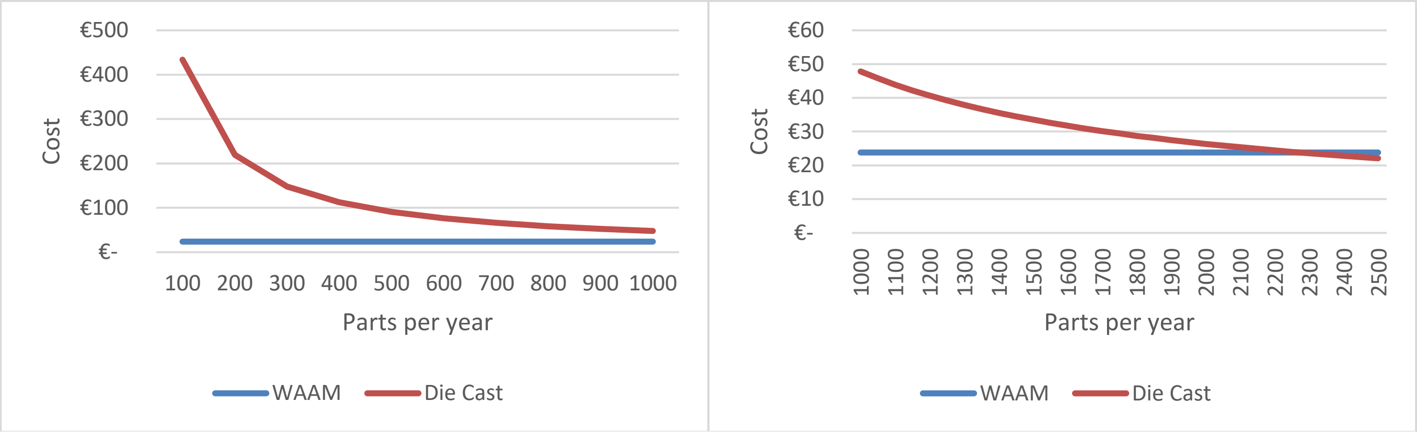


Figure 46 - Cost comparison between WAAM and Die Cast with variable quantity

When comparing each type of cost between WAAM and die cast, in figure 48, it is clear that the latter has a better cost in almost every aspect except for the tooling cost. The tool in question is the mold used for the part being the most impactful cost driver in the process. That is why, as seen before, the cost of the part will greatly decrease with the increase of production since this cost will be distributed for each one of the parts.

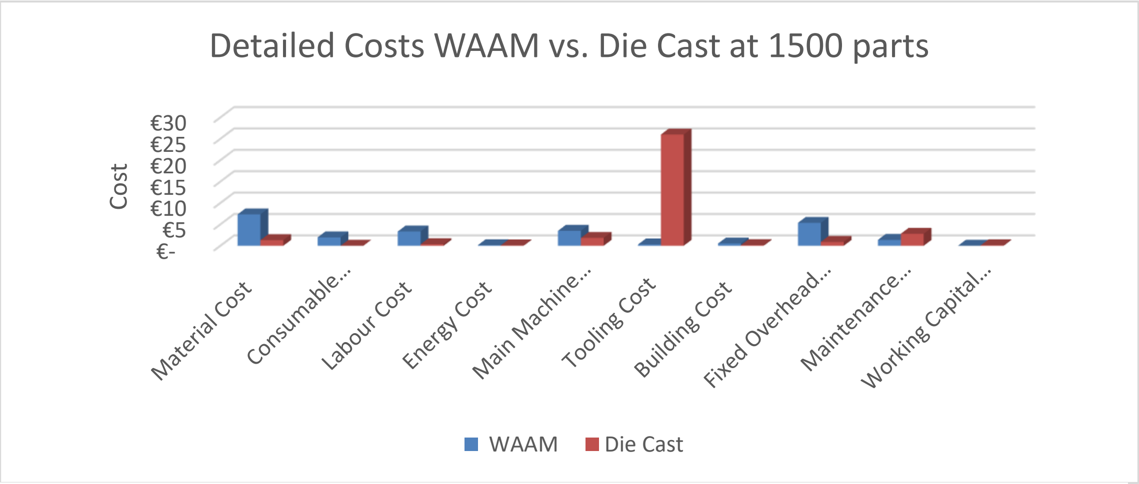


Figure 47 - Breakdown costs comparison between WAAM and Die Cast

5.4 Life Cycle Assessment

The first step was the definition of the goal and scope of the analysis. It was already established the importance of a sustainability study in today's production paradigm, therefore, in this section, the environmental performance of WAAM will be assessed and compared to a traditional method, complete machining, using the case study artifact, built in stainless steel 316l. Since the cost model started from the preparation of the substract and the setups and ended with the machining stage, the environmental analysis will have the same scope, thus a cradle-to-gate analysis is applied.

The functional unit in this analysis is the production of one part. The specification of the inventory (LCI) is the next step, and it was obtained from the cost model data and the case study performed. For the WAAM, 0.902kg of deposition material are necessary for the production process, with 0.15kg of that recycled. Adding to this, there will be the weight of the substract material, accounting for 0.496kg, of the final total weight of 1.248kg. A total weight of 0.43kg of Argon will also be used going to the atmosphere. For the complete machining process only one block of 4kg will be considered. Of this 2.75kg will be recycled having the final part 1.25kg. The steel 316l was already present in the databases available while the Argon was considered in its liquid form due to not existing in the gas form within the databases of SimaPro.

For the energetic values, in the deposition phase of WAAM, all of them were based on the ones obtained in the case study measures, and the remaining values (finish-machining in WAAM, and all the process in complete machining) were obtained and adapted by the publications of Gutowski [99]. This amounted to a total of 21.6MJ for WAAM and 62.4 for complete machining.

The net of resources for both processes are presented in figures 49 and 50, where a more schematic approach is taken.

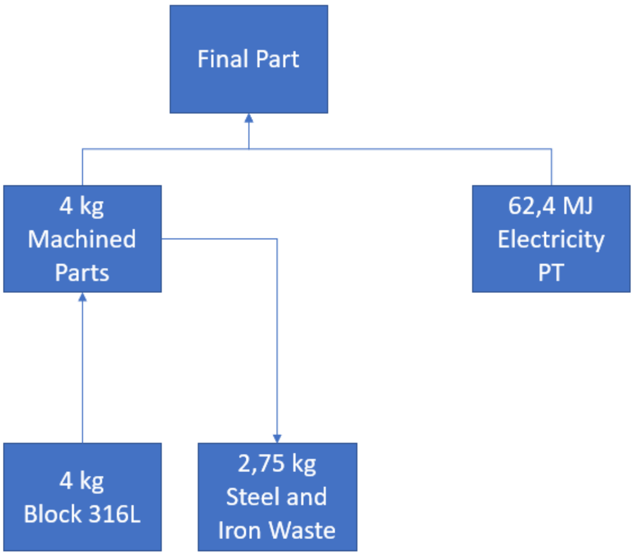


Figure 48 - Net of resources regarding the Complete machining production

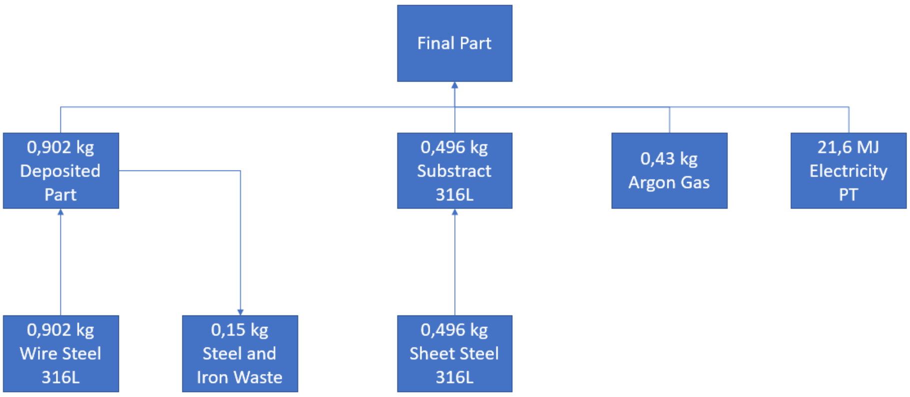


Figure 49 - Net of resources regarding the WAAM production

For the third step of the LCA, both ReCiPe midpoint and endpoint analysis were made, and the normalized values for the impact were selected for a better understanding of the results. As previously mentioned, the midpoint analysis takes into account 18 categories while the endpoint only considers 3.

Impact category	Unit	Total	Wire Steel	316L Sheet	Argon	Electricity
Climate change	kg CO2 eq	7,521815	3,657234	2,180723	0,658435	1,025423
Ozone depletion	kg CFC-11 eq	4,77E-07	2,27E-07	1,31E-07	4,54E-08	7,34E-08
Terrestrial acidification	kg SO2 eq	0,045855	0,022149	0,012753	0,003914	0,007039
Freshwater eutrophication	kg P eq	0,002398	0,00122	0,000712	0,000269	0,000197
Marine eutrophication	kg N eq	0,009537	0,003689	0,00207	0,001283	0,002495
Human toxicity	kg 1,4-DB eq	4,034654	2,314652	1,311998	0,217182	0,190822
Photochemical oxidant formation	kg NMVOC	0,027733	0,014254	0,008531	0,001941	0,003008
Particulate matter formation	kg PM10 eq	0,035069	0,02011	0,011633	0,001468	0,001859
Terrestrial ecotoxicity	kg 1,4-DB eq	0,001259	0,000728	0,000406	3,87E-05	8,57E-05
Freshwater ecotoxicity	kg 1,4-DB eq	0,544895	0,338409	0,186874	0,007826	0,011787
Marine ecotoxicity	kg 1,4-DB eq	0,555417	0,346703	0,191423	0,007075	0,010215
Ionizing radiation	kBq U235 eq	0,886447	0,394784	0,220486	0,164009	0,107168
Agricultural land occupation	m2a	0,624501	0,319572	0,177393	0,027632	0,099904
Urban land occupation	m2a	0,124284	0,072732	0,041518	0,004236	0,005799
Natural land transformation	m2	0,000733	0,000327	0,000194	7,45E-05	0,000138
Water depletion	m3	0,163846	-0,02328	-0,01278	0,196635	0,003273
Metal depletion	kg Fe eq	18,79463	12,04594	6,72021	0,010514	0,017961
Fossil depletion	kg oil eq	1,890885	0,896783	0,522883	0,174193	0,297026

Table 12 - ReCiPe Midpoint analysis for WAAM

The biggest impact in most categories comes from the material (both deposition material and substract material), followed by the electricity and then the shielding gas as seen in table 12.

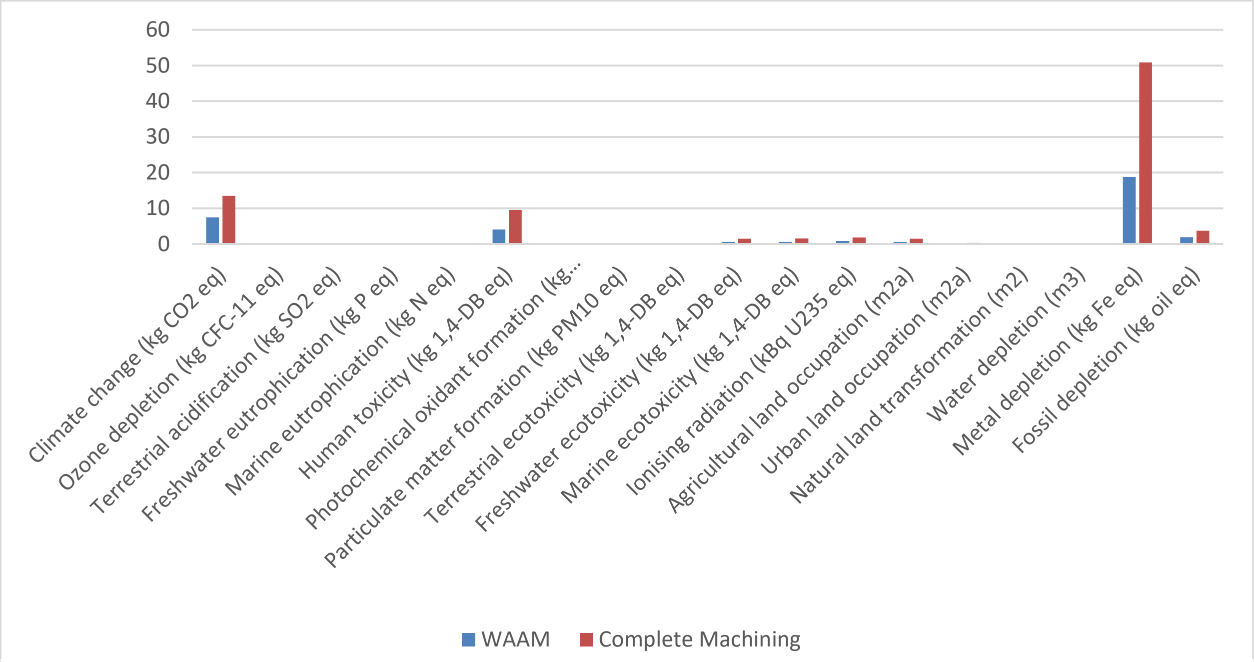


Figure 50 - ReCiPe midpoint comparison between WAAM and Complete Machining

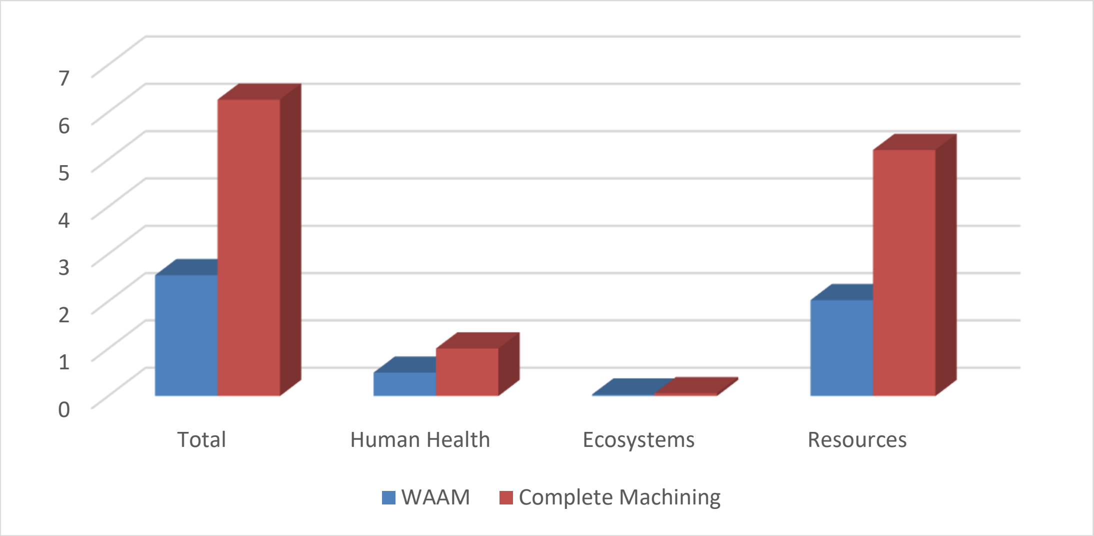


Figure 51 - ReCiPe endpoint comparison between WAAM and Complete machining

In the figure 51 it is possible to see the comparison between the ReCiPe midpoint values in WAAM and complete machining. As it was expected the areas with the most impact are metal depletion and climate change and in almost every category the complete machining has a bigger impact than WAAM.

With figure 52, it is possible to conclude that complete machining is much worse for the environment than WAAM since it has a bigger impact in all the categories. This was expected since the material usage, BTF ratio, is much higher when producing a part by complete machining than with WAAM. The milling machines are also much more powerful, and therefore require more energy to operate. The only difference would be the shielding gas, which as a residual impact when compared to the material and energy impacts.

Chapter 6 – Conclusions and Future Work

It is clear that the Additive Manufacturing industry is growing each year and as a result of this expansion, it is expected that the economic viability of more and more processes is going to be assessed. The focus of this thesis is therefore the evaluation of the capabilities of WAAM, using a thorough analysis of the process and then comparing it with traditional processes, both in an economic standpoint and in an environmental one.

With this, the main cost model was created for WAAM and the respective finish-machining, and a subsequent one was made to simulate a complete machining operation and at last, a die-cast model was adapted for a case study part. Even though the cost was analyzed for the case study part, the cost model is versatile and sturdy, allowing the consideration of different inputs such as material, parameters, or even annual production.

The PBCM approach was used since it is a great tool that can relate the importance of all costs and the nuances of the engineering processes. Thus, being built with a logical analysis it can somewhat accurately predict the costs for the real processes modeled.

The case study part was the basis for the results shown, and it was designed after a thorough discussion with experts in the WAAM technology to be simple enough to make a general analysis but with different cross-sections to represent real-world needs. Even though the results would be different if using a different part, they shall not be discarded since the part is a good representation of some common needs.

With the first part of the results, it was possible to conclude that the material cost is the factor with the biggest impact on the process followed by the machine cost of the finishing due to the high costs of wire and milling machines. It is also noteworthy that, for the full process, the variable costs are higher than the fixed costs, with this being expected in such a versatile process.

In the integrated machinery analysis, it was possible to infer that from a uniquely economic standpoint it is not viable to integrate the machines. This happens due to the big increase in the idle time of the machines since when the welding machine is depositing the milling machine is idle and vice-versa.

With the subsequent sensitivity analysis, it was possible to validate the cost model and simultaneously understand the impact of each input on the final cost. It was seen that overall, the material inputs are the ones with the most impact on the final cost with a surprisingly big impact with the variation of the daily machine uptime.

With remaining sensitivity analysis that did not follow the -30% to 30% variation, it was possible to conclude that the BTF is the most important variable with a 2,5 times cost increase with a BTF of 2 (instead of the original 1,2). This occurred since this input is the one with the largest influence in all the processes and increasing it causes not only the increase of the material use but also of every time related to the processes (just like the deposition time). Regarding the worker dedication analysis, it was possible to conclude that is not cost-efficient to have a full-time worker just in charge of WAAM since it is a very automated process, only requiring some attention.

With the quantity analysis, it is concluded that due to the high versatility of WAAM even small production volumes can be done without harming the total cost. However, the maximum number of parts per batch should be taken into account mostly due to the cooling and setup times.

In the comparative cost analysis, it is possible to conclude that WAAM is better than complete machining with any amount of parts produced with smaller costs in almost every category. The biggest difference is within the machine costs since milling machines are generally more expensive than welding machines. Even though the material costs seem similar, a lot more material is used in the milling process, but it has cheaper materials. Compared to die cast it is possible to conclude that it is also advantageous for low production volumes (until 2000 around parts per year). This happened due to the high tooling costs (related to the die) in the die casting process.

Regarding the LCA, it was concluded than due to the smaller BTF ratio and consequent utilization of less material, WAAM is a manufacturing method with less environmental impact than complete machining. This was seen across almost all the categories of ReCiPe midpoint and in all categories of ReCiPe endpoint.

For the future work there are several suggestions for a possible extension of this thesis. Firstly, and maybe the easiest, to complete the current spaces with data bases to easily change the inputs with no need to do it manually each time. This should be done for the materials, both deposition and substrate, for the gas and for the machinery. If more than one type for part is manufactured, is it also recommended to update the part section.

It is also suggested to redo the full analysis with different parts and if possible, with different parameters in order to verify the validity of the claims for a bigger spectrum of parts. Then perform a new sensitivity analysis, to complement the results.

Another suggestion would be to increase the number of activities within the scope of the cost model since only the two main activities are analyzed here. From the previous transportation and storage, until the end-of-life of the product, the cost should be analyzed and compared to evaluate the real impacts. Inspections and non-destructive testing are also necessary, so can be added. As a result, the scope of the LCA could also be broaden.

Related to the previous suggestion, more complementary methods can be modeled such as interlayer rolling and a plastic deformation operation after the deposition. With this the process will be more complete and give more possibilities of analysis.

As for the LCA, it is recommended to perform the analysis once again with different materials, BTF and machines, and posteriorly compare the results with different manufacturing methods such as die cast.

Finally, a comparison between WAAM cost models should be made in order to consider the real impacts between them and assure their precision and which aspects were considered in them.

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Annex A

Technical Drawing