Economic and Environmental Potential of Wire Arc Additive Manufacturing

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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 was 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 ones.
With the results presented in the end of 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, 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 Arc Additive Manufacturing

1. Introduction

With an ever-increasing competitive market there is the need to find newer and better manufacturing methods. Recently, there has been an explosion within the Additive Manufacturing (AM) market due to its inherent advantages such as the material savings and geometry versatility [1]. Several AM technologies have been developed and tested, including Wire Arc Additive Manufacturing. Compared to other AM processes, WAAM has a very high deposition rate which allows to build bigger parts in a faster time [2].

One of the main drivers of markets is the cost, therefore when making any type of analysis to a process, a cost estimation should be carried out [3]. There is also a progressively growing concern regarding the environmental impact of products, which leads to the need for new manufacturing methods that are environmentally sustainable [4].

Even though WAAM offers some advantages, such as the ones stated before, there is still a need to quantitively measure the impact of those advantages. Due to its different nature from most other AM processes, and complete opposite type of process to substrative processes, existing models used for other methods cannot be applied. Furthermore, there is still a need for more thorough models with different approaches to both the process and the cost [5].

The aim of this thesis is thus the extensive evaluation of the WAAM method, with a focus on the economic impacts, while creating a tool that allows future assessments easier. A Process Based Cost Model was developed to satisfy the technical needs while creating a sturdy financial tool. After that, a case study of a part was carried out in order to, not only estimate the cost, but also to measure the total energy consumption of this method which, subsequently, allowed to assess the environmental impact it has on several categories.

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.

2.1 Additive Manufacturing

Additive Manufacturing is a set of processes that allow building three-dimensional parts from a digital model by adding thin layers of material in a consecutive manner [6]. This process is the parallel of the ones called conventional manufacturing techniques that create products carrying out the successive removal of material, therefore incurring in a much more wasteful procedure [7].

According to the American Society for testing and Materials there are 7 types of AM processes: Vat photopolymerization, Material Extrusion, Material Jetting, Binder jetting, Powder Bed Fusion, Direct Energy Deposition and Sheet Lamination [8].

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 [9]. A justification for the growth of this type is the prohibitively high costs of some metals when trying to use traditional manufacturing methods [10].

2.2 Wire Arc Additive Manufacturing

It is a Direct Energy Deposition process 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 [2].

With the research made in WAAM it was possible to find that this process can use several types of materials and can provide several types of features [11]. 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 [12].

One of the most researched topics related to WAAM is the mechanical properties of the parts 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 [13]. 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.

2.2.1 Advantages and Disadvantages in WAAM

Some advantages of WAAM are: Possibility to build large metal parts with an extremely high deposition rate. Its 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 process, 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 to the costs. Somewhat bad finishing, almost always requiring finish machining operations

2.3 AM Cost Models

One of the most notable AM cost models developed is the work by Hopkinson and Dickens in 2003 [14]. 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. 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. This cost model was designed to predict the cost for low and medium production volumes. It was concluded that one of the main factors is the ability to fill the bed to the maximum.

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.

One of the first WAAM cost models was developed by Martina and Williams [5], where a comparison between this method and traditional machining from solid was performed. It was 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, from the University of Bath, it was published a more robust cost model [15]. 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. The results from the model previously mentioned [15], pointed out that WAAM outperforms both alternative AM methods and traditional methods for several geometries.

2.4 Environmental Analysis

One of the main current goals is sustainable development [16]. Traditional methods have a higher BTF ratio than AM, which results in a proportional bigger waste of material. However, there is a lack of research of the sustainability of WAAM.

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 [17].

The first LCA on focused on WAAM was developed in 2016 by Bekker, Verlinden and Galimberti [18]. This study mainly evaluated capabilities of the ISO methodology and provided a framework for the development of new environmental assessments for WAAM.

A few years later, in 2018, this time only Bekker and Verlinden [19] 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. It was concluded that WAAM had a similar impact to Green Sand Casting and a smaller impact than Milling.

In 2020, Priarone et al [20], 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. It was concluded that WAAM can be a powerful manufacturing method that can have several benefits across the production process on parts.

3. Methodology

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

3.1 Overall Methodology

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 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.

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.

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 artifact was designed to validate all the results with a real-life scenario.

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.

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 1, the full tree explaining the full methodology taken when developing this thesis.

3.2 Economic Analysis

To perform the economic analysis, a Process Based Cost Model, PBCM, was used. The PBCM comes as the combination of a technically accurate model which will estimate with precision the process while taking into account the financial nuances, all in an early stage of development of new parts.

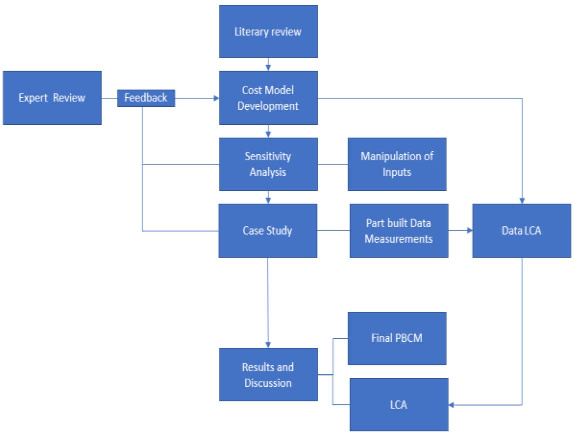

Figure 1 – Overall Methodology

The cost of every product developed 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 linked to the design of the product and obviously the cost of the final product is a direct consequence of the processes chosen [3]. In general, PBCM are able to react quite easily to any desired changes of the process.

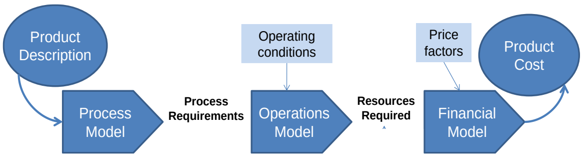

Figure 2 - Process-Based Cost Model Approach

For the creation of a PBCM, 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 2. This should always be accompanied with reliable data of the process [21].

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.

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.

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. With the inventory analysis all the inputs and outputs of the processes are identified and considered. In the impact assessment phase, it is where the environmental influences are evaluated according to the desired parameters. 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 [22].

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. In the ReCiPe endpoint analysis only 3 categories are assessed.

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.

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, as seen in figure 3. Using SolidWorks, the first drafts were produced and then modified until having the expert's approval.

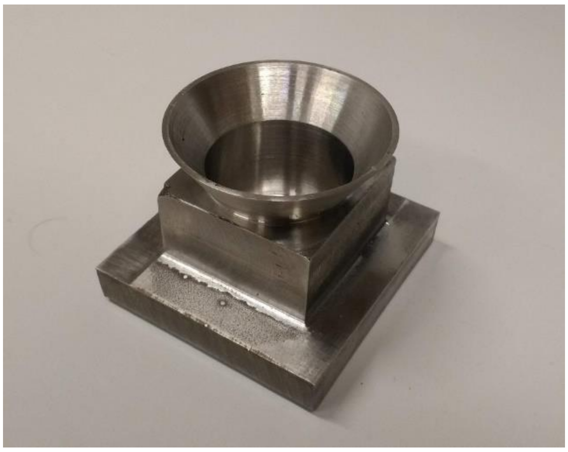

Figure 3 - Final part produced

The second step was to gather all the equipment and software. During the printing of the part, the power of the WAAM process was measured The posterior machining was done using the machines present in the IST Manufacturing and Process Technology Laboratory , even though they are different from the one present in the cost model.

4. Cost Model Development

The goal of this section is to provide a description about the cost model development for this thesis.

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.

The WAAM manufacturing method was decomposed in 5 main phases: Pre-processes, Preparation, Main Process, Finish Machining and Post-processes. It was decided that for the scope of this thesis to only consider the preparation, main process and finish machining phases.

4.2 Inputs

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 and Production Data, Material Information, WAAM Inputs and Milling Inputs.

The exogenous inputs are common for all phases and its values are heavily dependent on the specific situation of the factory/company and the production data is the one where the number of units per batch and per year is specified.

In WAAM, two main types of materials need to be acknowledged. The first one is the welding material and the second one is the substract material. For this set of inputs, the shielding gas was also considered as one of the intervening materials of the process.

The WAAM inputs are the core of the process and were divided into 4 different categories: welding machine, the moving system, the part, and the process parameters. All of last mentioned are self-explanatory.

The Milling inputs are the last ones in this cost model. In the current state of WAAM a finish machining process is always necessary, and milling was the chosen process for this model. It is out of the scope of this thesis to make a thorough analysis of the milling process. Thus, it was decided to proceed with a very straight forward analysis without compromising the rest of the cost model.

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 types of 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.

4.4 Costs

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.

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.

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

The variable costs are the ones that depend directly on the annual production. The fixed costs are calculated utilizing the equation 1, meaning that there is an investment allocated to the good (such as building or 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.

The variable costs considered are:

$$\text{Material Cost} = (\text{Cost Deposition Material} + \text{Cost Substrate}) \times \text{Annual production} \times (1 + \text{Rejection Rate}) \quad (2)$$

The final cost of material, in equation 2, is mainly dependent on the costs of the deposition material and substrate material, with the addition of rejected parts also considered.

$$\text{Consumables (Gas) Cost} = \text{Cost Shielding Gas} \times \text{Annual production} \times (1 + \text{Rejection Rate}) \quad (3)$$

The cost of the shielding gas is composed by the total cost of gas used in the deposition times the production volume, as seen in equation 3.

$$\begin{aligned}\text{Scrap cost}_{Milling} &= -\,\text{Annual production} \times \text{Rejection Rate} \\ &\times \left(\text{Volume part} \times BTF \times \rho_{depmat} \times \text{Scrap Cost}_{depma\,t} \right. \\ &\left. + \frac{\text{Volume Substrate}}{\text{Units per batch}} \times \rho_{subsmat} \times \text{Scrap Cost}_{subsmat}\right) \\ &- \text{Annual production} \times \text{Total Volume Scrap} \times \rho_{depmat} \times \text{Scrap Cost}_{depmat}\end{aligned} \quad (4)$$

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 in equation 4.

$$\begin{aligned}\text{Labor Cost} &= \text{Direct Wages} \times \text{Annual production} \times (1 + \text{Rejection Rate}) \\ &\times (\text{Total Worker Time} + \text{Total Printing Time} \times \text{Worker Dedication})\end{aligned} \quad (5)$$

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, as observed in equation 5.

$$\begin{aligned}\text{Energy Cost} &= \text{Annual production} \times (1 + \text{Rejection Rate}) \times (\text{Power Machine} + \text{Power AM system}) \\ &\times \text{Time Deposition Part} \times \text{Cost of Electricity}\end{aligned} \quad (6)$$

It is important to notice that when inputting the variables related to energy costs, presented in equation 6, 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.

The fixed costs considered are:

$$\begin{aligned}\text{Machine Cost} &= \text{Acquisition Cost Machine} \\ &\times \frac{\text{Interest Rate} \times (1 + \text{Interest Rate})^{\text{Accounting Life of Machine}}}{(1 + \text{Interest Rate})^{\text{Accounting Life of Machine}} - 1} \times \text{Utilization Rate}\end{aligned} \quad (7)$$

$$\begin{aligned}\text{AM System Cost} &= \text{Acquisition Cost AM System} \\ &\times \frac{\text{Interest Rate} \times (1 + \text{Interest Rate})^{\text{Accounting Life of Equipment}}}{(1 + \text{Interest Rate})^{\text{Accounting Life of Equipment}} - 1} \times \text{Utilization Rate}\end{aligned} \quad (8)$$

Both the welding machine, in equation 7, and the AM system, in equation 8, follow the same equation regarding cost, as previously explained. Both machines are non-dedicated, hence the utilization rate needs to be considered.

$$\begin{aligned}\text{Tooling Cost} &= \text{Tooling \%} \times \text{Acquisition Cost Milling} \times \frac{\text{Interest Rate} \times (1 + \text{Interest Rate})^{\text{Life tools}}}{(1 + \text{Interest Rate})^{\text{Life Tools}} - 1} \\ &\times \text{Utilization Rate}\end{aligned} \quad (9)$$

The cost for the tools of the milling machine, in equation 9, 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.

$$\begin{aligned}\text{Maintenence Costs} &= (\text{Machine Costs} + \text{AM System Cost(or tooling)} + \text{Building Cost}) \times \text{Maintenence \%}\end{aligned} \quad (10)$$

The maintenance cost, in equation 10, is a fraction of the money spent that year on machinery and building.

$$\text{Overhead Costs} = \text{Overhead Percentage} \times \text{Labor Cost} \quad (11)$$

The overhead costs, in equation 11, 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.

$$\begin{aligned}\text{Building Costs} &= \text{Building Space Price} \times \text{Machinery Area} \times (1 \\ &+ \text{Idle Space}) \times \frac{\text{Interest Rate} \times (1 + \text{Interest Rate})^{\text{Building Recovery}}}{(1 + \text{Interest Rate})^{\text{Building Recovery}} - 1} \\ &\times \text{Utilization Rate}\end{aligned} \quad (12)$$

Building costs, in equation 12, 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).

5. Results and Discussion

5.1 Test Case Results

Figure 4 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.

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.

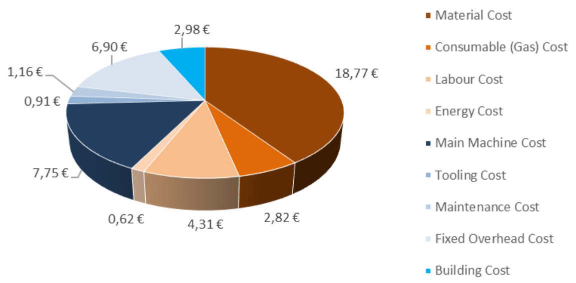

Figure 4 - Full processes costs in €

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

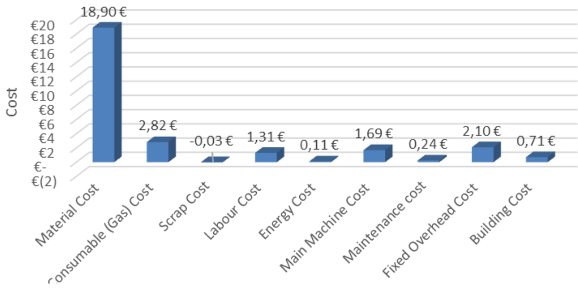

Figure 5 - WAAM deposition process costs

As expected, and is presented in figure 5, the cost with the main impact on the WAAM stage is the material cost. This occurs due to the high cost of the wire. 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.

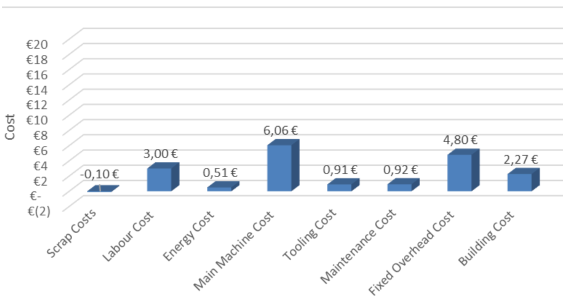

Figure 6 - Finish Machining process costs

Figure 6 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.

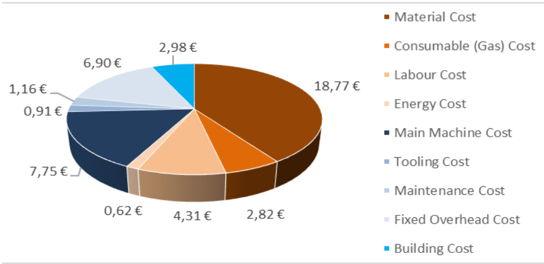

Figure 7 - Costs in a part for integrated machinery

In a first look at the figure 7, 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€.

5.2 Sensitivity Analysis

The sensitivity analysis is a crucial part of a cost model. It 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. Only the most important values are shown here.

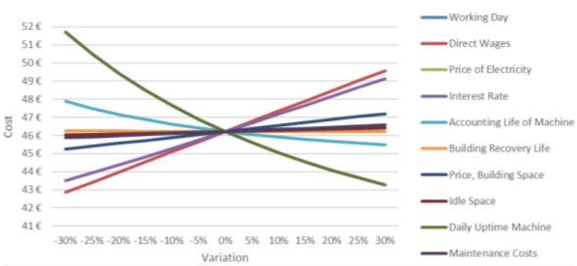

Figure 8 - Sensitivity Analysis of Exogenous Inputs

The most impactful input of the exogenous inputs is the daily uptime of the machines, as seen in figure 8, 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. The second most impactful input are the direct wages and the third variable with the main impact is the interest rate.

In figure 9, a sensitivity analysis is done to some of the material inputs. The one with the biggest impact is the cost of the wire.

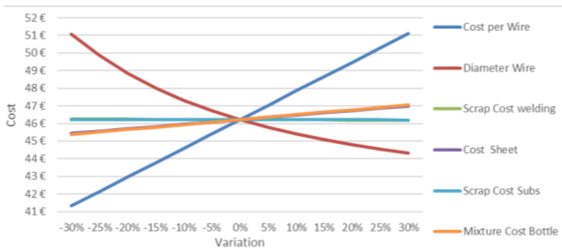

Figure 9 - Sensitivity Analysis of Material Inputs

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.

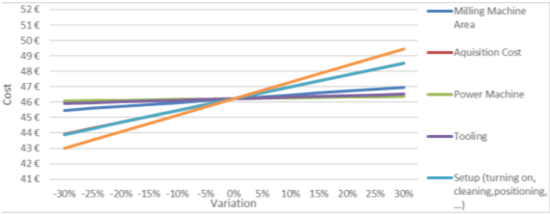

Figure 10 - Sensitivity Analysis of Finish Machining Parameters

Regarding the finish machining process, in figure 10, 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.

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

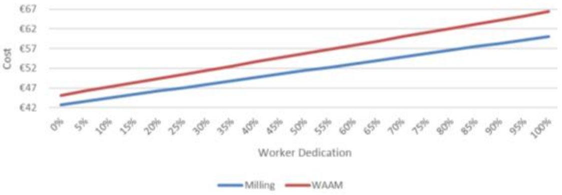

Figure 11 - Sensitivity Analysis of Worker dedication

It is possible to see in figure 11 that worker dedication 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.

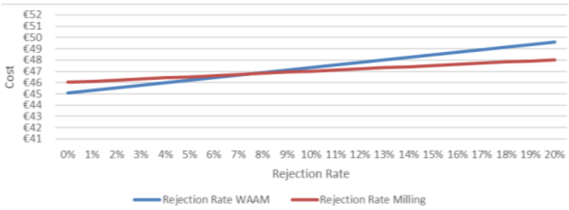

Figure 12 - Sensitivity Analysis of Rejection rate for the deposition process and the finish machining process

In figure 12 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.

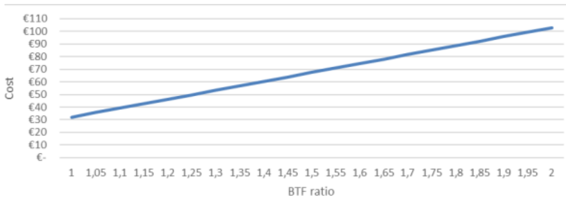

Figure 13 - BTF ratio effect on final price of machine

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 13.

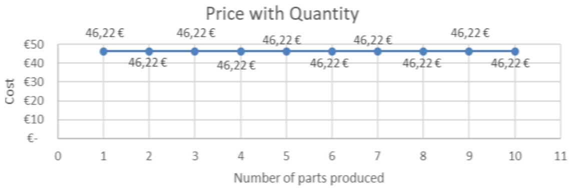

Figure 14 - Price per part with production volume

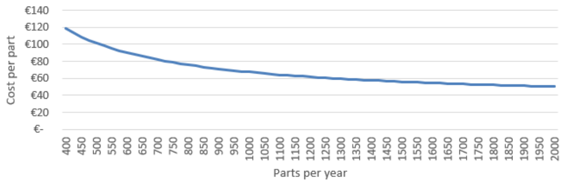

Figure 15 - Price per part with production volume for dedicated machinery

Although figure 14 looks trivial, it is at the same time it is very important. Figure 14 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.

Contrasting the previous analysis, a second analysis, seen in figure 15,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.

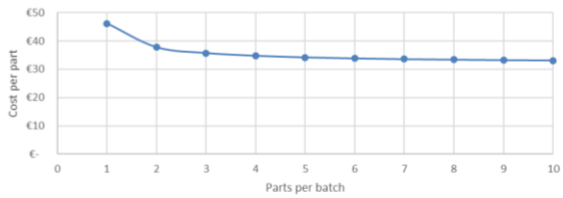

Figure 16 - Price per part variation with number of parts per batch

For the figure 16 the number of parts per batch is analyzed. 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.

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 [23].

5.3.1 Milling

The complete machining process was derived from the WAAM second process.

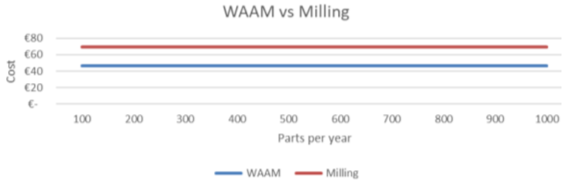

Figure 17 - Cost comparison between WAAM and Complete Machining with variable quantity

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 in figure 17 that the total costs of the complete machining process are higher than the WAAM ones which is possible to explain with the following analysis.

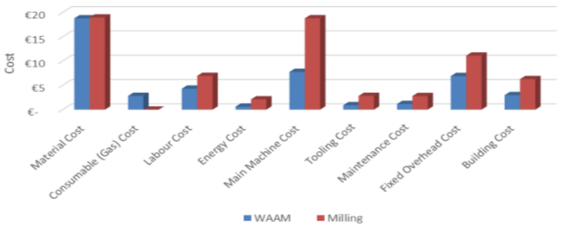

Figure 18 - Breakdown costs comparison between WAAM and Complete machining

In figure 18 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.

5.3.2 Die Cast

The second method to which WAAM was compared is die casting.

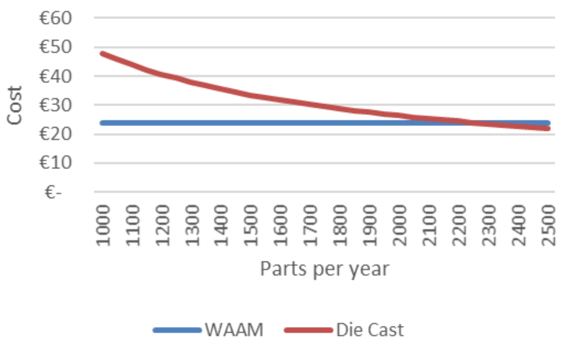

Figure 19 - Cost comparison between WAAM and Die Cast with variable quantity

The cost model was adapted from a PhD Thesis [23]. To make a realistic analysis the WAAM model was also altered, changing the variables to a part manufactured in Aluminum.

Since Die Cast has dedicated tooling, the cost is not a straight line anymore and with more production the cost for each part will decrease. It is possible to see in figure 19 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.

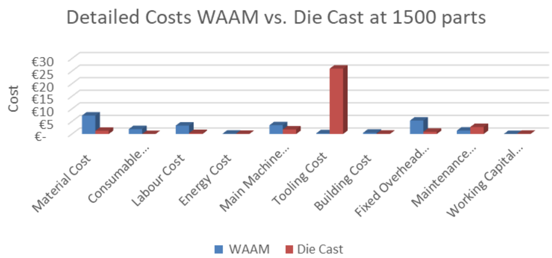

Figure 20 - Breakdown costs comparison between WAAM and Die Cast

When comparing each type of cost between WAAM and die cast, in figure 20, 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.

5.3 Life Cycle Assessment

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. A cradle-to-gate scope 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 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 from literature.

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

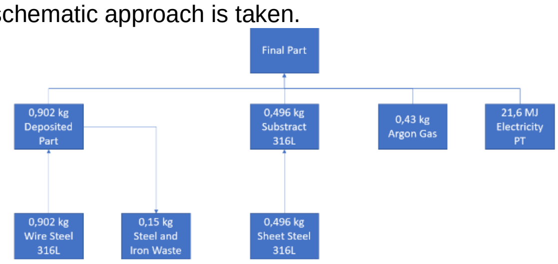

Figure 21 - Net of resources regarding the WAAM production

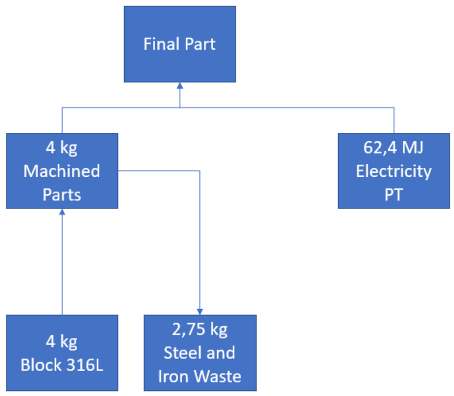

Figure 22 - Net of resources regarding the Complete machining production

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.

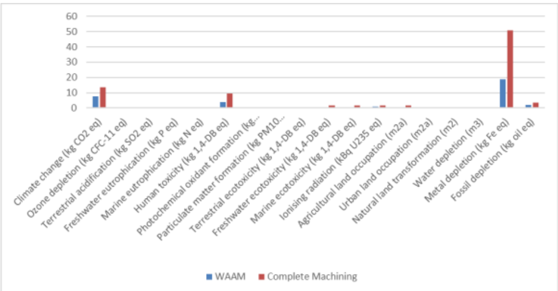

Figure 23 - ReCiPe midpoint comparison between WAAM and Complete Machining

In the figure 23 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 24, it is possible to conclude that complete machining is 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.

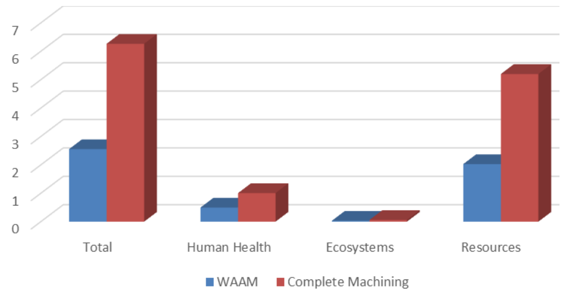

Figure 24 - ReCiPe endpoint comparison between WAAM and Complete machining

6. Conclusions and Future Work

Even though the cost was mainly analyzed from the case study artifact, the cost model is versatile and sturdy, allowing to consider different inputs such as material, parameters, or even annual production. Undeniably, results would be different if using a different part, however, 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 milling machine cost demonstrating the importance of a small BTF ratio. In the integrated machinery analysis, it was concluded that in most circumstances it is not worth to integrate both machines because of the idle machine time it represents.

With the subsequent sensitivity analysis, it was seen that overall, the material inputs are the ones with the most impact on the final cost, and there was a surprisingly big impact with the variation of the daily machine uptime. The remaining sensitivity analysis that did not follow the -30% to 30% variation it was possible to conclude that BTF is the most important variable with a 2,5 times cost increase with a BTF of 2. The worker dedication analysis also allows to conclude that is not efficient to have a full-time worker just in charge of WAAM.

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, and it is better than die cast until reaching higher production volumes (more than 2000). This analysis does not contemplate the mechanical properties of the part and it is based on a simpler model of milling only allowing to confirm that WAAM is in fact economically beneficial to some extent.

Regarding the LCA, it was concluded than due to the smaller BTF ratio, the WAAM is a much more sustainable manufacturing method than complete machining. With the increasing growth in awareness in topics such as global warming, the utilization of more eco-friendly manufacturing methods is a key aspect in today's world.

For the future work there are several suggestions to continue 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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