DEPARTMENT OF MECHANICAL AND INDUSTRIAL ENGINEERING

TOMÁS MEALHA MARTINS RODRIGUES CUNHA
BSc in Science of Industrial Engineering and Management

A PROCESS-BASED COST MODEL FOR WIRE AND ARC ADDITIVE MANUFACTURING

INTEGRATED MASTER IN INDUSTRIAL ENGINEERING AND MANAGEMENT

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ABSTRACT

In engineering one of the main criteria to evaluate new technology or product is its economic viability. This can only be done by identifying the costs related to the process or product. Within the Smart WAAM project, which aims to study the use of wire and arc additive manufacturing (WAAM) technology to create, repair and expand the life of large industrial components, it was necessary to develop a cost model to study the economic viability of this technology.

This thesis's primary goal is to develop a cost model for the WAAM technology, considering a product life cycle approach. For this purpose, it was necessary to develop a model to estimate the cost of the WAAM technology, as well as the main factors influencing the cost.

A process-based cost model (PBCM) was developed since it allows to analyse the costs of the different life cycle phases of a product and estimates the production costs. The study main steps were the objective and scope definition, using a cradle to gate approach, the process description, and the cost model's development. The object of study was an experimental WAAM machine developed at NOVA School of Science and Technology, and the functional unit was a hollow stainless steel AISI316LSI cube of approximately 7x7x7 cm. The data collection process included the compilation of secondary data available in public websites, but also primary data was collected through unstructured interviews with researchers who developed and worked with the WAAM machine. The model was validated, and the factors influencing the cost were identified.

It was possible to determine that the production of 500 cubes has a total cost of 259.95€ per piece. The WAAM process and the surface finishing process and substrate removal represent 84% of the total cost. The main factors that influence the total cost of the process are the acquisition cost of the machines for the production and parts finishing, the cost of the tools, namely the cutters, and the production overheads.

Key words: Wire and Arc Additive Manufacturing, Life Cycle Cost, Process-Based Cost Model

RESUMO

Um dos principais critérios para a avaliação de uma nova tecnologia ou produto, na engenharia, é a sua viabilidade económica. Esta, só pode ser estudada através da identificação dos custos inerentes ao processo ou produto. No âmbito do projeto Smart WAAM, que pretende estudar a utilização da tecnologia fabrico aditivo usando fio consumível e arco elétrico (WAAM) para criar, reparar e expandir a vida útil de grandes componentes industriais, foi necessário desenvolver um modelo de custos que permita estudar a viabilidade económica da utilização desta tecnologia.

O principal objetivo desta dissertação é o desenvolvimento de um modelo de custo para a tecnologia WAAM, considerando uma perspetiva do ciclo de vida do produto. Para esta finalidade, foi necessário desenvolver um modelo que permita estimar os custos da tecnologia WAAM, assim como os principais fatores que influenciam o custo.

Foi desenvolvido um modelo de custo baseado no processo, pois permite analisar os custos das diferentes fases do ciclo de vida do produto, bem como fazer estimativas dos custos de produção. Inicialmente o estudo consistiu na definição do objetivo e do âmbito, utilizando uma abordagem berço ao portão, a descrição do processo e o desenvolvimento do modelo de custo. O objeto de estudo foi um equipamento experimental desenvolvido na NOVA School of Science and Technology e a unidade de análise foi um cubo oco de aço inoxidável AISI316LSI com aproximadamente 7x7x7 cm. Foram recolhidos dados secundários (por exemplo preços de energia e matéria-prima) e dados primários recorrendo a entrevistas não estruturadas a investigadores que desenvolveram e trabalham com o equipamento. Por fim, o modelo foi validado e foram identificados quais os fatores que mais influenciam o custo.

Foi possível determinar que a produção de 500 cubos, tem o custo total de 259.95 € por peça. O processo WAAM e o processo de acabamento e remoção do substrato representam 84% do custo total. Os principais fatores que influenciam o custo total do processo são: o custo de aquisição das máquinas de produção e acabamento das peças, o custo das ferramentas, nomeadamente as fresas, e as despesas gerais de produção.

Palavras-Chave: Fabrico Aditivo usando Fio Consumível e Arco Elétrico, Análise Económica de Ciclo de Vida, Modelo de Custos Baseado no Processo

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Acronyms

C_0: machine-specific coefficient

C_1: machine-specific coefficient

P_{stb}^{M}: power demand of the machine tool in stand-by mode

t_s^M: start-up, set up, workpiece clamping/unloading time

$\mathrm{SEC_i^M}$: specific energy consumption during cutting

$\mathrm{C^{Machining}}$: machining total cost

$\mathrm{E_{MT}}$: electrical energy consumption of the machine tool

$\mathrm{t_{c_i}}$: cutting time (h) per tool

T_i: tool life (h) per tool

$\mathrm{q_L}$: consumption rate of the cutting fluid (kg/h)

$\mathrm{m_c}$: mass of the material that has to be removed

t_{tc}: tool change time

t_c: cutting time

T: tool life

C_{MT}: indirect cost rate for machining

C_{MO}^{M}: labour charge rate for machining

t_{MT}: total machining time

α: fraction of time of attendance of machine operator

C_{EE}: cost of electric energy

C_{tool}: cost of cutting tool

$\mathrm{C_{lub}}$: cost of the cutting fluid

$\mathrm{C^{WAAM}}$: WAAM total cost

$\mathrm{q_G}$: consumption rate of the shielding gas (l/h)

$\mathrm{C_W}$: indirect cost rate for the WAAM system

$\mathrm{C_{MO}}^{\mathrm{W}}$: labour charge rate for the WAAM system

$\mathrm{t_{WT}}$: total time for the WAAM process

β: fraction of time of attendance of the WAAM operator

C_{EE}: cost of electric energy

${P_{stb}}^{W}$: cost of cutting tool

${t_s}^{W}$: cost of the cutting fluid

SEC^{W}: specific energy consumption during deposition

m_{wire} : mass of the (wire) material that has to be deposited

t_{dw}: dwell time

C_{gas}: cost of the shielding gas

t_d: deposition time

r : opportunity cost of capital

n : machine

Abbreviations

AM: additive manufacturing

WAAM: wire and arc additive manufacturing

HF-WAAM: hot-forging wire and arc additive manufacturing

LCA: life cycle assessment

LCC: life cycle cost

PBCM: process-based cost model

CNC: computerised numerical control

SEC: specific energy consumption during cutting

MRR: material removal rate

1. INTRODUCTION

The first chapter begins with the context and motivation for conducting the study, followed by the problems and objectives. Then, the approach and contributions will be presented and, finally, the document organisation.

1.1. Context and Motivation

Additive manufacturing (AM) or 3D printing can be defined as the technology that produces a 3D figure by using deposition, solidification, or fusing methods (Bekker & Verlinden, 2018). AM is a disruptive technology with a broader product customization range when compared to traditional methods. Not only this, but it also offers the possibility to manufacture a product in one phase, decreasing the lead-time and minimizing material and resource waste while also diminishing the supply chain steps (Bekker & Verlinden, 2018).

Huang et al. (2013) points out that the benefits of AM compared to traditional processes can be summarized as follows:

- Material efficiency: Due to the layer upon layer production system, it is possible to improve the efficiency of the raw material usage when compared with traditional methods that have a higher rate of waste material.
- Resource efficiency: AM methods do not need as many additional resources as traditional technologies.
- Part flexibility: AM enables designing a complex part without focusing on assembly or the number of parts.
- Production flexibility: Due to the reduction of bottlenecks, setup times and number of parts, AM enables the possibility of producing smaller batches with fewer costs than traditional methods.

There are several technologies or AM processes (Huang et al., 2013), among them wire and arc additive manufacturing (WAAM) is a technology that prints a piece or product by wielding layer upon layer (Bekker & Verlinden, 2018). In contrast to other AM technologies, WAAM allows to build medium to large pieces due to the use of robotics arms and the high deposition rate (Ding et al., 2015). However, compared with other AM technologies, WAAM products have a problem with the finished surface, which causes a need to use a hybrid production with machining to remove the extra material corresponding to the layered surface (Bekker & Verlinden, 2018). WAAM is a technology that has increased industrial interest due to the ability to build medium-to-large products with high deposition rates. However, more studies are needed to understand the economic viability of this technology (Priarone et al., 2020).

To develop this technology the project smart WAAM was sponsored by EIT raw materials and the European Union. This project is led by NOVA School of Science and Technology has as partners the French National Centre for Scientific Research, Norwegian University of Science and Technology, OCAS NV, and the Université de Bordeaux. The scope of the smart WAAM is: the microstructural engineering and integration of non-destructive testing methodologies. The objective is to improve the lifetime of industrial components through the implementation of in-line multiparametric non-destructive testing considering a life cycle approach and contribution to the economic, social and environmental performance of the industrial system.

1.2. Problem and Objectives

In the smart WAAM project, it was necessary to study the cost of WAAM technology. Cost estimation is one of the essential engineering tools because it allows analysing the economic viability of a given process or product. It will enable to understand how a process can or cannot be implemented. Although this technology has been the subject of study in recent years, it is still understudied. To fulfil this research gap, in this thesis a life cycle cost model was developed to evaluate the economic viability of a WAAM machine developed at the Nova School of Science and Technology of the Universidade Nova de Lisboa (NOVA SST).

A process-based cost model (PBCM) of the WAAM machine was developed to understand the costs related to the technology implementation, considering all associated processes, as it is a hybrid production model. This study intends is to contribute with a model that estimates the costs of implementing this WAAM technology. The model can be used as a part of an extended tool to enable a more informed decision making at an early stage.

In this way, a process-based cost model (PBCM) for a product manufactured by NOVA SST WAAM machine was developed. This model was applied to the production of 500 stainless steel AISI316LSI hollow cubes with 7x7x7 cm in order to identify the main driver costs, as well as the effect that their variation may cause on the implementation costs of WAAM technology.

1.3. Approach and Contributions

At first, bibliographical research was done in order to characterize and understand the existing information about AM, particularly WAAM. This information also served as a basis for the subsequent steps. Next, it was described how a life cycle assessment is carried out to substantiate the necessary methodology. Finally, from the literature review, two works (Priarone et al. (2019) and Priarone et al. (2020)) related to life cycle cost models for WAAM were selected for a detailed analysis. Moreover, two cost models (Priarone et al. (2019) and Cunningham et al. (2017)) for WAAM available in the literature were analysed and compared.

After the elaboration of the state of the art, the WAAM machine to be studied was characterized, as well as the rationale for its existence. Next, the life cycle cost model was developed with the following steps:

- Goal definition.
- Scope definition: In this stage, the WAAM machine was characterised, as well as the process to be analysed and the cost model to be used was developed
- Life cycle Inventory: Here, the data necessary to carry out the cost estimative was obtained from interviews with researchers working at NOVA SST and from public websites with current market prices.
- Results and discussion: At this stage, the model was validated, and the sensitivity of the inputs was analysed. Finally, costs were discussed, and the main cost drivers of the analysed production process were identified.

At the end of the life cycle cost model development, a final analysis was made in order to conclude the study.

1.4. Structure

This thesis is organised into four chapters. The first chapter is the present one, where an introduction of the thesis is made. The other chapters are described below:

- **2 State of Art:** This chapter conducted a study and literature review on AM, followed by a more in-depth literature review on WAAM technology. Another object of study was life cycle assessment, where it was described and presented how to perform it. Finally, two life cycle cost models and two cost models were analysed. At last, a comparison between the two cost models was made in order to compare the two approaches.
- **3 Life Cycle Cost Model:** This chapter initially established the methodology to be adopted for the elaboration of the model, as well as the scenario to be analysed. Next, the context was described, and the causes of the development of the hot forging WAAM technology were presented. Finally, the life cycle cost model was executed, where the machine was characterised, the cost model was developed and applied, and at the end, the results were analysed.
- **4 Conclusion:** In this chapter, the last considerations are carried out in order to conclude the study.

2.
State of Art

2.1. Additive Manufacturing

Over the last decades, there has been a significant development in AM technologies. AM or 3D printing is a technology that consists of producing a 3D figure by using deposition, solidification, or fusing methods to build it (Bekker & Verlinden, 2018). These technologies have a massive potential because, while traditional technologies use subtractive processes to make an object, AM technologies build products layer by layer based on a 3D model data (ASTM, 2021). These methods enable the flexibility and ability to produce complex components with less material consumption (Priarone et al., 2019).

AM technology is composed of different types of processes that build products in different ways. Some processes use inkjet-type printing heads to spray binder or solvent into powdered ceramics or polymer. While others use laser or electron beams to melt or sinter metal or plastic powder together (Huang et al., 2013). Huang et al. (2013) enunciated some of the most used AM technologies.

- Fused deposition modelling;
- Inkjet printing;
- Laminated object manufacturing;
- Laser engineered net shaping;
- Stereolithography;
- Selective laser sintering;
- Electron Beam Melting;
- Digital light processing.

AM gives enormous opportunities for the industry and society. It could be the next step toward a revolution in the industry. Huang et al. (2013) identify the three top benefits of AM to society as the following:

- Healthcare products customized to the needs of individual consumers which is expected to improve population wellbeing significantly;
- Reduced raw material usage and energy consumption, which is a key contribution to environmental sustainability;

- On-demand manufacturing, which presents an opportunity to reconfigure the manufacturing supply chain to bring cheaper products to consumers faster while utilizing fewer resources.

AM is a disruptive technology that gives an ample opportunity to the industry since it offers a large customization of products, the possibility to produce a product in one phase, decrease the lead time, reduce material and resources waste, and diminish the supply chain steps (Bekker & Verlinden, 2018).

Design innovation is another opportunity linked to the utilization of AM technologies since it enables the production of complex objects without the necessity of using several processes. This allows designers to focus on the product design instead of focusing on design for manufacturing and design for assembly. This new way of looking at design allows the product's manufacture near the clients, which will reduce the supply chain since objects will have fewer components. This will directly impact warehouses, transportation, and packaging, which will not be needed like they are now (Huang et al., 2013).

The advantages of AM compared to traditional processes can be summarized as Huang et al. (2013) proposed:

- Material efficiency: While subtractive methods have a high rate of wasted material, AM, due to the layer upon layer production system, has a low rate of wasted material and can use the leftover material to produce new products.
- Resource efficiency: AM methods do not need additional resources like traditional technologies do (ex., cutting tools).
- Part flexibility: As mentioned above, AM permits designers not to focus on the manufacturing or assembly processes, enabling the production of complex products with less parts.
- Production flexibility: The AM machines do not need set up, enabling the efficient production of small batches. This technology reduces the production bottlenecks due to its diminishing of pieces. Another reason is the fact that the product quality only depends on the process and not on the operator, like traditional methods.

AM is a disruptive technology that needs to be developed since it has some disadvantages like Huang et al. (2013) proposed:

- Size limitations: In most cases of AM technologies, the size of the printer represents a constraint to the dimensions of the product to be built. Another problem is the lack of strength of materials like liquid polymers and resin’s powders that do not permit the production of bigger pieces. Another problem is the reduced deposition rate, which would imply a significant amount of time to produce a large piece.
- Imperfections: Most of the products produced by AM methods require a finishing surface step, due to the layer-by-layer method, most of the time, the surface seems to be unfinished.

- Cost: The AM equipment is costly, but over the following years, due to the growth of this market, it seems probable that the costs will decrease.

2.2. WAAM

WAAM is a technology that uses a robotic arm to print a piece or product by wielding layer upon layer (Bekker & Verlinden, 2018). This method is based on an energy deposition on a metal wire (raw material), when the metal is melted, it is deposited layer-by-layer, by a robotic arm, on a substrate to build a component or product (Priarone et al., 2019).

In contrast to other AM technologies, WAAM, theoretically, allows to build medium to large pieces with a high deposition rate (Ding et al., 2015). This technology presents novel opportunities in fabrication, repair, and refurbishment of products (Kokare et al., 2022). Another important point is that WAAM has a sustainability potential due the lesser material removal and shorter lead times, when compared to traditional methods (Seow et al., 2020). However, WAAM technology has a problem with the finishing step caused by the layered surface finish, and this requires a machining step to remove the excess material (Bekker & Verlinden, 2018). A good example was the study where Bekker & Verlinden (2018) proposed a hybrid approach of WAAM and Computerized Numerical Control (CNC) milling for building a complex part with low material utilization. In this case, the outline was produced with extra thickness to be milled to guarantee a suitable surface finishing. Nevertheless, with the development of this technology and the consequent improvement of parameters, equipment and printing strategies, the problem related to the layered surface finish will be minimized over time (Bekker & Verlinden, 2018).

Priarone et al. (2020) pointed out that a limited number of studies have compared WAAM with other technologies regarding environmental and economic competitiveness. So, the decision on what technology to use should be made by a comparison of the WAAM technology with traditional technologies. This comparison needs to consider the material characteristics too. Material properties like isotropy and tensile strength may change with the utilized material, like the tolerance and geometric possibilities (Bekker & Verlinden, 2018). However, investigations about the properties of WAAM products have shown promising results. In the case of titanium, the ductility is similar to extruded titanium, and the strength is only 10% less than extruded products. In the case of fatigue life of titanium produced by WAAM, it exceeded the titanium products produced by extrusion in most tested specimens (Wang et al., 2013).

WAAM technology typically can be divided into three types, depending on the heating source it uses (Wu et al., 2018): Gas Metal Arc Welding (GMAW)-based, Gas Tungsten Arc Welding (GTAW)-based, and Plasma Arc Welding (PAW)-based. In table 2-1 the main characteristics of each type of WAAM are described.

Figure 2-1 shows a WAAM process based on gas metal arc welding. This approach results in a metal deposition as an electric wire by creating an arc with DC power. During the process, an inert gas is added to shield oxygen and pollutants from the weld pool (Bekker & Verlinden, 2018).

Table 2-1 Comparison of various WAAM techniques. Adapted from Wu et al. (2018)

WAAM	Energy source	Features
GTAW-based	GTAW	Non-consumable electrode; Separate wire feed process; Typical deposition rate: 1-2 kg/hour; Wire and torch rotation are needed;
GMAW-based	GMAW	Consumable wire electrode; Typical deposition rate 3-4 kg/hour; Poor arc stability, spatter;
	Cold metal transfer (CMT)	Reciprocating consumable wire electrode; Typical deposition rate: 2-3 kg/hour; Low heat input process with zero spatter, high process tolerance;
	Tandem GMAW	Two consumable wires electrodes; Typical deposition: 6-8 kg/hour; Easy mixing to control composition for intermetallic materials manufacturing;
PAW-based	Plasma	Non-consumable electrode; Separate wire feed process; Typical deposition rate 2-4 kg/hour; Wire and torch rotation are needed;

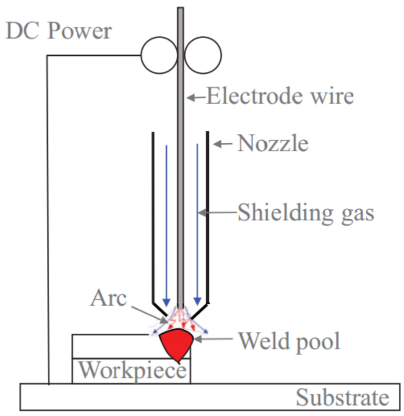

Figure 2-1 Schematic of gas metal arc welding. Adapted from Bekker & Verlinden (2018)

WAAM techniques use metals that are commercially available in the form of wires. These wires can be of various materials. Wu et al. (2018) state that the most used materials to produce WAAM products are:

- Titanium alloys: thanks to the high strength-to-weight ratio and high cost of titanium alloys, the aerospace industry has widely studied the application of AM in aerospace components. The utilization of WAAM to produce titanium components has enormous business potential, particularly for large-sized components with complex structures.

- Aluminium alloys: although there have been several successful trials for manufacturing aluminium components, there are some problems. Firstly, the production of this material by WAAM is only suitable for large and complex thin-walled structures since the cost of producing small and simple parts by traditional methods is lower. On the other hand, some aluminium series, such as AL 7xxx and AL 6xxx, are difficult to cast due to turbulent melt pools and weld defects, which occur during the deposition phase. Finally, the mechanical properties of the components produced are inferior to those manufactured by traditional methods.
- Nickel-based superalloys: this is the second most studied material to apply to WAAM due to their high strength and outstanding oxidation resistance at high temperatures. Nickel-based superalloys are widely used in aerospace, aeronautical, chemical, petrochemical, and marine industries.
- Other metals: other metals have been studied to produce WAAM components, such as magnesium alloy AZ31 for automotive applications, Fe/Al intermetallic compounds, Al/Ti compounds, bimetallic steel/nickel, and steel/bronze parts for the aeronautic industry. To produce intermetallic components with accurate pre-designed composition is still a challenge for WAAM.

2.2.1. Strengths and Limitations of WAAM

WAAM is a technology with advantages when compared to other technologies, although there are a limited number of studies on this technology (Priarone et al., 2020).

One of the strengths of AM and WAAM is the ability to build lightweight structures like the sofa presented in figure 2-2, this could not be produced by CNC casting or other traditional methods (Bekker & Verlinden, 2018).

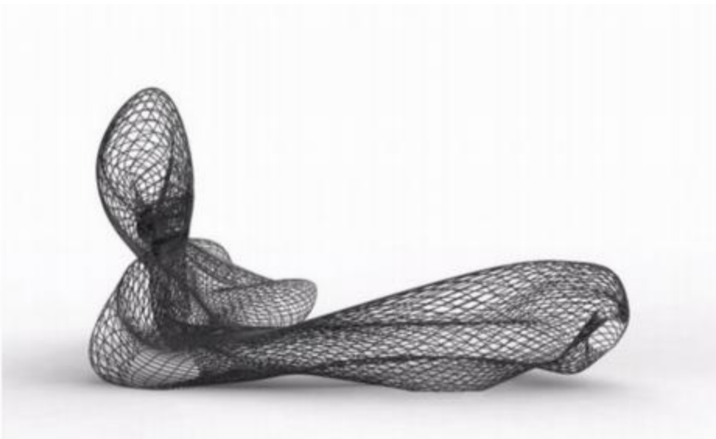

Figure 2-2 Dragon Bench sofa, made in stainless steel by WAAM. Retrieved from Bekker & Verlinden (2018)

Another strength of WAAM technology is the high material efficiency and freedom of shape, which decreases material consumption (Bekker & Verlinden, 2018). This ability to make the process more efficient reduces the buy-to-fly ratio for high-cost materials, such as titanium alloys and nickel alloys. On the other hand, it also reduces production times and costs and increases the productivity of design and prototyping (Li et al., 2019).

A further limitation of WAAM is the reduced lifespan of the manufactured products. This is due to the use of extremely high heat sources that cause a reduction in the effective fatigue life and tensile strength (Li et al., 2019).

One of the advantages of WAAM, when compared to other AM technologies and traditional methods, is the ability to produce large components that theoretically could be of any size (Bekker & Verlinden, 2018). On the other hand, one of the limitations of WAAM is the low dimensional accuracy and a reduced feature resolution (Priarone et al., 2019). As it happens with tensile strength, the low dimensional accuracy is due to the use of extremely high heat sources, which cause residual stress and distortion (Li et al., 2019). However, Colegrove et al. (2013) developed a method of reducing these effects by using two rollers, a profile roller and a slotted roller, which reduced surface roughness and distortion, with the slotted roller being more effective.

Priarone et al. (2019) studied the comparisons between two methods: a standard milling process and a combination of WAAM and milling. This study allowed to make a comparison while the solid to cavity rate varied, this ratio is defined as the ratio between the mass of the final piece and the mass of the product without a cavity. The conclusion was that when the ratio increases, the WAAM technology turns into a less efficient option.

Due to the high temperatures used to melt the wire metal during the WAAM process, it is necessary to pay attention to the cooling rate, as well as the existence of residual stress. This leads to a limitation for WAAM technology, as it cannot deliver finished products, which have to be post-processed to obtain the desired shape and size (Singh et al., 2021). A summary of the strengths and limitations found in the literature are refereed in table 2-2.

Table 2-2 Strengths and limitations of WAAM

Strengths	Limitations
Ability to build lightweight structures	Decrease in the lifetime of the metal components
Raw materials efficiency	Low dimensional accuracy
Produce parts of any size	Low efficiency for high solid-to-cavity ratios
Freedom of shape	Need for post-processing
High deposition rate	

2.3. Life Cycle Cost (LCC)

Although this thesis's objective is to develop a life cycle cost model, in appendix 1 an introduction to LCA is made to better understand the methodology. In recent decades, the research based on the life cycle assessment has been growing, as well as the scientific publications in this area. Thus, life cycle assessment is a technique to analyse all the life cycle of a process, product, or system, which are: raw materials, design, material preparation, production, post-processing, use, maintenance and end of life (Ribeiro et al., 2020). This method consists of 4 steps: definition of the goal and scope, inventory of the materials and resource flows, assessing the environmental/social impact or cost of the system and interpretation of the results (Bekker & Verlinden, 2018).

When a disruptive technology is being studied, it is necessary to analyse its cost-effectiveness compared with traditional concurrent methods. This necessity happens due to the role that cost has as a factor in the decision making to analyse the economic viability of products (Ribeiro et al., 2020)

2.3.1. Goal Definition

The objective of a life cycle cost (LCC) is to build a methodology to track the economic viability of a product manufactured using WAAM technology. To achieve the study's goal, an existing model, either a single model or a combination of several, can be used to calculate all costs. The life cycle may involve all phases from raw material to end-of-life, or it may focus on a smaller number of life phases, like a cradle-to-gate approach. The cradle-to-gate approach is more used in comparative studies when two similar products produced with different technologies are evaluated since, depending on the technology used, there are analogous phases, such as obtaining the raw material, use, or maintenance.

In the case of a LCC that studies products manufactured by WAAM technology, the motivation is usually related to the fact that WAAM is a recent and disruptive technology since it is an additive technology that allows the construction of products from medium to large sizes, but it has some limitations like the poor finish surface, that usually needs machining processes after WAAM. This leads to the necessity to compare this production approach with the traditional ones. Another complementary aspect is that it is a technology whose economic viability is not yet widely studied, thus requiring further investigations.

Another important point is the need to explicitly state the type of production used, as this can impact the results since an integrated approach does not lead to the same results as a single approach. In the case of the study done by Priarone et al. (2020), a WAAM based approach was used, with the substrate done by forming and machining, to compare it with a traditional machining technique. In the case of the work done by Priarone et al. (2019), a WAAM based approach was used with the substrate manufactured by traditional methods to compare with a traditional method. In these two examples, it was also necessary to mention that they were comparative studies. In the studied developed by Kokare et al. (2022), it was proposed a digital platform were the LCA and LCC can be obtain for products manufactured by WAAM. Once again it is stated the kind of production that is used, being a WAAM process with post processing machining.

2.3.2. Scope Definition

The first step of the scope definition is the description of the product or products to be studied, as well as the type of metal to be used and the WAAM machine that will produce the product, and if it is a comparative study, it must enunciate the type of traditional process that will serve as a comparison. For example, in Priarone et al. (2020), a comparative study is proposed to produce three products:

- a cantilever beam made with the ER70s-6 steel, whose standard process is machined from billet,
- an aerospace bracket made with Ti-6Al-4V titanium, whose process is machined from forging,
- and an aerospace frame with the AA2319 aluminium, whose traditional process is machined from billet.

For those comparison Priarone et al. (2020) used two different types of WAAM configurations. A configuration was used for the first two products that rely on plasma-arc power sources. The last one used a setup that relies on Cold Metal Transfer as a deposition process.

One of the fundamental points of the scope definition is the choice of the functional unit. Usually, in LCCs that study WAAM technology, the functional unit is the production of a single part. Another important point is the definition of productivity and economic metrics, usually considered production time and cost.

Another critical step of the scope definition is the characterisation of the study boundaries. This step depends on the life cycle model chosen to perform the research. In the case of the two works analysed here, a cradle-to-gate approach is followed, and therefore the boundaries include the production of raw materials, the pre-manufacturing phases to produce the incoming feedstock materials and all the manufacturing steps leading to the production of a finished product.

After characterising the study boundaries, it is necessary to draw up a diagram representing the unit processes to be studied and their respective elementary flows. In the study from Priarone et al. (2019), the unit processes are: raw material production, hot rolling for the workpiece and the material that will feed the WAAM process, wire drawing, substrate machining, WAAM process, and finish machining. These processes can be observed in the diagram of unit processes pictured in figure 2-3, where the elementary flows between each unit process are also displayed. Since their study has an economic and environmental analysis, the energy flows and emissions are also represented. In the case of the works Kokare et al. (2022) and Kokare et al. (2022) the production system boundaries were Identified, being study only the production phase.

In the study by Priarone et al. (2020), a diagram was drawn up, which can be seen in figure 2-4. There are similarities with the diagram represented in figure 2-3. The main difference is the addition of the unit processes and their elementary flows, that are related to the traditional process to be compared. In the case of the WAAM process, the unit processes are raw material production, wire production, substrate production, WAAM and finish machining. The unit processes of the traditional process are raw material production, working piece production and rough and finish machining.

The elaboration of diagrams such as the ones illustrated in Figure 2-3 and Figure 2-4 is very important because it allows the conception of the production system. This step is beneficial for the life cycle inventory phase. It provides a better understanding of the production system, the resource flows that occur during the production of WAAM products, and the costs related to each unit process. In this way, it will be easier to identify the data needed to carry out the study in the life cycle inventory phase.

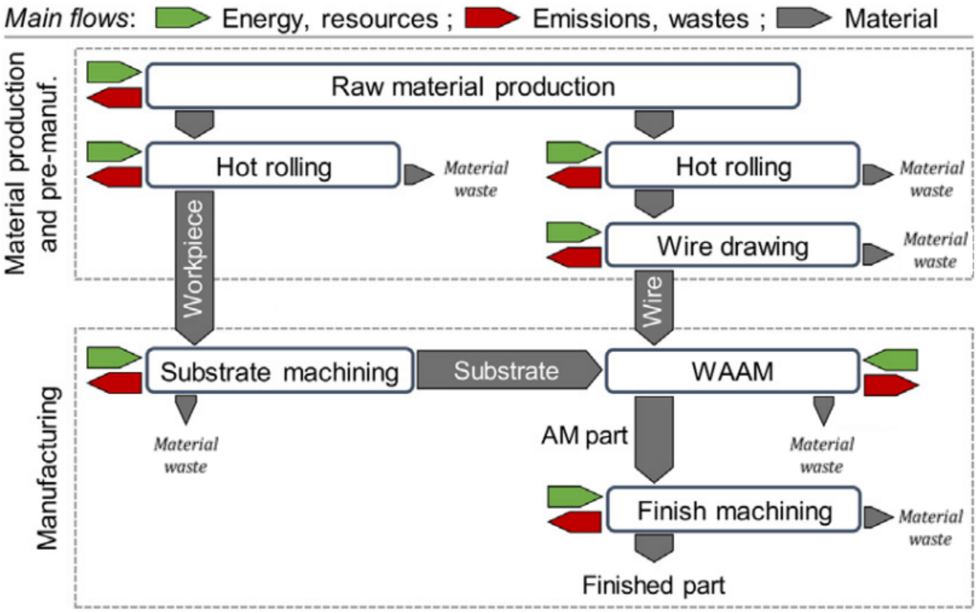

Figure 2-3 Diagram of unit processes. Adapted from Priarone et al. (2019)

The last step in the scope definition of the LCC is the presentation of the cost model used to carry out the study. This step is very important as it is directly related to the life cycle inventory and to the discussion of results. Two different cost models are presented below, used to calculate the costs associated with the production of one or several WAAM products.

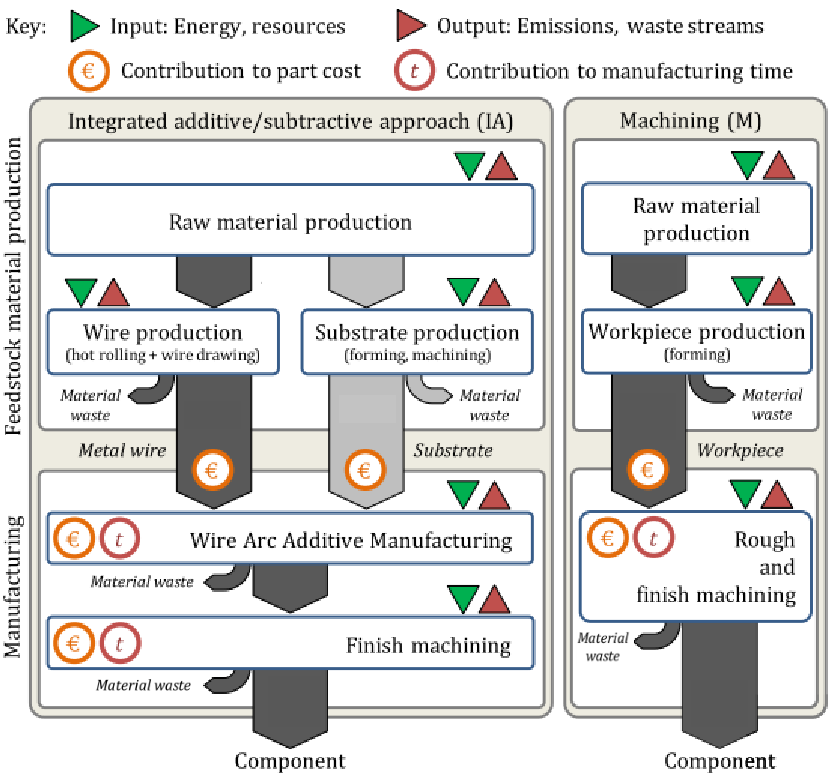

Figure 2-4 Diagram of unit processes. Adapted from Priarone et al. (2020)

In the study from Priarone et al. (2019), two cost models were proposed, one for each process unit, namely the substrate and finish machining and the WAAM process. For this, several types of costs were considered, for the machining unit process, indirect costs were considered, such as equipment depreciation costs and production and administration overheads. The labour costs associated with the production and the direct costs, such as electric power and cutting tools, were also considered. To obtain the total machining time, the start-up time, set up time, workpiece clamping/unloading time, the cutting time, and the time for the tool changes were considered.

To calculate the energy consumption of the substrate machining and finish machining processes, the model proposed by Kara & Li (2011) was used, where it is presented a model of unit process energy that correlates the specific energy consumption with the material removal rate. This correlation is shown in equation 1. The electrical energy consumption of the machine tool during the idle, cutting and tool change operational modes is presented in equation 2. The machining costs were calculated based on equation 3.

$$SEC = C_0 + \frac{C_1}{MRR} \qquad (1)$$

Where:
SEC: specific energy consumption during cutting (kWh/kg);
C_0: machine-specific coefficient;
C_1: machine-specific coefficient;
MRR: material removal rate.

$$E_{MT} = P_{stb}^{M} \cdot t_s^{M} + \sum_{i=1}^{n} \left({SEC_i}^{W} \cdot m_{c_i} + {P_{stb}}^{M} \cdot t_{tc_i} \cdot \frac{t_{c_i}}{T_i} \right) \qquad (2)$$

Where:
E_{MT}: electrical energy consumption of the machine tool;
P_{stb}^{M}: power demand of the machine tool in stand-by mode (kW);
t_s^{M}: start-up, set up, workpiece clamping/unloading time (h);
SEC_i^{M}: specific energy consumption during cutting (kWh/kg);
m_c: mass of the material that has to be removed (kg);
t_{tc}: tool change time (h);
t_c: cutting time (h);
T: tool life (h).

$$C^{Machining} = C_{MT} \cdot t_{MT} + {C_{MO}}^{M} \cdot \alpha \cdot t_{MT} + C_{EE} \cdot E_{MT} + \sum_{i=1}^{n} \left(C_{tool_i} \cdot \frac{t_{c_i}}{T_i} \right) + C_{lub} \cdot q_L \cdot t_c \qquad (3)$$

Where:
$C^{Machining}$: machining total cost;
E_{MT}: electrical energy consumption of the machine tool;
t_{c_i}: cutting time (h) per tool;
T: tool life (h) per tool;
q_L: consumption rate of the cutting fluid (kg/h);
C_{MT}: indirect cost rate for machining (€/h);
C_{MO}^{M}: labour charge rate for machining (€/h);
t_{MT}: total machining time (h);

α: fraction of time of attendance of machine operator ($\alpha \leq 1$);
C_{EE}: cost of electric energy (€/kWh);
C_{tool}: cost of cutting tool (€);
C_{lub}: cost of the cutting fluid (€/kg).

Still, Priarone et al. (2019) used a model similar to equation 3, where the same system of boundaries is used to calculate the WAAM product's costs. This model also considered indirect costs, the costs associated with energy consumption, for which idle time, deposition time and dwell time were considered. The dwell time should be chosen carefully to avoid the collapse or re-melting of the deposited material. To obtain the costs associated with producing this type of product, the cost of shielding gas was also considered. This model is represented in equation 4.

$$C^{WAAM} = C_W \cdot t_{WT} + {C_{MO}}^W \cdot \beta \cdot t_{WT} + C_{EE} \cdot \left({P_{stb}}^W \cdot {t_s}^W + SEC^W \cdot m_{wire} + {P_{stb}}^W \cdot t_{dw}\right) + C_{gas} \cdot q_G \cdot t_d \quad (4)$$

Where:
C^{WAAM}: WAAM total cost;
q_G: consumption rate of the shielding gas (l/h);
C_W: indirect cost rate for the WAAM system (€/h);
${C_{MO}}^W$: labour charge rate for the WAAM system (€/h);
t_{WT}: total time for the WAAM process (h);
β: fraction of time of attendance of the WAAM operator ($\beta \leq 1$);
C_{EE}: cost of electric energy (€/kWh);
${P_{stb}}^W$: cost of cutting tool (€);
${t_s}^W$: cost of the cutting fluid (€/kg).
SEC^W: specific energy consumption during deposition (kWh/ kg);
m_{wire} : mass of the (wire) material that has to be deposited (kg);
t_{dw}: dwell time (h);
C_{gas}: cost of the shielding gas (€/l);
t_d: deposition time (h).

Although it is not a LCC study, Cunningham et al. (2017) propose a cost model and sensitivity analysis for WAAM technology. This cost model consists of a time-based activity-based costing approach. For the elaboration of this model, the activities necessary to produce WAAM products were considered, which are: substrate preparation, set up, deposition, cooling, rolling, heat treatment, machining, substrate removal and inspection. The activities such as wire deposition, cooling and rolling are repeated cyclically for each deposited layer. The costs of the activity rates were based on the sum of direct and indirect costs for each activity, however, costs associated with sales expenses, such as administration, management, and facility, were excluded from the model. This study was done on two different products produced using WAAM technology compared to two powder-based metal AM processes, which are Electron Beam Melting and Direct Melting Laser Sintering and conventional CNC machining.

To implement the cost model proposed by Cunningham et al. (2017), machine data was defined as fixed operational parameters between setups, user inputs were defined as variables that change between setups, indirect costs were generated mainly from machine data, and direct costs were generated from the information presented above and based on market prices.

To carry out Cunningham et al. (2017) study, data was generated both from material removal rates, such as substrate preparation, as from software Autodesk, which was used to generate the tool paths of deposition for both products. Data was also obtained from calculations, such as active deposition and motion times, and from literature, such as set up, rolling and cooling times, which limited the study since the data was based on the use of Titanium Alloy Ti6A14V, and therefore it was necessary to consider the use of this material. For this study, some assumptions were made to simplify the model. One of these simplifications was related to indirect costs, in which estimations were made based on labour and machine overheads. A 46% capacity utilisation at 16 operational hours for 252 days was assumed to calculate the indirect depreciation costs. The labour cost was assumed as an indirect cost, and it was considered that the WAAM machine required constant observation. The inspection costs were not considered due to the inexistence of similar data for other products.

For the WAAM processes, a summary metrics approach developed by Baumers et al. (2012) was used to provide an equivalent cost per kilogram of product. Naturally, the value was updated to 2017, which is the date of Cunningham et al. (2017) article. The comparison was made for WAAM BTF ratios of 5, 10, 15, and 20.

To find out which were the key cost drivers in the model developed by Cunningham et al. (2017), a sensitivity analysis, more specifically a One-Factor-at-a-Time sensitivity analysis approach, was used. For this, the maximum and minimum values for the machine and user inputs were considered, considering realistic industry values and price fluctuations. Industry indexes were used to obtain average values for the variables and rates. To calculate the sensitivity indices, equation 5 was used.

$$Sensitivity\ index = \frac{D_{max} - D_{min}}{D_{max}} \tag{5}$$

In the case of the study carried out by Priarone et al. (2020), the same cost model developed by Priarone et al. (2019) was used. This cost model considered the cost of consumables, production costs, including set up, work frame calibration, substrate preparation and part building, labour costs, delivery costs and costs related to overheads and facility charges. This cost model was used for both the WAAM process and the traditional process. As this study is a Life Cycle assessment, cost is one of the categories of the decision model developed.

2.3.3. Life Cycle Inventory

The objective of the life cycle inventory is to collect and compile data regarding each elementary flow of the processes required to produce WAAM products. In the case of a comparative study, it is necessary to collect and compile data regarding the elementary flows of the processes that will be compared to the WAAM technology. The first step is to clarify where the data used comes from. Usually, the data for the process to be studied (WAAM) is collected on an experimental basis, while the data for the processes used as comparisons are taken from databases. Although, according to Priarone et al. (2020), the data for the WAAM process was obtained from the Welding Engineering and Laser Processing Centre at Cranfield University, and the raw material production, pre-manufacturing phases, and machining data were collected from the Cambridge engineering selector database.

In the study carried out by Priarone et al. (2019), the first step was the case study explanation, where a product was produced with the combination of a substrate produced through machining and a top produced through WAAM technology. This process was compared with standard milling. One of the objectives of the study was to compare the two processes based on the solid to cavity ratio, which can be defined as the ratio between the final mass of the product and the mass that would be contained in the bounding volumetric envelope of the part itself (Campatelli et al., 2020). The data concerning the manufacturing processes were experimentally characterised, and the data concerning the materials production and the pre-manufacturing phases were collected from the literature.

The next phase of a life cycle inventory is the material production and pre-manufacturing characterisation. In the case of the work from Priarone et al. (2020), it was necessary to quantify the wastes. As such, it was considered a rate of 1.14 for wire drawing and 1.05 for hot rolling, this rate is the ratio between the material input and output. The WAAM process waste was quantified based on laboratory experiments, and the leading causes were in-process material vaporisation, small droplets of molten material and wire scraps. For the WAAM process, it was assumed a material utilization efficiency of 98%. The costs of feedstock materials were obtained based on market values, with a 15% range of variation. In the study by Priarone et al. (2019), the values used for the wastes were slightly different since the ratio between input and output for hot rolling was assumed to be 1.05, and 1.12 for wire drawing and the material losses for the WAAM process were neglected. The values used for the life cycle inventory of the WAAM unit process, and the machining unit process are listed in table 2-4 and table 2-5, respectively.

The last life cycle step characterises the WAAM unit and machining unit processes. In this phase, the values assumed for the model's realisation are inventoried. In the case of a LCC study, it is necessary to state the costs necessary to produce the product, the machine parameters, and the process-related consumption, such as energy consumption.

In the study of Priarone et al. (2019), the life cycle inventory of the unit process begins by identifying the machine that was used for the WAAM process, as well as the characterisation of the deposition, such as the wire diameter, the welding speed, the wire feed speed and the flow rate during deposition. The specific energy consumption was measured as well. The process, dwell time, start-up time, set up, and post-processing was considered. For the calculation of the indirect costs, it was assumed the methodology from (Baumers et al., 2012), for which it was considered the administrative and production costs, a machine depreciation of 8 years, an annual operation time of 5000 h/y and a maintenance and consumables cost of 6% of the machine cost, per year. For the cost of the WAAM machine, it was also considered the energy source and the robotised handling system. The shielding gas flow rate was measured. The annual (1616 working hours) labour cost was estimated, assuming that during set up and post-processing, the operators, are working and the existence of supervisors. A similar approach to the one mentioned above was taken in the life cycle inventory for the machining unit process. The specific electric energy was obtained through equation 1. The standby power and the idle time were considered to calculate the energy consumption. The parameters were chosen based on the recommendations of the supplier's catalogue. Due to economic and environmental feasibility, dry cutting conditions were chosen. The material removal rates for roughing and face milling, semi-finishing, and finishing operations were considered. The cost of the machine was evaluated, the indirect costs were estimated, and the purchase cost of the endmill was considered. The tool life was assumed for roughing, semi-finishing and finishing operations.

A similar methodology to the one used by Priarone et al. (2019) was followed in the Priarone et al. (2020) study. For the life cycle inventory for the WAAM unit process, average deposition rates and the specific electric energy were taken for aluminium, steel, and titanium and are listed in table 2-4.

The energy consumption associated with the movements was neglected, and to correct the electric energy demand to primary energy, a coefficient of 0.38 was used. The cost associated with tools was not considered since this is a per part study based on a series production. The WAAM process and auxiliary equipment's energy consumption and the shielding gas consumption were monitored during the productive and non-productive times. In the case of the life cycle inventory for the machining, the unit process times were estimated based on the material removal rates. The specific electric energy was presented for each process and for each material used regarding the energy consumption. The methodology used to identify the ranges of cost variation was the same presented in the study of Priarone et al. (2019).

Table 2-3 Data for life cycle inventory for the WAAM unit process. Retrieved from Priarone et al. (2020)

Data	Aluminium	Steel	Titanium
Average deposition rates	2,40 kg/h	0,94 kg/h	0,66 kg/h
Specific electric energy	63 MJ/kg	23.7 MJ/kg	33.4 MJ/kg

Table 2-4 Data for life cycle inventory of the WAAM unit process. Retrieved from Priarone et al. (2019)

WAAM	
Wire diameter	0,8 mm
Welding speed	300 mm/min
Wire feed speed	4,55 m/min
Flow rate	38.13 m3/s
Specific energy consumption	1.36 kWh/kg
Dwell time	100 s
Time for start-up, set up and post processing	30 min
Administrative and production cost	5.46 €/h
Indirect cost	8,61 €/h
WAAM machine cost	85 000 €
Shielding gas flow rate	14 l/min
Shielding gas cost	2,14 €/m3
Workpiece cost	0,50 €/kg
Wire cost	1,80 €/kg
Annual labour cost	35 000 €

Table 2-5 Data for life cycle inventory of the machining unit process. Retrieved from Priarone et al. (2019)

Machining	
C0	3,524
C1	2066
Standby power	2,2 kW
Idle time	15 min
Material removal rates for roughing and face milling	149.2 mm3/s
Material removal rates for semi-finishing	35.8 mm3/s
Material removal rates for finishing	6.0 mm3/s
Machine cost	200 000 €
Indirect cost	12,86 €/h
Endmill cost	20 €/tool
Roughing tool life	30 min
Semi-finishing tool life	45 min
Finishing tool life	45 min

2.3.4. **Results and Discussion**

In this phase, calculations are made to obtain the product's life cycle costs. In the case of a comparative study, the costs associated with the product or set of products produced by other means of production are also computed. These costs are then presented. At the discussion stage, the results and features are commented as well as the changes that they may cause, since they are correlated with the performance indicators, such as the process efficiency when changing the solid-to-cavity rate.

The results and discussion phase of the study carried out by Priarone et al. (2019) presented the energy consumption, production costs, and manufacturing times. These values are presented for the two approaches studied, considering the data reported in the life cycle inventory phase and using the cost and energy models presented in the scope definition phase. Next, some considerations about the results are exhibited. One of the considerations is the relationship between the efficiency of the process and the solid-to-cavity rate. Although the integrated approach is generally more time-consuming than the traditional approach, the solid-to-cavity rate increases the time consumption for the WAAM integrated process increases as well. This happens because there is a linear relationship between the time spent for the WAAM process and the increase of the material to be deposited when the deposition rate is fixed. Regarding costs, it should be noted that manufacturing expenses have the most weight in the total cost since the cost of feedstock material is low.

In the study conducted by Priarone et al. (2020), the results concerning the economic perspective were also presented. The aluminium frame was the product that presented a much lower cost for the WAAM approach when compared with the conventional approach. The production cost of the titanium bracket was slightly higher for the WAAM approach, and the manufactured steel beam through the WAAM approach had a much higher cost than the conventional one. In terms of efficiency, measured through production time, both approaches had similar values for aluminium frame and titanium bracket, but in the case of steel beam, the production time of the WAAM approach was much higher than the traditional one. In terms of the products' mechanical characteristics, yield strength and tensile strength were found to be slightly lower for the WAAM approach, and in some cases, it was verified a higher elongation at break values than the expected values for the parental materials.

2.3.5. **Conclusions**

The conclusions are the last stage of a LCC study, in which it is verified if the goal and scope were reached, and the conclusions of the study are presented. In the study conducted by Priarone et al. (2019), the conclusions state that the goal of developing a framework that can be used to assess and compare the performance of a WAAM based approach and machining has been achieved. It is also highlighted that the main factor considered for the study was the solid-to-cavity ratio. As this study also has an environmental component, it was concluded that the WAAM approach is favourable due to the efficient use of raw materials, however, it still presents higher costs and production times than the conventional methods. Finally, the fact that the breakeven point varies with the solid-to-cavity ratio proved the importance of having a decision tool for the production phase.

In the study carried out by Priarone et al. (2020), the purpose of comparing WAAM based additive/subtractive manufacturing approaches and machining was achieved. It was further noted that the cost and time of production depend on the component to be produced and the material to be used. This is due to the solid-to-cavity ratio's importance for the results. Finally, although the results obtained in this study are only valid for the conditions assumed, the model developed is useful as a decision support tool when considering environmental and economic factors.

In the work of Kokare et al. (2022) It was concluded that the product produced by WAAM was more economical to produce In batches of 4, being the cost of one piece 52.31 € and 18.45 € for a batch of 4 pieces. In another study it was possible to Identify the main cost drivers In the production of a specific component, which where In the first place labour cost and followed by the machine cost (Kokare et al., 2022)

2.4. **Cost Models a Comparative Analysis**

To better understand the similarities and differences in the existing WAAM cost models, table 2-6 shows the input data for the cost models proposed in the work of Priarone et al. (2019) and Cunningham et al. (2017).

It is clear that the Priarone et al. (2019) model does not analyse the same activities as Cunningham et al. (2017) model.

The difference between these two models happens because Cunningham et al. (2017) model is an activity-based cost model that focuses on the costs of all the activities involved in the production of WAAM products, considering the stages of heat treatment, substrate removal and inspection, which are not present in Priarone et al. (2019) model. It should be noted that the substrate removal stage is not considered because the substrate was produced through traditional methods in order to be a part of the final part, thus facilitating the process.

Another important fact is that Priarone et al. (2019) model lumps the substrate machining and finish machining stages with the same inputs to calculate the associated costs. This happens because both processes are based on machining to remove material. Because the costing methodologies for each process are different also means that the data used In the two models may be different, even if they are used to cost the same task. These differences are noticeable since, in Priarone et al. (2019) model, costs are calculated for each unit process, whereas in Cunningham et al. (2017) model, cost rates result from the sum of direct and indirect costs for each activity.

Another difference between the two models is the way of quantifying energy consumption. In Cunningham et al. (2017) model, energy consumption only appears in some activities, excluding WAAM, and appears as a rate. In Priarone et al. (2019) model, energy consumption is calculated and well described.

Table 2-6 Main cost model inputs

Activity	Input Data	Priarone et al. (2019)	Cunningham et al. (2017)
Substrate Preparation	Substrate size		X
	Substrate material		X
	Substrate mass	X	
	Substrate cost/kg	X	X
	Cutting tool cost	X	X
	Number of parts per build		X
	Cutting tool life	X	X
	Material Removal Rate		X
	Set up time	X	X
	Loading time	X	X
	Start-up, unloading time (h)	X	
	Total machining time (h)	X	
	Cost of electric energy (€/kWh)	X	
	Cost of the cutting fluid (s/kg)	X	
	Power demand of the machine tool in stand-by mode (kW)	X	
	Specific energy consumption during cutting (kWh/kg)	X	
	Mass of the material that has to be removed (kg)	X	
	Tool change time (h)	X	
	Cutting time (h)	X	
	Coolant flow rate and cost/litre		X
	CNC power rating		X
	Non-cutting motion time		X
WAAM deposition	Time for WAAM process (h)	X	
	Power demand of the WAAM system in stand-by mode (kW)	X	
	Time for start-up, set up and post-processing of WAAM (h)	X	
	Specific energy consumption during deposition (kWh/ kg)	X	
	Dwell time (h)	X	
	Autodesk motion and deposition tool paths		X
	Cooling and rolling time		X
	Wire mass	X	
	Wire cost/kg	X	X
	Inert gas cost/kg	X	X
	Travel speed		X
	Wire feed Speed	X	X
	Inert gas flow rate	X	X

This is due to the nature of the study where Priarone et al. (2019) model was proposed since energy consumption of the WAAM production process is also one of the factors studied in addition to process costs. This means that some of the inputs are not directly related to costs but are related to energy consumption, which in turn is needed to calculate the cost of the system. Some examples of these inputs are start-up, set up, workpiece clamping/unloading time used to compute energy consumption, specific energy consumption during cutting and mass of the material that must be removed, which serve the same purpose.

Table 2-6 Cost models comparative analysis. Cont.

Activity	Input Data	Priarone et al. (2019)	Cunningham et al. (2017)
Heat Treatment	Heat treatment time		X
	Ramping Time		X
	Furnace Power Rating		X
Machining	BTF Ratios		X
	Cutting tool life	X	X
	Material Removal Rate		X
	Set up time	X	X
	Loading time	X	X
	Start-up, unloading time (h)	X	
	Coolant flow rate		X
	CNC power rating		X
	Non-cutting motion time		X
	Total machining time (h)	X	
	Cost of electric energy (€/kWh)	X	
	Cost of the cutting fluid (s/kg)	X	
	Power demand of the machine tool in stand-by mode (kW)	X	
	Specific energy consumption during cutting (kWh/kg)	X	
	Mass of the material that has to be removed (kg)	X	
	Tool change time (h)	X	
	Cutting time (h)	X	
Substrate Removal	EDM time		X
	EDM wire consumption rate and cost/kg		X
	EDM feed rate		X
	EDM Power Rating		X
Inspection	Set up		X
	Inspection time		X
Indirect costs	Labour cost for each activity	X	X
	Machine Cost for each activity	X	X
	Labour input/ fraction of time of attendance of the machine operator for each activity	X	X
	Machine depreciation cost	X	X
	WAAM depreciation cost	X	X
	Maintenance	X	
	Production and administration overheads	X	

Although the material removal rate only appears as input for cost in Cunningham et al. (2017) model, it should be noted that this parameter was also used in Priarone et al. (2019) model to calculate the specific energy consumption during cutting.

There are some similarities in the calculation of indirect costs between the two models. However, it should be noted that different approaches were considered for the labour force since, in the case of the Priarone et al. (2019) model, the need for labour is considered as a fraction of the time that the worker was allocated to the machine, whereas in the case of Cunningham et al. (2017) model a conservative approach is followed, where it is considered

that the WAAM machine needs constant supervision. Another difference in the calculation of the indirect cost is that production and administration overheads and maintenance costs were considered in Priarone et al. (2019) model and were not used in Cunningham et al. (2017) model.

The use of different WAAM processes also influences the type of inputs that are used. This happens in the WAAM activity, where Cunningham et al. (2017) model considers cooling and rolling time. These times are associated with the cyclically cooling and rolling of the deposited material, improving the final product's mechanical characteristics. In the Priarone et al. (2019) model, this does not happen.

3.

WAAM Life Cycle Cost Model Development

3.1. WAAM Life Cycle Cost Model Proposal

After understanding the advantages that WAAM technology has on different industries, from aeronautic to the automotive industry, it is necessary to understand the economic viability of this technology. Although there are already some studies in the area, as shown in the sub-chapter 2.4, the economic viability of the WAAM technology has been not much studied, and therefore, a cost model proposal will be made to calculate the costs involved.

For the development of the cost model, a PBCM was chosen since it allows the calculation of the costs associated with the production of WAAM parts and allows the estimation of costs for future WAAM implementations. Considering that the WAAM technology is a technology under study, this cost model approach is the most indicated because it allows an estimate of the costs associated with adopting this technology, allowing a more informed decision making.

A LCC model was developed to study better the use of WAAM technology, whose objective is to develop a cost model that allows estimating the costs associated with the production of WAAM parts using a cradle-to-gate approach. On the other hand, the LCC model also aims to estimate the costs related to a given part. For this, a scenario of producing 500 hollow cubes with approximately 7x7x7 cm was considered. It should be noted that all the processes required to produce this part were considered.

The object of study is a new variant of HF-WAAM designed, manufactured, and tested at the NOVA School of Sciences and Technology. The section 3.2 will provide an overview of this new technology. The WAAM machine is shown in figure 3-1.

Figure 3-2 shows the scheme that expresses the study methodology. Firstly, a theoretical framework of the HF-WAAM technology and the reasons that lead to its necessity will be made. Next, the goal of the study is defined. Here the focus of the study will be defined, as well as some limitations of the study and the approach to the life cycle model.

After the goal definition, the scope of the study will be defined. In this step, firstly, the WAAM machine will be characterised, and then the productive system to be studied will be presented, where the study boundaries are defined, as well as some of the limitations of the study. The unit processes and the function unit are also defined and explained. Moreover, it is also at this point that the processes where there is a waste of material are defined. Finally, the cost model is developed. As already mentioned, this is where the PBCM is developed and explained so that it can be used.

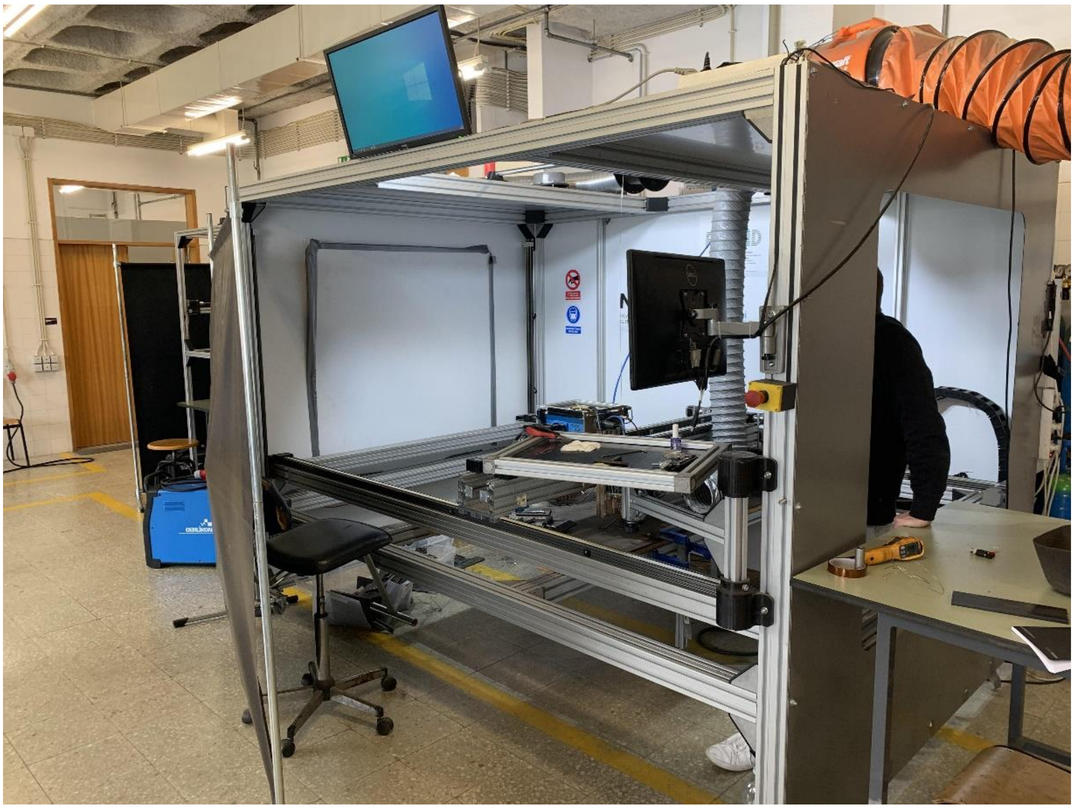

Figure 3-1 WAAM machine

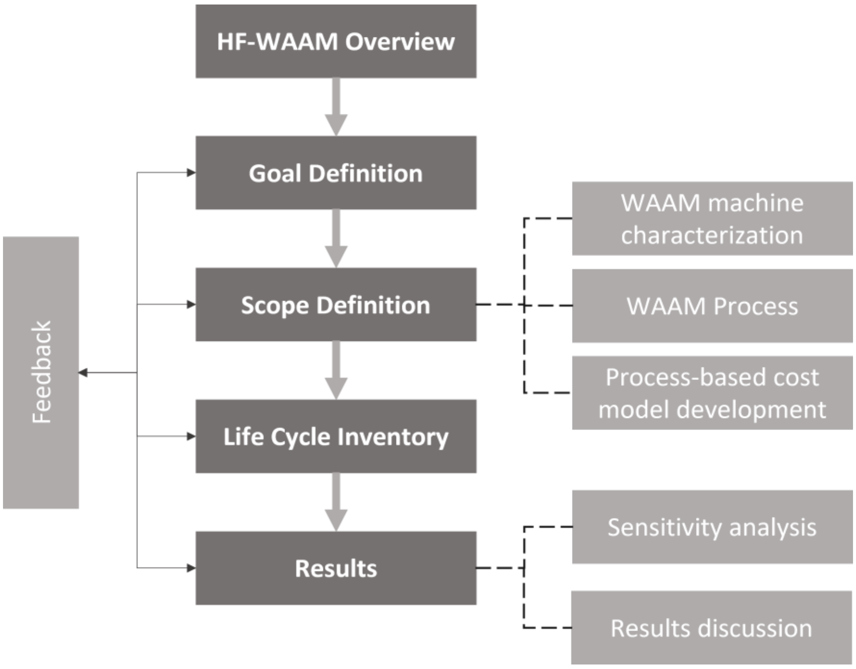

Figure 3-2 Life Cycle Cost Model methodology

Once the cost model is elaborated, it is necessary to collect primary data from interviews with researchers working at NOVA SST and secondary from public websites that will be used on the model. Table 3-1 shows the experience of the experts interviewed. At this stage, similarly to the scope definition, some limitations and assumptions of the study are also presented.

Table 3-1 Experience of the experts interviewed

Expert	Academic Degree	Experience with AM	Experience with WAAM	Experience with LCC
1	PHD	> 5 years	> 5 years	-
2	MSc	2 years	1 year	2 years
3	PHD	> 5 years	2 years	> 5 years

Finally, the results will be presented by applying the cost model to the described production scenario. In this stage, there will be two approaches. Firstly, a sensitivity analysis will be carried out to validate the model and verify which inputs cause the most variation in the product's final cost. The other phase will be the cost discussion to identify the main production cost drivers and understand the cost distribution in the total cost by identifying the value of the variable and fixed costs. On the other hand, this phase also includes the identification of total cost frontiers.

An important point that is represented in figure 3-2 is the influence that the various stages of the LCC model have on each other. As the identification of limitations and assumptions may force changes in other stages of the study.

3.2. Hot Forging Wire Arc Additive Manufacturing

This section was written considering as main reference the work developed by Duarte et al. (2020), where a new variant of WAAM, based on the addition of hot forging to the process, was proposed.

The WAAM machine for which the cost model will be used is a technology based on hot forging and therefore has the name hot forging wire arc additive manufacturing (HF-WAAM). This WAAM machine uses the Metal Inert Gas (MIG) welding technique to melt the metal that will be deposited and form the final part. This technique uses an electric arc to melt the metal and inert gas to protect the metal from the atmosphere.

While other AM technologies have a slow deposition rate and a good surface finish, WAAM has a high deposition rate but a low surface finish. Due to successive re-melting and thermal solidification cycles, the parts' microstructure shows coarse columnar grain structures. Other problems with WAAM are that the mechanical strength is low and anisotropic, which can cause premature failure of the components. Furthermore, the formation of pores represents a potential detrimental feature. The existence of pores may cause a significant reduction of the mechanical properties of the parts depending on their volume fraction and location. Another problem with pore formation is the difficulty that may exist in detecting these defects in non-destructive testing.

The reduction or elimination of large grain structures and pores has been an area that researchers have focused on. Several mechanisms have been developed and tested to improve the microstructure of the produced parts as well as the mechanical properties of the components produced by WAAM. Colegrove et al. (2014) have developed a mechanism that applies interpass cold rolling to reduce grain size and porosity. This process, although effective, is too time-consuming due to the process that takes place at a low temperature, which implies that the time intervals between each layer deposited are high.

Hai-ou et al. (2016) presented another alternative to decrease the grain size and porosity that consists of a hot micro-rolling tool. (Xie et al., 2016) showed a similar technique involving a hot-rolling tool with three rolls that simultaneously deform the three sides of the layers. Although these two approaches have quite satisfactory results, their application involves producing and using different AM equipment. It prevents using a normal welding source and a robot or XYZ table, making the process less economically competitive. Other possibilities that have been studied are the utilization of laser shock peening and ultrasonic peening, but although they can reduce residual stress and refine microstructures, rolling methods are more efficient.

The HF-WAAM variant was developed to decrease or eliminate coarse columnar grain structures and porosity without increasing the time between depositions. For this purpose, a new variant was developed, consisting of a multi-feed device where the different inputs are separate and can be controlled independently. These inputs are electric power, shielding gas, material feed, and mechanical work. The latter uses a hammer activated by a vibrating actuator placed inside the shaping gas nozzle. The existence of this hammer allows viscoplastic deformation at high temperatures to reduce residual stress, eliminate post-heat treatments, homogenize the grain structure, and increase ductility. Using a technology where the inputs are independent and where the viscoplastic deformation is done at high temperature allows the forging load to be reduced, the time between depositions does not increase, and there is greater agility in tooling and equipment utilization.

During the manufacturing process, the hammer travels along the same path as the torch and is in operation at the same time as the material is being deposited, causing the hammer to deform the part at temperatures well above the recrystallisation temperature. Due to the high temperature at which the process is carried out, it is possible to induce dynamic recrystallization of the deposited material as well as cause the pores to collapse with a much lower load than would be necessary if deformation were carried out at room temperature.

The recrystallisation of the grains in the WAAM processes has some advantages. Besides increasing the mechanical strength, it decreases the susceptibility to large grains due to the high density of nucleation sites on top of the deposited layer due to the existence of refined grains. Finally, the deformation of the deposited layers also reduces material waste in subsequent machining processes, as deformation at high temperatures reduces waviness and surface roughness, thus increasing precision.

One of the findings of the results obtained from the use of HF-WAAM is that each layer has a decrease in height and an increase in width, which becomes more pronounced as the hot forging increases, this occurs due to volume conservation and is accentuated in the case where a rectangular hammer is used instead of a cylindrical hammer as the contact area is smaller. This is because reducing the contact area increases stress and increases deformation.

Another positive result is that when the hammer is in operation, it has a much lower temperature than the melted material, which means that the characteristics of the material from which it is made do not change. Another positive point is the fact that there is no contamination of the deposited material by the hammer.

Regarding the hot forging process's effect on the grain structure, the results show that plastic deformation at high temperatures causes a grain refinement, increasing the produced component's strength. On the other hand, it was also visible in the results that using this WAAM variant allows the reduction of the number of pores, which is advantageous for the mechanical properties of the produced component.

The mechanical properties of products produced by the HF-WAAM variant were studied and compared with those of products produced by WAAM, and promising results were observed. In the experiments performed, an average increase in ultimate tensile strength of 8.9% and an increase in yield strength from 360 to 450 were observed. On the other hand, a reduction of 13.9 % in elongation was observed. This is because the grain size's reduction has on the structure of the component since with the decrease of the grain size, the number of boundaries between grains increases, which causes an increase in the difficulty of displacement. Naturally, the result of this effect is a slight reduction in elongation. On the other hand, as previously mentioned, reducing the grain size increases the strength of the produced component. However, it is important to note that reduced ductility is not a problem that precludes the use of AISI316L steel in most industries that require ductility.

The application of the HF-WAAM variant presents some advantages for production in addition to the advantages described above, which concern the characteristics of the materials produced. These advantages concern the efficiency of production and its costs. Since deformation occurs at high temperatures, three advantages can be highlighted. Firstly, the fact described above allows the forces exerted by the hammer to be much lower than those required for an identical process at low temperatures, thus making energy consumption almost negligible. On the other hand, this variant allows the use of traditional motion equipment, namely XYZ tables and 6-axis robots, this fact is crucial because it allows the system to be more flexible and allows the new variant not to be a constraint for the chosen equipment. Finally, this variant does not imply an increase in time between each deposition, allowing the system to maintain the same productivity as a conventional system without a hammer.

About the degree of development of the HF-WAAM variant, it is between TRL 4 and TRL 5, according to the technology readiness levels scale. This happens because the technology in question has been validated in the laboratory but has not yet been validated in a relevant environment.

3.3. Goal Definition

Over the last decades, the AM industry has been developed and studied because of the way it has revolutionised the production of different types of products and materials. One of these techniques is WAAM, a recent and disruptive technology that theoretically allows metallic printing structures that can have any dimension. However, this technology still presents some limitations, such as the lack of precision, the need for a substrate and the need for post-processing machining. Besides these limitations, WAAM is still a production technique not well studied, which leads to the need of this study, which aims to develop a cost model that allows knowing the costs involved in the production of WAAM products.

This study aims to develop a cost model that allows tracking the costs involved in the life cycle of WAAM products and study its economic viability. This LCC object of study is a WAAM machine designed, produced, and tested at the NOVA School of Science and Technology. The material to be studied will be stainless steel AISI316LSI. This study will be oriented to the production of 500 hollow cubs with 7x7x7 cm. The production scenario to be studied is a hybrid WAAM process.

In this study, the life cycle approach will be the cradle-to-gate since the study's main objective is to develop a cost model that enables the estimation of the costs associated with the manufacture of the parts.

3.4. Scope Definition

3.4.1. Characterization of the WAAM Machine

The following subchapter was based on the work developed by Duarte et al. (2020), where a new variant of WAAM, based on the addition of hot forging to the process, was proposed.

The developed WAAM machine, like other WAAM machines, has enormous potential in some industrial sectors. Although the HF-WAAM has not been developed for a specific industry like other WAAM machines, its application is of particular interest for heavy industries such as aeronautics, shipbuilding, automotive and mould making. One of the main reasons for the interest in this technology is the fact that these industries use materials whose acquisition cost is very high, such as the use of titanium in the aeronautical industry. The fact that WAAM technology is based on the deposition of material to create a structure generates an enormous potential since it is no longer necessary to use a large amount of material to achieve the desired shape of the component through subtractive methods, as is the case of traditional processes. This causes a reduction in the waste of raw materials.

Another great advantage that WAAM technology has for this type of industry is creating large parts since, theoretically, the part produced can be of any size. In the case of the studied machine, the torch was intruded into a three-axis position system with a working envelope of 2760x1960x2000 mm. This means that the system to be studied will be able to produce parts up to these dimensions, although, as mentioned before, the torch can be placed in another type of structure.

Another important point about the type of industry where this technology can be applied, and the type of product produced is the poor surface finish of the deposited material. This causes a lower precision of the WAAM technology in relation to other types of additive technologies. This limitation implies that these technologies can only produce components with geometries of medium complexity.

The WAAM machine to be analysed is equipped with a PRO MIG 3200 power source from KEMPY that deposits 1 mm diameter AISI316L stainless steel on the substrate, it also has connections to the tool steel hammer by an M6 leadscrew, two pneumatic cylinders as vibrating actuators, namely a FESTO ADVC-6-5-A-P that produces a force of 17 N and 55 N at a pressure of 0.6 MPa and a SMCCU10-10T that causes a force of 55 N at 0.6 MPa. A 5/2-way bistable solenoid valve Festo VUVS-LK20 was used to actuate the pneumatic cylinders, which was controlled by a data acquisition device. In figure 3-3, the torch and its components are illustrated.

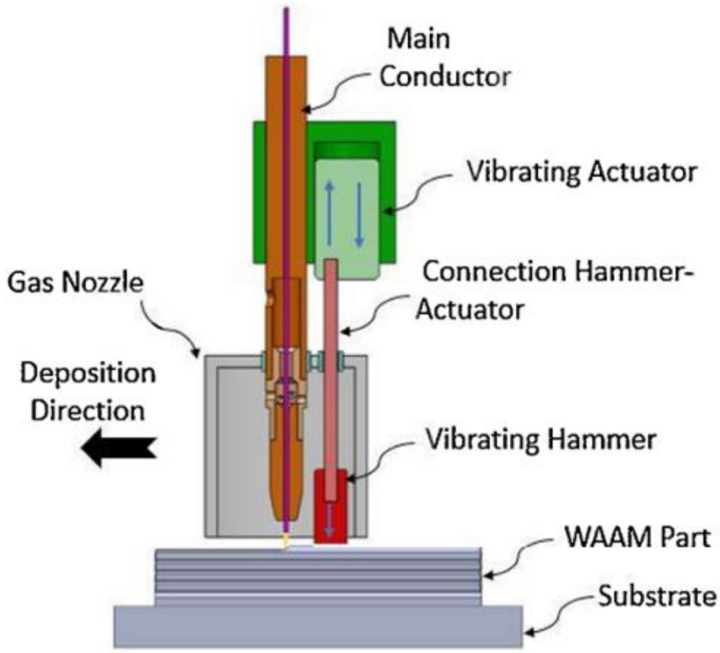

Figure 3-3 HF-WAAM illustration

3.4.2. WAAM Process

This sub-chapter will explain the WAAM process, from the material reception to the storage of the produced parts. For this purpose, a diagram was elaborated to illustrate the process and the operations involved in this process. The study's boundaries included the unit processes: substrate cutting and oxide removal, WAAM process, finish machining and substrate removal, heat treatment and inspection. The operations where material waste can be found were pointed out in the diagram. The diagram of the WAAM process is presented in figure 3-4. The process showed below was developed after interviews with experts working in NOVA SST.

The first step is the raw material reception and storage, which are the wire and the substrate. When the production starts, the set-up of the first operation is set, and next to the substrate is cut with a bandsaw, and then the oxides are removed from the substrate using a steel brush, at last, the substrate is washed with alcohol to guarantee there are not fats or other contaminates or substances that could disturb the production. After the substrate preparation, the material is checked, and if the substrate is in good condition, it goes to the WAAM process, if it is not, the substrate returns to the previous operation.

When the substrate arrives to the WAAM process, the setup of the WAAM process is done. The setup embraces preparing the torch, the wire, the shielding gas and placing the substrate. Then the deposition starts. During this step, there is material waste, but it is neglectable due to its small amount, and the welding nozzles used in the WAAM process will be considered consumable/tools in the cost model. After the WAAM process, the part is inspected, and if it satisfies the requirements, it will be forwarded to the next process, but if it has a fault, the part is scrapped due to the difficulty in reworking it.

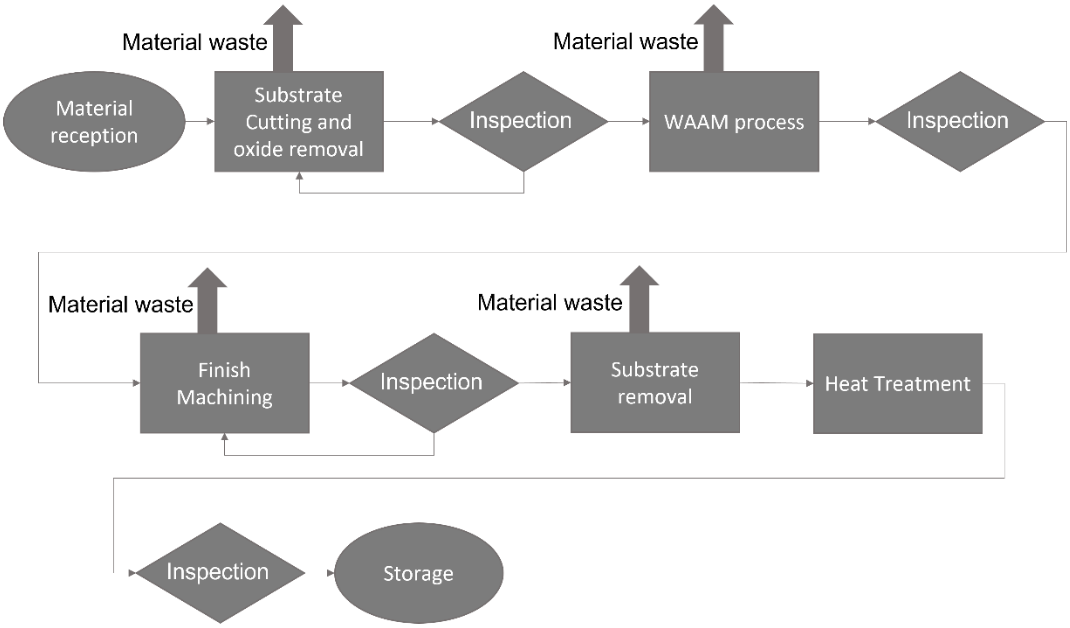

Figure 3-4 Diagram of the WAAM process

In the finish machining operation, a CNC machining is used to refine the part's surface. This stage consists of setup and machining. During this stage, consumables/tools are used, such as the machine's milling cutters. A significant amount of material is removed, considered waste material in the diagram. Then the part is inspected to know if the part needs to be reworked in the previous step or if it can go to the next operation.

After machining, it is necessary to remove the part from the substrate unless the substrate is a massive part of the final product. This will depend on the kind of structure and application of the final product. As has been mentioned before, the WAAM process is not efficient in producing massive structures, so if the product has a massive part, it is a good practice to manufacture it by traditional methods. In the diagram, the substrate removal is considered a different operation from finish machining, although, in this study, it is considered that this stage is integrated into the finishing machining as the same unit process to simplify the cost model since the machine used is the same. At last, the diagram shows material waste at the substrate removal corresponding to the substrate since it cannot be reused due to the surface's roughness and the difficulty of reworking it.

After the substrate removal, the component needs a heat treatment to normalize the structure. So, when the part arrives to this stage, an operator puts it in the oven. After the heat treatment has concluded, the component is sent to the last inspection. The inspection will depend on the kind of application since that will condition the requirements in this stage. If there are special requirements related to the piece's structure, the inspection must be done with x-rays or ultrasounds, but a visual inspection will be enough in case of no structural requirements. Except for the last inspection, the previous inspections will be part of the previous unit processes for simplifications. The functional unit considered is one hollow cube with approximately 7x7x7 cm.

3.4.3. **Cost Model**

When developing a cost model, the first step is to identify the most significant costs associated with producing a given part while maintaining the model's reliability and credibility. The time horizon used for the calculation of costs will be one year.

The production costs to be calculated can be separated into two types of costs: variable costs and fixed costs. Variable costs are costs dependent on the volume of production, which means that they vary in absolute terms but are constant in terms of unit cost. Fixed costs do not vary with production, which means that if there are no changes in the system, costs do not change. However, fixed costs become more diluted in unit costs as the volume increases. In table 3-2 are presented the division between variable and fixed costs. This division allows a better understanding and analysis of the results.

Table 3-2 Fixed and variable costs

Fixed Costs	Variable Costs
Machine	Materials
Overheads	Consumable
Maintenance	Energy
	Labour
	Tools

It is important to define the concepts associated with time and utilisation in a manufacturing context. For such, time can be divided into available time and unavailable time, where the first comprises uptime and idle time. The uptime is the time in which the workstation is working, while the idle time is all the time in which the workstation could be working but has no work to be carried. Unavailable time is associated with all types of unforeseen breaks, such as scheduled breaks, maintenance, and the time when the factory is closed. Finally, downtime is the idle time added to the unavailable time. In relation to factory costs, these must be associated with the time when the stations are producing parts, so these expenses are allocated to uptime. Another critical concept is dedication. Since a machine can be dedicated or non-dedicated. When a machine is dedicated, it means that the uptime is equal to the time that the machine is being used to produce the part being studied.

When developing a PBCM, it is necessary to identify each process's inputs and outputs since the cost model is based on the division of the production cycle into several processes, and their inputs and outputs are used to calculate the production costs.

The inputs of each process can be divided into two categories: general inputs and specific process inputs. General inputs coincide with all processes and are influenced by the company or laboratory where the products are produced, such as wages or working days per year, while specific process Inputs are related to the process in question. This means that these inputs are relative to a process and can vary. Therefore, some processes can have inputs that are not coincident with other processes. Table 3-3 and table 3-4 present the specific process inputs and general inputs, respectively.

The inputs for table 3-3 table 3-4 are explained below:

- The dedication input informs if the machine only produces the product to be studied or if it also produces others. And the allocation represents the percentage of time spent on that task.
- Then follows the number of workers assigned to the task and the percentage of their working time that they spend on the operation, which corresponds to the dedication.
- Acquisition cost is the cost of the machine.
- Set up and machine time are needed to prepare the machine to start operation and the time the machine is running.
- Travel speed and standby time are the length of material deposited per hour and the time between depositions, respectively.
- Maintenance and overheads are expressed as a percentage of the machine cost.
- At last, it is necessary to consider the quantity of consumables required for the production and their costs and the number of tools and their costs.

The inputs for table 3-4 are explained below:

- Days per year corresponds to the days the factory operates per year.
- The wage Is the labour cost per hour.
- The unit energy cost Is the cost of the energy.
- The machine life is when the machine is available, and the production life is when the part will be produced.
- Opportunity cost rate is the interest at which the investment is annualized.

Other inputs are essential to develop the cost model: part information, material information, scrap input, and line utilization. The inputs used are the number of layers and the layers' length within part information. Material information is the kind of material and cost. In relation to scrap input, it is necessary to know the amount of material that is approved, the quantity of the non-approved material and the amount of material reworked, and the cost at which the waste material may be sold, as well as the material removal rate and the volume that is removed from the part at the time of finishing. Regarding line utilization, it is necessary to consider the scheduled and non-scheduled breaks of the operators, unplanned breakouts, non-working times, and maintenance stoppages. Equation 6 shows how it is computed the available time.

Table 3-3 Specific process inputs

Specific Process Inputs	Unit
Dedication	Yes/No
Allocation	%
Nº of workers	Number
Worker's dedication	%
Acquisition cost	€
Set uptime	h
Machine time	h
Standby time	h
Travel speed	m/h
Maintenance	%
Overheads	%
Power consumption	kW
Consumable required	unit
Consumable cost	€/unit
Tools number	Number
Tools Cost	€

Table 3-4 General inputs

General Inputs	Unit
Days per year	Days/year
Wage	€/h
Unit Energy Cost	€/kWh
Equipment Life	years
Production life	h
Opportunity cost rate	%

$$Avaliable\ time = 24h - (scheduled\ and\ non\ scheduled\ breaks +\ non\ working\ time + time\ for\ maintenance\ stoppages) \tag{6}$$

To compute the product production cost, it is necessary to know how much material is needed to produce the part. For this purpose, it is mandatory to consider the number of parts that have quality and are passed to the next process, the number of defective parts, and the number of parts that can be reworked. Equation 7 shows how to calculate the number of parts to satisfy the requirements. This calculation is performed from the end of the production line to the beginning. It is also important to mention that the only material that can be reworked is the substrates since the printed part, if defective, is considered waste material.

$$Number\ of\ parts_i = \frac{Number\ of\ parts_{i+1}}{\%passes_i + \%defective_i \times \%rework_i} \quad (7)$$

To calculate fixed costs, it is necessary to calculate the uptime computed by equation 8, but before it is needed to perform some intermediate calculations to compute the required time through equation 9 and the cycle time. Cycle time depends on the process that is being carried out. Equation 10 presents the calculation for cycle time for WAAM and equation 12 for calculating cycle time for finishing machining.

$$Uptime = \frac{T_{required}}{Allocation} \quad (8)$$

$$T_{required} = Cycle\ time \times Number\ of\ parts \quad (9)$$

$$Cycle\ time_{WAAM} = Setup\ time + \sum_{i=1}^{n}\left(\frac{Length\ of\ layers_i}{Travel\ speed}\right) + Standby\ time \times \left(N_{layers} - 1\right) \quad (10$$

If the length of the layer is the same for all the layers at the part to be analysed, then:

$$Cycle\ time_{WAAM} = Setup\ time + \left(\frac{length\ of\ layers}{Travel\ speed}\right) \times N_{layers} + Standby\ time \times (N_{layers} - 1) \quad (11)$$

$$Cycle\ time_{Finish\ machining} = \frac{Volume\ to\ be\ reemoved}{MRR} \quad (12)$$

Knowing the uptime, it is possible to calculate downtime and idle time, computed by equation 13 and equation 14, respectively.

$$Total\ downtime_i = \frac{24h \times Days\ per\ year - Uptime}{Days\ per\ year} \quad (13)$$

$$Idle\ time_i = Available\ time - uptime \quad (14)$$

Henceforth, equations for determining the costs associated with the production of WAAM products will be presented, starting with variable costs. The first cost to be considered is the materials costs. For wire, it is necessary to consider the wire cost, the weight of the raw material, and consider that the wasted material can be sold. Its value is taken from the total cost of the raw material cost. The raw material cost is possible to compute with equation 15. Equation 17 computes the shielding gas cost by multiplying the volume of shielding gas required by the cost per litre of shielding gas. Equation 18 calculates the substrate cost, and, as in the wire cost equation, the waste material Is considered to calculate the total substrate cost. It is important to note that shielding gas and substrate are consumables, not raw materials.

$$Wire\ cost = Cost_{Wire} \times Wire\ weight - Cost_{Material\ waste} \times Material\ waste\ weight - Cost_{Scrap} \times Scrap\ weight \quad (15)$$

Scrap weight is computed by equation 16. This equation can be used for WAAM scrap and substrate scrap.

$$Scrap\ weight = Material\ used\ weight \times (1 - \%passes - \%defective_i \times \%rework) \quad (16)$$

$$Shilding\ gas\ cost = Volume\ required_{Shielding\ gas} \times Cost_{Shielding\ gas} \quad (17)$$

$$Substrate\ cost = Cost_{Substrate} \times Substrate\ area - Cost_{Substrate\ used} \times Substrate\ used\ weight - Cost_{Scrap} \times Scrap\ weight \quad (18)$$

As with shielding gas, the cost of other consumables is also computed by the number of tools used per hour of the process. The equations for calculating the cost of shielding gas and substrate are not presented as the same equation because the way to achieve the substrate cost is different from the shielding gas cost. The tools costs are given by equation 19, where the number of tools needed and their cost are considered.

$$Tool\ cost = Cost_{Tool} \times Number\ of\ tools \quad (19)$$

The labour cost is presented in equation 20. Only the directly involved workers in the process are considered for the labour cost, as the others are considered in the overheads. On the other hand, since workers do not need to constantly work on a given process, the operator's dedication is also considered. Labour costs also include the number of workers, the hourly wage and the time required.

$$Labour\ cost = Dedication \times Wage \times Number\ of\ workers \times T_{required} \quad (20)$$

For the energy cost, two types of formulas can be used, one for all processes and the other for the WAAM process, although for calculation purposes, the general equation for all processes can be used for the WAAM process since the difference between the costs obtained is negligible compared to other costs associated with the process studied. In the case of the general equation for calculating the energy cost, it is necessary to consider the time required, the process energy consumption and the unit energy cost. For the more accurate calculation of the WAAM machine consumption, the methodology is similar, the only difference is that the energy consumption during deposition and during standby time is detached, which are then multiplied by the respective times and then summed. Finally, they are multiplied by the number of pieces and the unit energy cost. The equations for the energy cost for the different processes and the WAAM machine are the equations 21 and 22, respectively.

$$Energy\ cost = T_{required} \times Power\ consumption \times Unit\ cost_{Energy} \quad (21)$$

Or

$$Energy\ cost_{WAAM} = \left(\sum_{i=1}^{n}\left(\frac{Length\ of\ layers_i}{Travel\ speed}\right) \times Power\ consumption_{Deposition} + Standby\ time \times (N_{layers} - 1) \times Power\ consumption_{Standby}\right) \times Unit\ cost_{Energy} \times Number\ of\ parts \quad (22)$$

Next, the equations are presented to obtain the value of fixed costs. For this purpose, a logic is adopted in which fixed costs are annualised so that the investment becomes a set of payments over the useful life of the machine (n) with an opportunity cost of capital (r). Equation 23 represents the way to calculate annualised fixed costs.

$$Fixed\ cost_{ji} = I_i \times \frac{(1+r)^{n_j} \times r}{(1+r)^{n_j} - 1} \quad (23)$$

The machine investment is calculated considering the cost of the machine, the quantity, and allocation. This is because the machine can be allocated to more than one workpiece, which means that the machine investment must be divided by more than one product. Equations 24 calculate machine investment.

$$Machine\ investment = Cost_{Machine} \times allocation \times Number\ of\ machines \quad (24)$$

Maintenance investment and overhead investment are calculated as a percentage of fixed costs. In the case of maintenance investment, it is calculated as a percentage of machine investment since it is the only kind of equipment that requires maintenance. The overhead investment is related to all existing costs not directly associated with production and is calculated as a percentage of all fixed costs. Equations 25 and 26 compute maintenance investment and overheads investment, respectively.

$$Maintenance\ investment = Machine\ investment \times Maintenance \quad (25)$$

$$Overheads\ investment = (Machine\ investment + Tool\ investment + Machine\ investment) \times Maintenance \quad (26)$$

3.5. Life Cycle Inventory

Multiple sources of data were used to collect and compile data regarding each input required to produce WAAM products. The data collection process included the compilation of secondary data available in public websites such as EDP (2022), Alibaba.com (2022) and

Haas CNC Machines (2022). Also, primary data was collected through unstructured interviews with researchers who developed and worked with the WAAM equipment, since they have access to experimental data and also have a deep knowledge about the equipment function. The data was collected in the period of time between September 2021 and February 2022.

For the application of the cost model, the production of 500 hollow cubes with 7x7x7 cm was considered. The wall thickness was defined as 5.5 mm for the side and top faces, and for the bottom face, a thickness of 1.3 mm was considered due to deposition parameters. Therefore, for the part information, the number of layers and their dimensions for the lower face, the four lateral faces and the upper face were obtained. For the base, 12 layers with 7 cm in length each, 49 layers with 257 mm in length for the side faces and 54 layers with 7 cm each for the top surface. These inputs were calculated considering that the material is deposited initially to create the bottom surface, then the side surfaces are deposited, wherein each layer the material is deposited over the edges of the base and finally, the top surface is deposited with the mouth in a lateral position, thus making the thickness of the wall similar to the thickness of the side walls.

Regarding the information on materials, three materials required for production were identified: stainless steel plates, shielding gas composed of Argon, and the wire of stainless steel AISI316LSI. The last one is raw material, and the other two consumables are used during the process. The costs of the materials were provided by experts working in NOVA SST and can be seen in table 3-5.

Table 3-5 Material information

Material	Wire	Shielding gas	Substrate
material required	1.01 kg	717.84 l	0.015m^2
Cost	5.33 €/kg	0.03 €/l	257.07 €/m^2

Note: Data obtained by interviews with experts working in NOVA SST.

Although scrap was considered for the cost model development, it was not considered in the estimate made since the value to be received for it is quite neglectable compared with the other production costs. Furthermore, it was considered that all the material passed the inspections, so there is no rework. This is due to a lack of information on passes and reworks.

However, the volume value removed from the part and the material removal rate was calculated concerning scrap information. Once again, the cost of waste material was not considered, and these values were used to calculate the machining time of the finish machining process and substrate removal. The material removal rate is 262.5 cm^3/min, considering the depth of cut 0.5 mm, the width of cut 35 mm and the feed rate 250 mm/s, these values were obtained in the laboratory of NOVA SST. For the calculation of the removed volume, it was considered that in each exterior wall of the cube, excluding the inferior surface, 0.5 mm was removed and that in the inferior face, only the substrate was removed. Given the dimensions of the cube, the volume removed from the walls was 12.25 cm^3. For the substrate part, it was computed that 15 cm^3 were removed, considering that the substrate measures are 15 cm in length, 10 cm in width and 1 cm in height. The buy to fly ratio of the deposited part under these conditions is 1.1, which agrees with the literature (Priarone et al., 2019). Researchers from the area provided the data mentioned above through unstructured interviews. Regarding the line utilization, the values presented in table 3-6 were considered for the duration of each break.

Table 3-7 shows the values corresponding to the general inputs. To obtain the days per year were considered the working days and stoppages due to periods in which production may be stopped, as is the case of holidays. The wage was calculated based on a gross wage of 1500 €, a unique social tax of 23.75% and a holiday and Christmas bonus. For the other data, the typical values of the industry were considered. The unit energy cost was obtained from EDP (2022).

Table 3-6 Line utilization inputs

Non-working Time	14.3 h/day
Scheduled Breaks	1.0 h/day
Unscheduled Breaks	0.5 h/day
On Shift Maintenance	0.1 h/day
Unplanned Downtime	0.1 h/day

Note: Data obtained by interviews with experts working in NOVA SST.

Table 3-7 General inputs data

Days per Year	230	days/year
Wage	14.12	€/hour
Unit Energy Cost	0.169	€/kWh
Interest	10	%
Equipment Life	10	years
Production Life	10	years

Note: Data obtained in public websites.

In table 3-8 are the specific process inputs. For the cost model, it was considered that none of the machines are dedicated, although later, we will study the scenarios in which this happens. The acquisition costs of the heat treatment and CNC milling were obtained through Alibaba.com (2022) and HAAS CNC MACHINES (2022). The setup times were obtained from unstructured interviews with researchers, and the machining times were obtained in the same way, except for the WAAM and finish machining and substrate removal processes since the latter was estimated as previously mentioned. Since, for the WAAM machine, the machine time is computed, the travel speed was obtained through unstructured interviews with researchers. In the case of finish machining and substrate removal, the setup time is 30 minutes, but it was considered that there are two setups since the workpiece must be machined from above and below. In the case of power consumption, a conservative approach was used, so the values used correspond to the maximum power of the WAAM machine. In the case of the WAAM machine, the power consumption considered was the highest of the range of values obtained in the laboratory since only the deposition time was measured, which may represent an almost insignificant impact on the overall study. The standby time was considered as 1 minute for the bottom and top faces and 30 seconds for the construction of the side faces. The maintenance and overhead percentages were obtained through unstructured interviews with researchers. The tools considered are the forging nozzles for the WAAM process and cutters for finishing machining and substrate removal. The cost of the tools was collected through unstructured interviews with researchers.

Table 3-8 Specific process input data

	Reception	Substrate cutting and Oxide removal	WAAM	Finish machining and Substrate removal	Heat treatment	Inspection	
Dedication	-	No	No	No	No	No	
Allocation	-	5	90	40	40	20	%
Number of workers	1	1	1	1	1	1	units/ shift
Worker’s dedication	-	50	20	25	5%	30%	%
Acquisition cost	-	2500	300000	60000	5 500	2 350	€
Power consumption	-	1.2	1.89	11.2	15	-	kW
Setup time	0.25	0.05	1	1	0.008	0.08	h
Machine time	-	0.106	-	0.15	1	0.5	h
Standby time	-	-	0.017	-	-	-	h
Travel speed	-	-	21.6	-	-	-	m/h
Maintenance	-	10	10	10	10%	10%	%
Overheads	-	40	40	40	40%	40%	%
			1.007				kg
Consumable	-	-	717.840		-	-	l
			-	0.015			m^2
			5.333	-			€/kg
Consumable cost	-	-	0.025		-	-	€/l
			257.066	-			€/m^2
Tools number	-	-	4	301	-	-	unit
Tools cost	-	-	8	100	-	-	€/unit

Note: Data obtained by interviews with experts working in NOVA SST.

3.6. Results

3.6.1. Model Validation and Sensitivity Analysis

Once all the cost model inputs have been clarified, it is necessary to perform a model validation. Therefore, the model's inputs were varied to check whether the total cost varied as expected. This validation, carried out using a sensitivity analysis, allows to identify each input's variation in the final cost and find out if it is significant.

The sensitivity analysis was performed by varying the inputs of each process, keeping the other inputs the same, to determine the variation of the total cost per piece. To do so, the inputs were varied between -30% and 30% and in the case of percentage variables, a variation was made between 10% and 100%. It should be noted that inputs directly impact costs linearly, making the graphical representations show a linear trend.

The following charts will show the variation of the total cost as a function of the variation of the inputs of each process, as well as the part information and material information. The variation of the tools variables was made separately from the process.

For the analysis of the variation of inputs of part information, material information, and the processes except for the WAAM process and finish machining and substrate removal, a maximum of 290 € and a minimum of 250 € were considered since the largest variation that occurs is 2.1 %. This way, it is possible to make a better comparison between inputs. In the case of the WAAM process, finish machining and tools, it was considered a maximum of 320 € and a minimum of 200 € since the largest variation that occurs in this process is about 15.6 %. In the case of percentage inputs, a similar approach was considered, but in this case, considering a different range for the WAAM process. Therefore, a maximum of 290 € and a minimum of 250 € has been considered for all the processes and a maximum of 400 € and a minimum of 100 € for the WAAM process.

Figure 3-5 shows the part information sensitivity analysis. For this, a cost of 259.95 € per part produced was calculated. For the sensitivity analysis, it was considered that at each variation, the layers with different lengths vary proportionally, the same approach was taken for the number of layers since depending on the place where the material is being deposited, the standby time also varies. In figure 3-5, it is possible to observe that the number of layers has more effect on the total cost than the length of the layers. Since the number of layers, when varied to the maximum, varies the total cost by 1.17%, while the variation caused by varying the layer's length is 0.8 %. This happens because the amount of raw material and the deposition time vary significantly when varying the number of layers than layer length.

Figure 3-6 represents the sensitivity analysis of the material information for the three materials. The amount of material and its cost vary almost equally the part's total cost. However, there is a significant difference between the materials since both the wire and the substrate cause a variation of less than 1% each, while the shielding gas causes a variation of 2.04 % while the required material varies by 30%.

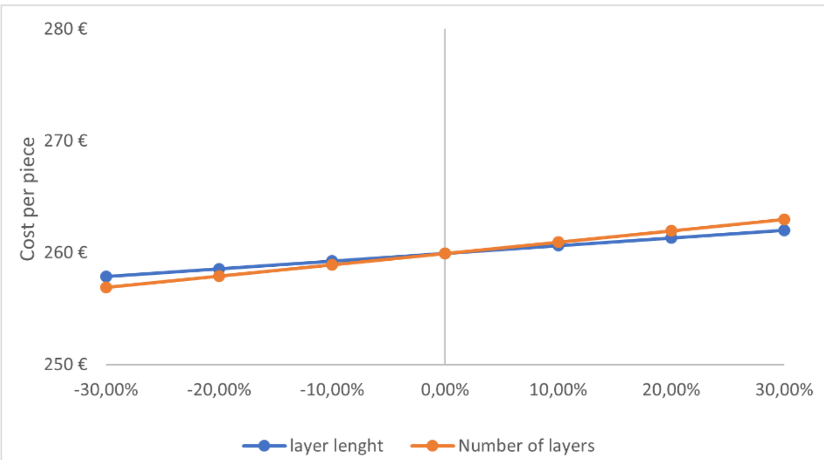

Figure 3-5 Sensitive analysis of the part information

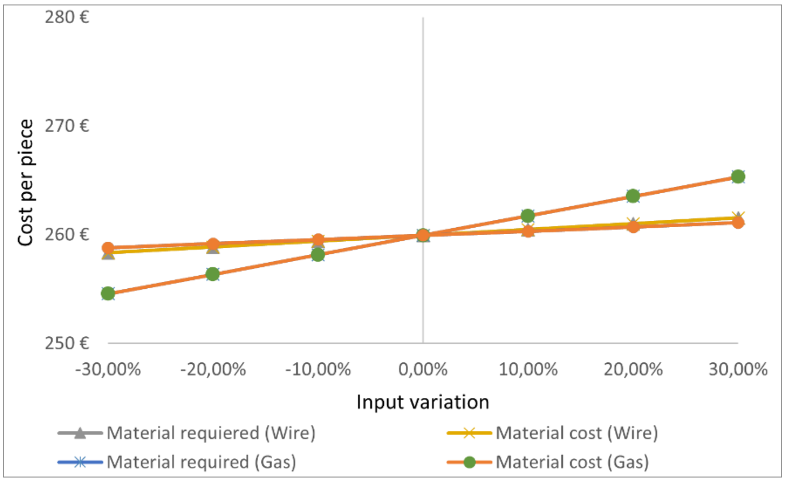

Figure 3- 6 Material information sensitive analysis

In appendix 2 are presented the figures A2-1 and A2-2, which represent the sensitivity analysis of the absolute and percentage inputs of the substrate cutting and oxide removal process, respectively. Due to the short cycle time, low allocation, and low machine cost, it is possible to observe that the effect inputs have on total part cost is very low, less than 0.2% for absolute inputs.

Figure 3-7 shows the sensitivity analysis of the inputs to the WAAM process. As described previously, this process has a different cost range as the variable acquisition cost has a huge effect on the part's total cost, varying it by 15.62 %. This is due to the high cost of the WAAM machine and the allocation being very high for this process, 90%. The other input that most influences the total cost is travel speed, with a variation of 1.82 %. This variation is due to changing the deposition time that, besides changing the machine's cycle time, also causes the change in the amount of gas consumed, which, as seen previously, is the raw material with the greatest effect on the final cost. As expected, the slope of the travel speed is negative since increasing it decreases gas consumption and deposition time.

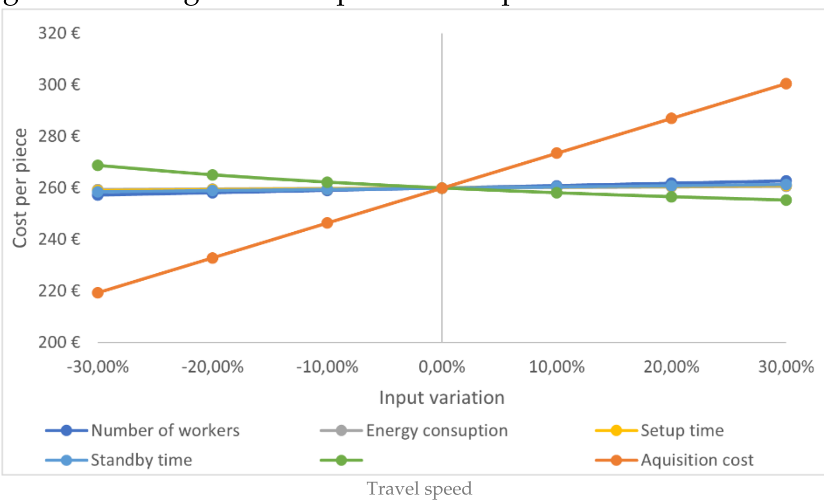

Figure 3-7 WAAM inputs sensitive analysis

In its turn, figure 3-8 represents the sensitivity analysis of the WAAM percentage inputs. As can be seen from the previous analysis and as will be verified later, the WAAM process is the one that most influences the total cost since it represents the largest part of it. Therefore, it is observable that the percentage inputs also vary the product's final cost significantly. Although the value of inputs is 10%, they are in quite different positions. It is notable that throughout the variation between 10% and 100%, the input that has the highest impact on cost is allocation due to machine cost.

On the other hand, the second input that makes the final cost vary the most is maintenance, which again happens because it is a cost that depends on the cost of the machine. Finally, the other input influenced by the machine's cost is overheads, which have a lower variation than maintenance because they depend on all fixed costs. The final proof that machine cost is very relevant for the variation of the final cost is that dedication is the percentual input that makes the part cost vary the least.

Figure 3-9 shows the sensitivity analysis for finish machining and substrate removal inputs. Although the variation that the inputs cause in the final cost is smaller than in the WAAM process, they have a superior influence than the substrate cutting and oxides removal process. In this case, the input that causes a bigger alteration is the machining time, with a variation of around 7.01 %. On the other hand, the other inputs cause a variation of less than 1% each unless the machine cost, which causes a variation of 1.39 %. These variations are

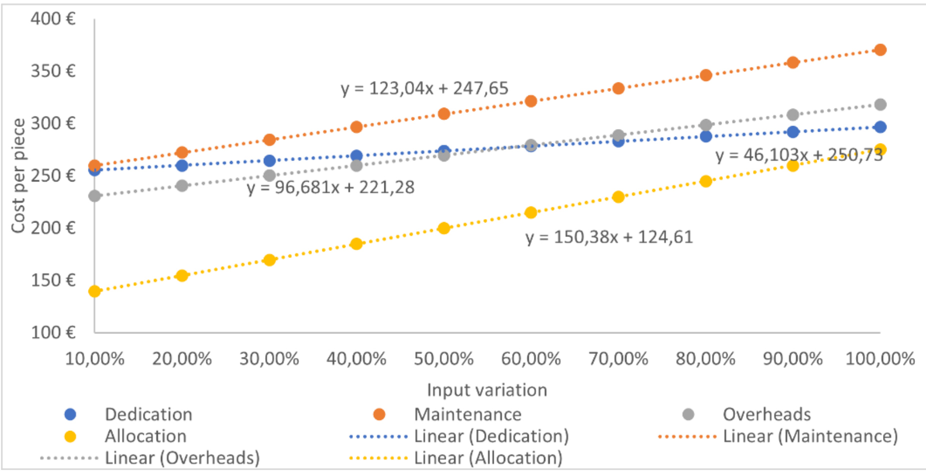

Figure 3-8 WAAM percentage inputs sensitive analysis

according to the forecasted since the machine time directly influences the number of cutters that are used, and the machine cost is the second highest with a big difference, 7.01 % to 1.39 %, due to the low allocation value, around 40 %.

Figure 3-10 shows the sensitivity analysis of the percentage inputs. Again, this process causes a more significant variation in final cost than substrate cutting and oxides removal and less than the WAAM process. In this case, the input that makes more variation in the final cost is the allocation that directly influences the cost of the machine allocated to the process, followed by the overheads since these depend on all fixed costs, including the machine. Finally comes maintenance, again due to the cost of the machine and the fact that the allocation is 40% and in last, the dedication since the labour cost is much lower than the others.

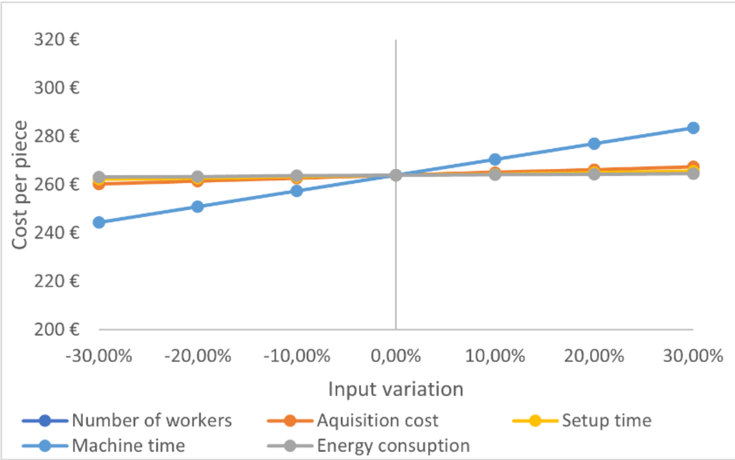

Figure 3-9 Finish machining and substrate removal inputs sensitive analysis

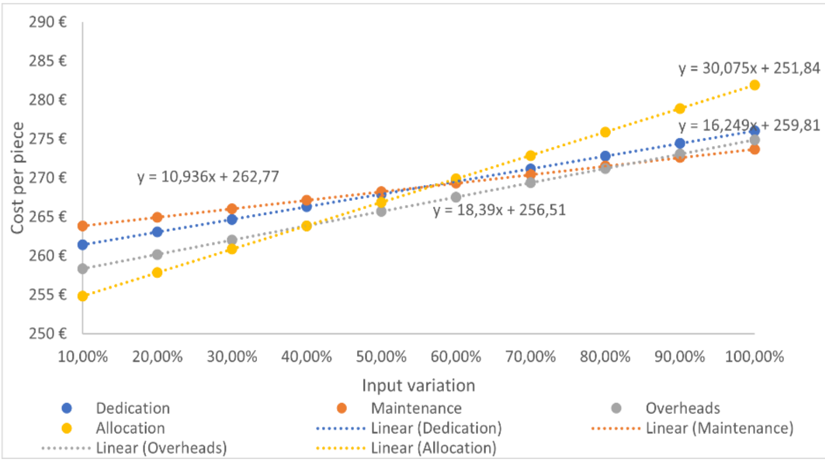

Figure 3-10 Finish machining and substrate removal percentage inputs sensitive analysis

As shown in figures A2-3 an A2-4, due to the low acquisition cost and low allocation, the heat treatment and inspection processes practically do not vary the final cost, with less than 0.4 % variations. In the case of figure 3-11 and figure 3-12, it is possible to notice that due to the low acquisition cost and allocation values, the percentage inputs hardly vary the total cost, except for the dedication that in both cases influences the total cost. However, the heat treatment dedication is slightly inferior to the dedication trend of the finish machining process and superior to the inspection process due to the cycle time being slightly inferior to the machining cycle time and almost twice the inspection cycle time.

Figure 3-13 shows the sensitivity analysis for the number of nozzles and the number of cutters and their cost. As with the material information sensitivity analysis, the quantity of a given input and its cost change the total cost equally. One effect previously observed is that the input of the cutters has a more significant expression in the total cost of the part, of about 7 %, while the number of nozzles does not change the total cost. This is due to the number of cutters needed and their cost being much higher than the cost of the nozzles.

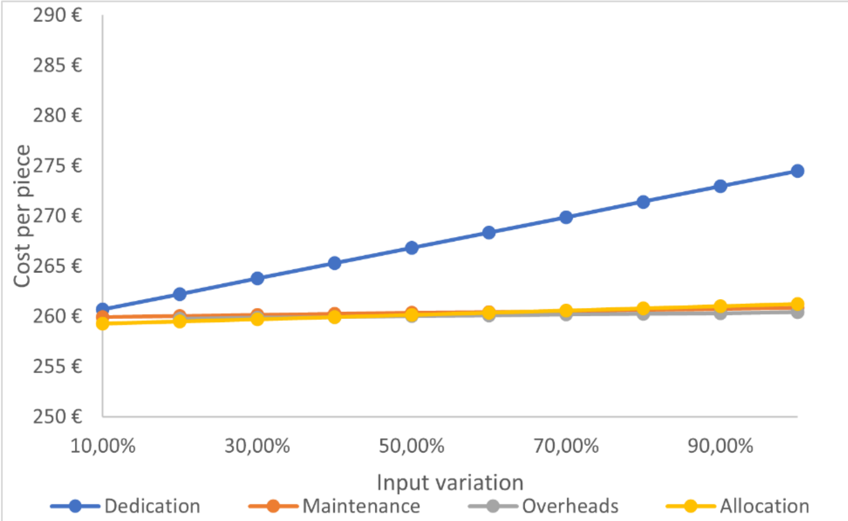

Figure 3-11 Heat treatment percentages inputs sensitive analysis

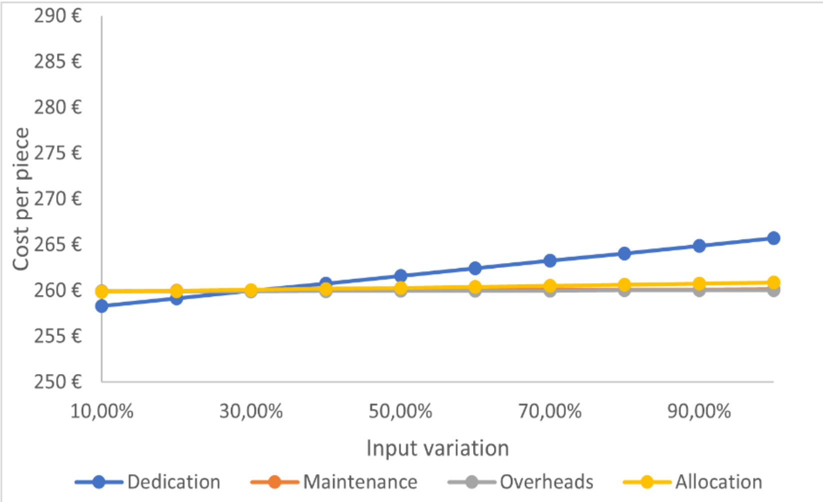

Figure 3-12 Inspection percentage inputs sensitive analysis

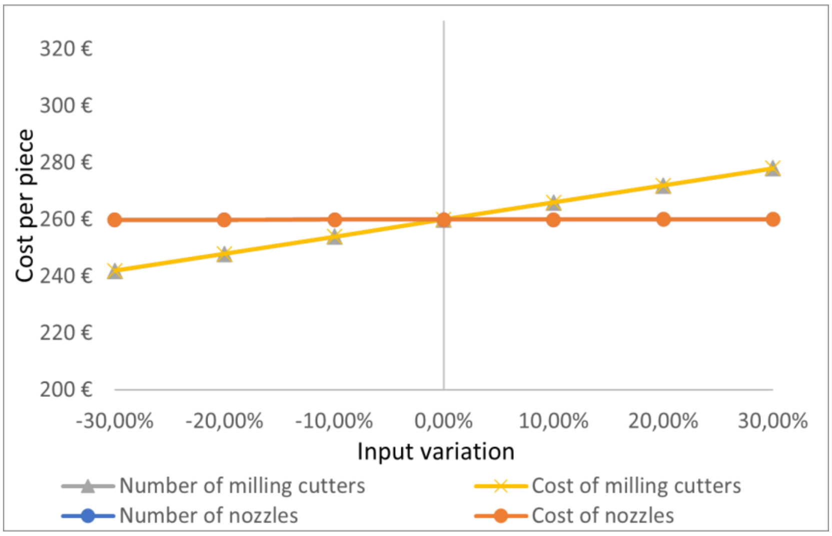

Figure 3-13 Tools sensitive analysis

3.6.2. **Final Results**

Obtaining the production costs of a part through the PBCM allows cost drivers to be identified, analysed, and compared, thus helping the decision-making process when studying the use of a new technology, such as the WAAM technology.

As already mentioned in the model validation phase, a cost per piece of 259.95 € was estimated to produce 500 cubes. Even though this is a scenario, using the PBCM allows estimates to be made whose final values are close to a real scenario. Since the main objective of this thesis is to develop a cost model that allows estimating the costs inherent to the production of parts using WAAM technology, the production costs mentioned above will be presented, separating the weight that variable and fixed costs have in the final cost of the part, to identify the cost drivers better.

In table 3-9 and table 3-10, it is possible to observe the variable and fixed costs and the respective percentages. As previously mentioned, the values presented are related to the cost per piece in the production of 500 hollow cubes. Observing table 3-9, it is possible to see that the total variable costs are 111.41€, representing approximately 43 % of the total costs per piece. In the case of table 3-10, it is possible to see that the value of fixed costs is 148.54 € which is approximately 57 % of the total costs per piece. On the other hand, table 3-9 shows that tooling cost is the highest, representing approximately 54.1 % of variable costs. This happens due to the cost of the milling cutters and the number needed. The second highest variable cost is the material cost because the cost of the substrate, the cost of the gas and the cost of the wire are considered. In the same way, observing table 3-10, the machine cost is the highest, as it was already observed in the sensitivity analysis. Note that the overheads also have a high value because it is considered that they represent about 40% of the sum of the other fixed costs.

Table 3-9 Variable costs and percentages

VARIABLE COSTS	Part Cost	Percentage of Variable Costs
Material Cost	27.17 €	24.4 %
Labour Cost	17.97 €	16.1 %
Tooling Cost	60.26€	54.1 %
Energy Cost	6.00 €	5.4 %
Total Variable Cost	111.41 €	100%

Table 3-10 Fixed costs and percentages

FIXED COSTS	Part Cost	Percentage of Fixed Costs
Main Machine Cost	96.37 €	65.9 %
Fixed Overhead Cost	42.51 €	28.6 %
Maintenance Cost	9.66 €	6.5 %
Total Fixed Cost	148.54 €	100%

Figure 3-14 shows the percentage of each variable and fixed cost as a function of the total cost of each part produced. The chart shows that the acquisition cost continues to be a relevant driver cost due to the high allocation value and the high cost of the WAAM machine. The second driver cost is the tooling cost, as was expected since this input was the higher of the variable costs due to the cost and number of the milling cutters. In third comes the overheads since they are a percentage of fixed costs, including the acquisition cost. Finally, the fourth most important driver cost is material cost, representing about 10% of the part's total cost. This is justified by the low raw material consumption of the WAAM machine. However, it should be noted that the machine and tools costs represent about 60.25 % of the production cost.

After understanding the structure of cost types, it is necessary to analyse the costs according to each process. Figure 3-15 shows in blue the costs of each process. It is possible to observe that the WAAM process and the process of finish machining and substrate removal are the processes that represent the largest portion of the total cost. This is justified because the machines used here are the most expensive in the production cycle because most of the raw materials are used in the WAAM process and because the most expensive tools are used in the finish machining and substrate removal process. It is observed that the other processes represent only 5% of the total production costs. In order to analyse the weight that raw materials and tools have in the process costs, figure 3-15 shows as orange the process costs without material and without tools. In this way, it is possible to observe that the reception, heat treatment, and inspection processes remain the same, whereas the substrate cutting and oxides removal process reduces significantly, although their cost is reduced. This is due to the

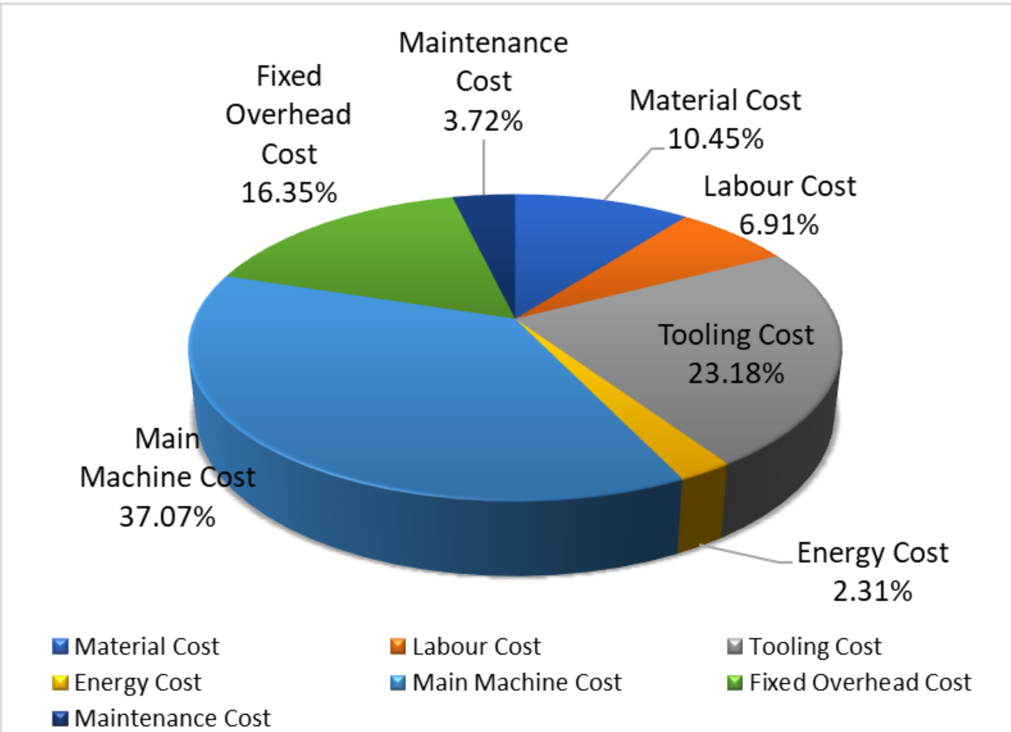

Figure 3-14 Cost allocation

cost of the substrate. On the other hand, when the cost of the wire, gas and tools used in the WAAM process is removed, its cost reduces from 168.92 € to 145.54 €, and as expected, the cost remains high due to the high WAAM machine cost and allocation. Finally, once again, the weight that the cutters have in the cost of the piece is clear since the machining process is greatly reduced when the cost of the cutters is removed, representing 76.7% of the total cost of the process.

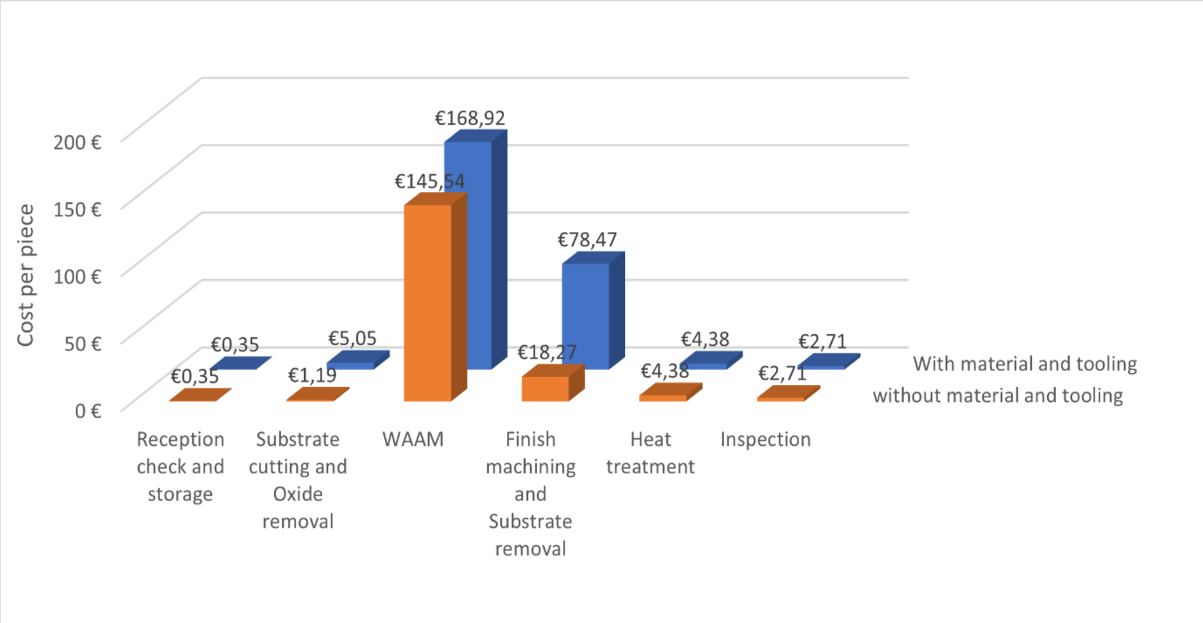

Figure 3-15 Cost per process with and without material and tools costs

In table 3-11, the cycle times of each process are represented. This analysis is important because it allows observing which processes occupy more time during the 6.49 h needed to produce a part. One of the conclusions that can be obtained is that the most time-consuming process is WAAM, which occupies 50 % of the production time. On the other hand, although the finish machining and substrate removal process is the second most expensive process and the second most time consuming with 18 % of the production time, it is very close to the time that heat treatment takes, which corresponds to 17 % of the production time. Finally, the other processes represent only 15 % of the production time, these being 4 % for reception, 2 % for substrate cutting and oxide removal and 9% for inspection. Figure 3-16 shows the cost of each process per hour. Through the analysis, it is possible to observe that the most expensive process per hour is the finish machining and substrate removal, which agrees with the previous analysis since this process is the second most expensive but has about one-third of the duration of the WAAM process that passes to the second place because its cost is diluted by the process time. The heat treatment process remained with a slight decrease due to the setup time. However, the reception and inspection processes, although of low value, increased their value due to their low cycle time, and the reception increased a lot, going from 0.35 € to 1.41 €. Finally, the substrate cutting and oxide removal process, similarly to the reception process, due to its low cycle time value, increased from 5.05 € to 32.46 €.

Table 3-11 Processes cycle times and percentages

Process	Time	Percentage
Reception check and storage	0,25h	4%
Substrate cutting and oxide removal	0,16h	2%
WAAM	3,26h	50%
Finish machining and substrate removal	1,15h	18%
Heat treatment	1,08h	17%
Inspection	0,58h	9%
Total	6,49h	100%

Finally, one of the advantages of using a PBCM is analysing costs according to production volume. This allows more information to be available for informed decision-making. In figure 3-16, it is represented the total cost curve per piece according to the produced volume for a scenario where the machines are all dedicated and for a scenario where the uptime and available time are equal. For a better visibility of the chart, it was established that the total cost would be 20000 € and that the maximum number of pieces would be 200. Observing figure 3-17, it is possible to observe that in the scenario where the uptime is equal to the available time, the cost value is almost constant since there is no idle time. The cost is only allocated to the part when it is being used. In the scenario where the machines are all dedicated, it is possible to observe that at the beginning, the cost of the piece is very high since the idle time is very high, and therefore the cost of the machine is allocated to the piece even if the production line is stopped. However, as the number of parts increases, the graph shows that the cost curve with all dedicated machines approaches the cost where the uptime equals the available time. So, it can be seen the effect that fixed costs have on product cost depending on the variation of the machine's allocation.

Another interesting analysis to understand the effect of fixed costs on part cost is to analyse the effect of the WAAM process on total part cost when machine allocation varies since the WAAM process is the process with the highest cost. Figure 3-18 shows the variation

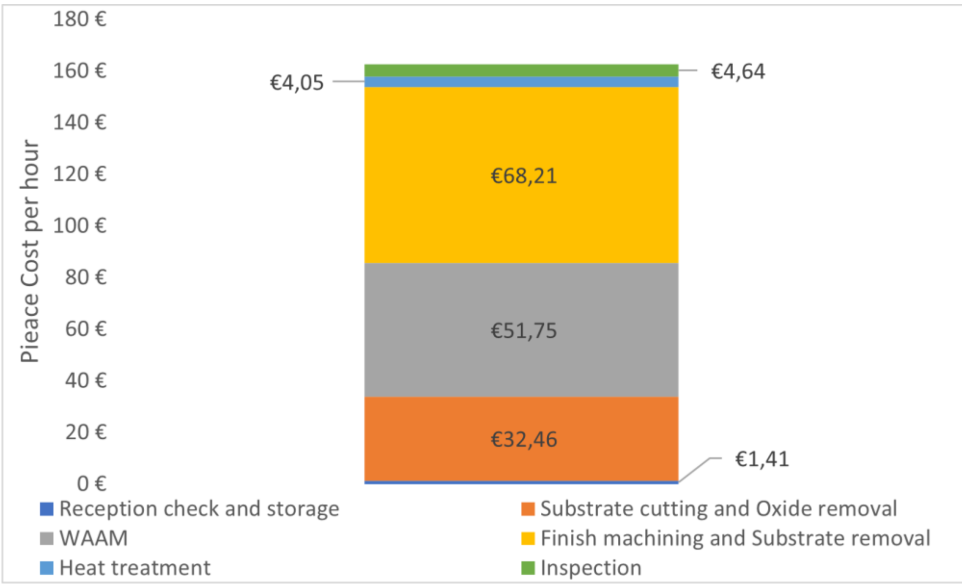

Figure 3-16 Process cost per hour

in product cost when the WAAM machine is dedicated and when the uptime is equal to the available time depending on the production volume. It should be noted that the effect in both curves is very similar to what was seen previously, with the only difference being when the uptime and available time are equal, and the production volume is reduced, the curve shows a high value of about 7300 € due to the other machines have constant allocation values, and therefore the fixed costs allocated to a part are higher.

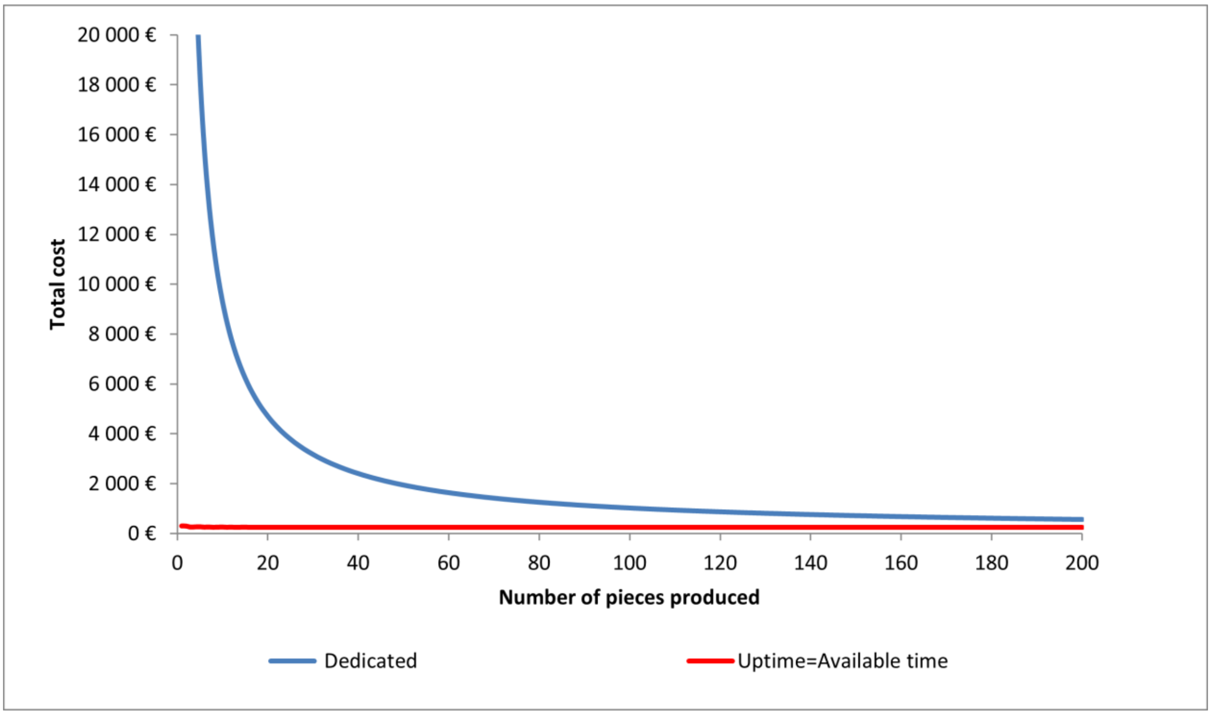

Figure 3-17 Model cost boundaries depending on processes allocation

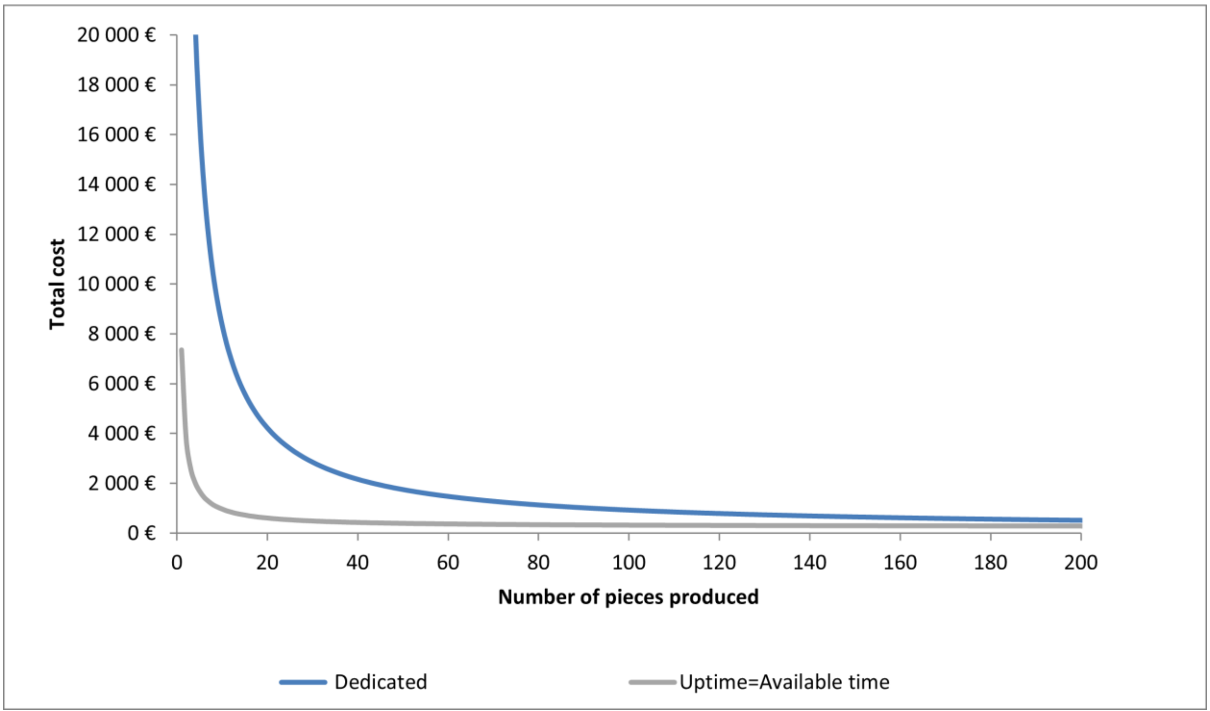

Figure 3-18 Model cost boundaries depending on WAAM allocation

4.
Conclusions and Future Work

Considering the smart WAAM project, it was established as an objective to develop a LCC model that would allow to compute and estimate the cost of producing WAAM products. This way, a PBCM that estimates the costs of implementing a hybrid WAAM system with additive and subtractive technologies was developed. The developed model allowed to estimate the costs associated with each phase of the product life cycle using a cradle-to-gate approach. Furthermore, the model was applied to estimate the cost of producing 500 hollow cubes of stainless steel AISI316LSI with 7x7x7 cm. Finally, it was possible to identify the main cost drivers of the production system studied. Therefore, this paper provides a PBCM that allows to analyse the economic viability of a WAAM production system before its implementation or obtaining the cost of an existing system. In this way, the PBCM developed is an essential tool for decision-making since, besides estimating the costs inherent to the 500 hollow cubes scenario of WAAM technology implementation, it also allows an economic analysis of an existing system to make it more efficient.

By applying the proposed PBCM, it was possible to estimate that the production of 500 hollow cubes would cost 259.95 € per piece. This value includes all variable and fixed costs associated with production. It was also possible to identify that the fixed costs are higher than variable costs, the former being 57% and the last 43% of the total cost. On the other hand, it can be observed that, in general, the highest costs are the machine cost, which represents about 37% of total costs, the tooling cost with about 23% and the overheads cost with about 16% of total costs.

In a subsequent analysis, it was identified that the processes that most influence the total costs, approximately 84%, are the WAAM process, due to the high cost of the machine, and the finishing machining and substrate removal process, due to the cost of the machine and the cost of the milling cutters required, since they cost 168.92 € and 78.47 € per piece respectively. Another interesting point was the analysis of the weight of the cutters' cost in the finish machining and substrate removal, which was identified as being around 77 % of the total cost pf the process.

When the process is analysed in terms of cycle time, the longest process is WAAM, with about 50 % of the total time. For this reason, when costs are calculated per hour, the WAAM process becomes the second highest, with the cost of finish machining and substrate removal rising to the highest.

Finally, the variation curves of the total cost per piece for a scenario where the processes are dedicated and another where the available time was equal to the uptime was analysed. This analysis made it possible to identify the cost boundaries when the production volume and idle time vary. And, as expected, when the production cost increases, the total cost per piece decreases significantly. This analysis was also made for a scenario where the only process considered a dedicated one was WAAM, and the other processes were in normal conditions. The conclusions were identical, being the only difference the first values of the curve, where the available time is equal to uptime, since the cost per piece was higher due to the other processes being in normal conditions.

Throughout the development of the model, some study limitations were identified. Firstly, the developed PBCM does not consider all WAAM products' life cycle phases, which are raw materials, design, transport, use, maintenance and end of life. On the other hand, it also does not consider the costs associated with the space occupied by the machine, as it was considered that the space occupied would be identical to traditional manufacturing production.

Concerning the model application, some limitations were also identified, such as the fact that a scenario was considered without the possibility of verifying the results. Another limitation of this study was that a low complexity piece was studied. This could hinder possible comparison with other production methods.

Since the production volume was small, making it impossible to assess the effect of the price at which the wasted material could have been sold. Data regarding the quality of the processes were also not considered. Although it was considered during the model development, the amount of material that must be reworked and the costs associated with these activities were not considered for the model application. At last, the sales price of the scrap from the parts that do not pass and cannot be reworked was also not considered.

Considering that WAAM technology is understudied compared to other technologies and has a lot of interest in the industrial context, some suggestions for future works will now be proposed. Firstly, the developed PBCM must be used for other parts with different complexities and materials to ascertain the model's ability to study WAAM parts and improve it. Since WAAM technology is emerging, the model should be updated to consider other developments and improvements that could change the PBCM accuracy in future works. On the other hand, it may be helpful to complement this model with the costs inherent to the other life cycle stages to compare better this technology to the traditional ones. Finally, it is also important to develop further studies on the economic viability of the WAAM technology and compare it with other processes in order to better understand in which scenarios the WAAM technology represents an added value for the production process in economic terms.

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APPENDIX

Appendix 1

Goal Definition

The first step of a LCA is defining the goal, where the study's objective is well defined and described. This is a vital step due to this phase's influence on all the LCA stages. Since the decisions made in other steps should be consistent with the goal. However, other phases' constraints may require a revision of the goal definition. (Bjørn, Laurent, et al., 2018)

According to Bjørn, Laurent, et al. (2018), the definition of the goal involves six aspects accordingly to ISO requirements, which are:

1. Intended applications of the results
2. Limitations due to methodological choices
3. Decision context and reasons for carrying out the study
4. Target audience
5. Comparative studies to be disclosed to the public
6. Commissioner of the study and other influential actors.

Aspects 1 and 3 are vital due to their importance in the decisions made in other stages of the LCA. The other aspects are related to communicating the results of an LCA.

The determination of the intended applications of the results is an important aspect due to the influence that it will have in later LCA phases, like drawing system boundaries, sourcing inventory data and interpretation of the results (Bjørn, Laurent, et al., 2018).

The second aspect is related to the limitations due to methodological choices, this will determine what the LCA results can and cannot be, for example, if a comparative study does not consider one or more life phases, it is essential to highlight how that choice limits the interpretation of results. The limitations stated here must be related to the goal and scope phases of an LCA, other choices made due to constraints must be documented at a later point (Bjørn, Laurent, et al., 2018).

Like the first aspect, the decision context and the reasons for carrying out the study are vital due to its influence in later stages. The reasons for carrying out the study must be understood and clearly connected to the intended application of the study (Bjørn, Laurent, et al., 2018).

The goal definition must state the target audience of the LCA study and clearly state if the LCA is a comparative study, and if it is to be disclosed to the public, it must have to fulfil the ISO requirements. At last, the commissioner and other influential actors must be stated to prevent conflict of interest (Bjørn, Laurent, et al., 2018).

Scope Definition

The second step of a LCA study is the scope definition. This phase clarifies the product system and how it should be assessed. For this purpose, the scope must have nine essential items, which, according to Bjørn, Owsianiak, et al. (2018), are:

- **Deliverables**: the deliverables must be in accordance with the proposed application of results defined in the goal definition.
- **Object of assessment**: the scope must have a precise and quantitative description of the function of the product system. The function unit defines the qualitative and quantitative aspects of the function. This usually includes a function and answers typically the following questions: what? How much? For how long? Where? How well? After the definition of the function unit, it is necessary to determine the reference flow. The quantity of product is needed to realise the function unit.
- **LCI modelling framework and handling of multifunctional processes**: in this part, the choice is made for the appropriate LCI modelling framework and the way that the multifunctional processes will be handled. The LCI framework can be defined in two different approaches, the attributional and consequential modelling frameworks. The attributional modelling framework answers the question: What environmental impact can be attributed to the product? The consequential modelling framework answers the question: What are the consequences of consuming the product?
- **System boundaries and completeness requirements**: the system boundaries demarcate the product system to be studied from the surrounding environment. Usually, the system boundaries are not ideal due to three reasons. The first reason is that most of the studies do not focus on all the life cycle stages (e.g., cradle-to-gate approach), the second reason is that, if the LCA has a comparative nature, some of the unit processes and its quantities may be similar. The last reason is that ideal boundaries are almost impossible to achieve since a unit process typically needs around 5-10 material or energy inputs that require another 5-10 inputs to be produced. The completeness requirements share the actual environmental impact of a product that the LCA aims to capture.
- **Representativeness of LCI data**: the representativeness of LCI data has three interrelated dimensions: geographical, time-related, and technological. The scope definition must express the guidance and requirements for the inventory analysis regarding to representativeness of the LCI data.

- **Preparing the basis for the impact assessment**: This item has two purposes. The first is to ensure that it is done according to the goal definition. The second is to prepare the inventory analysis since the elementary flows depend on the impact categories of the LCA.
- **Special requirements for system comparisons**: To compare two product systems that fulfil the same function, the ISO 14044 standard proposes some special requirements for the scope definition to guarantee that the product systems may be compared. To ensure the trustworthiness of the LCA, the international life cycle data guidelines propose that the uncertainties must be evaluated and communicated and that if a single indicator makes the comparison, this information must be highlighted.
- **Critical review needs**: A critical review is not always required, but a review made by experts not involved with the study is useful to increase the study's quality and credibility.
- **Planning reporting of results:** It is essential that the report must be clear and transparent to prevent erroneous and misleading use of the LCA.

Life Cycle Inventory Analysis

The Life Cycle Inventory Analysis aims to collect and compile data on elementary flows from all processes. The LCI output is a list of quantified elementary flows that cross the system boundary, and it will be the input in the LCIA phase. Sometimes, this phase involves the adjustment of the scope requirements. The LCIA, typically, is the step that needs more resources and effort. It is difficult to collect the highest quality data due to the cost that this would involve, but, fortunately, it is not required in most cases. Thus, the LCIA needs a structured approach to ensure that efforts are spent on collecting data related to the most important phases of the product's life cycle (Bjørn, Moltesen, et al., 2018).

Bjørn, Moltesen, et al. (2018) refer to six steps to do the LCIA, which are:

- **Identifying processes for the LCI model**: This step identifies the processes and their links and draws the initial system diagrams. The initial system diagram is made under the scope item, system boundaries. First, to detail the physical value chain, it is necessary to start with the reference flow and then construct the foreground. This process is done by levels, where: level 0 is the unit process; level 1 are the processes needed to deliver physical flows; level 2 is the processes required to provide flows that perform a supporting function; level 3 is the processes necessary to deliver services to the level 0 processes; level 4 are the processes required to produce and maintain the infrastructure. After identifying all the processes, this method is applied to the other level processes, commonly, the processes belonging to levels 3 and 4 are omitted because their contribution is insignificant, and it is difficult to find data.

- **Planning and collecting data**: The main objective of the planning step is to balance the data collection efforts based on the relevance of the data information. The data collection depends on the specificity level, which can be very high and high, medium, low, and very low. The very high specificity data are the inputs and outputs measured on-site, while high-quality data, usually, can be modelled from other site-specific data. Medium specificity data are collected from LCI databases or from the literature related to the specific process. The low specificity data are collected from the generic LCI database process or data from the literature. At last, very low specificity data is collected based on an expert or LCA practitioner's judgement.
- **Constructing and quality checking unit processes**: It is advisable to study several production cycles to guarantee that all the data covering a product is analysed. Sometimes the data collection covers one year of production to gather enough data that represents the full operation cycle of the process studied. To avoid the risk of constructing incomplete unit processes or existing errors in the data flow, it is advisable to check them before using them in the LCI model.
- **Constructing LCI model and calculating LCI results**: The inventory modelling is commonly done using dedicated software that supports the construction of the product system model, connects the relevant unit processes, links to available databases, and links the elementary flows in the inventory results. The LCI results are all the elementary flows in the process to be studied.
- **Preparing the basis for uncertainty management and sensitivity analysis**: It is important to analyse the study's uncertainty and sensitivity, understand how robust the LCI results are, and advise where future studies should focus. Uncertainty analysis allows to quantify the uncertainties of the result. Sensitivity analysis allows identifying the parameters that most influence the LCIA results. It is important to consider the parameters data to be analysed since it is unnecessary to collect all the process data for the sensitivity and uncertainty analysis.
- **Reporting**: The reporting of the inventory analysis must have the documentation of the LCI model at the system level, of each unit process, metadata, LCI results, data collected for uncertain and sensitivity analysis, and it must contain the assumptions of each life cycle stages.

Life Cycle Impact Assessment

Life cycle impact assessment is the fourth step of the LCA, and it aims to assess the magnitude of the contribution of each elementary flow to an impact on the environment. It is done by examining the product system using impact categories and category indicators and combining those with the inventory analysis results. This phase is very important since it transforms elementary flows into potential environmental impacts. The LCIA, in most cases, is done by using a LCA software that enables the automatization of this phase, letting the LCA practitioner to choose the LCIA model and the necessary settings. It is important to note that impacts resulting from this phase must be interpreted as impact potentials and not as actual impacts, risks, or safety margins (Rosenbaum et al., 2018).

The ISO 140040/14044 distinguish the LCIA steps between mandatory and optional steps. So, according to ISO 14040/14044, the mandatory steps of a life cycle impact assessment are:

- **Selection of impact categories, category indicators and characterisation models**: This phase must be in accordance with the goal and must be done during the scope definition to guarantee that the inventory data collection is targeted towards what is to be assessed in the end. The impact categories selection must be in accordance with the ISO guidelines that define that the impact categories cannot be redundant nor lead to double counting nor disguise significant imparts and must be complete and allow traceability. According to ISO, the selection for impact categories, category indicators, and characterisation models shall be consistent with the goal and scope definition, justified in the study report, comprehensive regarding environmental issues and well documented with all the information and sources being referenced.
- **Classification**: Normally, this step is handled automatically due to the considerable understanding that is needed.
- **Characterisation**: In this section, all elementary flows are assessed according to their contribution to an impact.

According to ISO 14040/14044, the optional steps of a LCIA are:

- Normalisation
- Weighting
- Grouping

Life Cycle Interpretation

The last phase of a LCA study is the interpretation, where the other phases results are analysed considering the limitations, uncertainties and assumptions made during the study. Hauschild et al. (2018) point out three main steps for the interpretation phase, which are: the identification of significant issues, the evaluation of the issues and the presentation of conclusions, limitations, and recommendations.

Significant issues to be identified can be methodological choices and assumptions, inventory data, weighting factors, characterization, and standardization. To assess the relevance of each issue, it can be used a sensitive analysis or a dominance analysis. To assess discrete choices done during the other stages of an LCA study, new scenarios with different possibilities can be created to determine the influence on the results (Hauschild et al., 2018).

The second element of the life cycle interpretation is the evaluation stage, where the stability and reliability of the results from the identification step are determined. This phase guarantees the strength of the conclusions and recommendations. The evaluation involves three elements: completeness check, sensitivity analysis and uncertainty analysis and consistency check. The first element serves to see if the significative data is complete. The second element is the sensitive check, identifying the most important elementary flows and key processes. The last element is the consistency check, verifying if the assumptions, methods, and data are consistent with the goal and scope. When the consistence check is being applied to a comparative study, it is necessary to evaluate the consistency of the allocation rules, boundaries settings and impact assessment (Hauschild et al., 2018)

The last step of the life cycle interpretation is drawing conclusions, limitations, and recommendations. The conclusions must be in accordance with the requirements defined on the scope and should be based on the significant issues and the evaluation of sensitivity, completeness, and consistency. The recommendations should be based on significant results and relate to the intended application of the study (Hauschild et al., 2018).

Appendix 2

The following appendix presents some of the sensitive analysis charts.

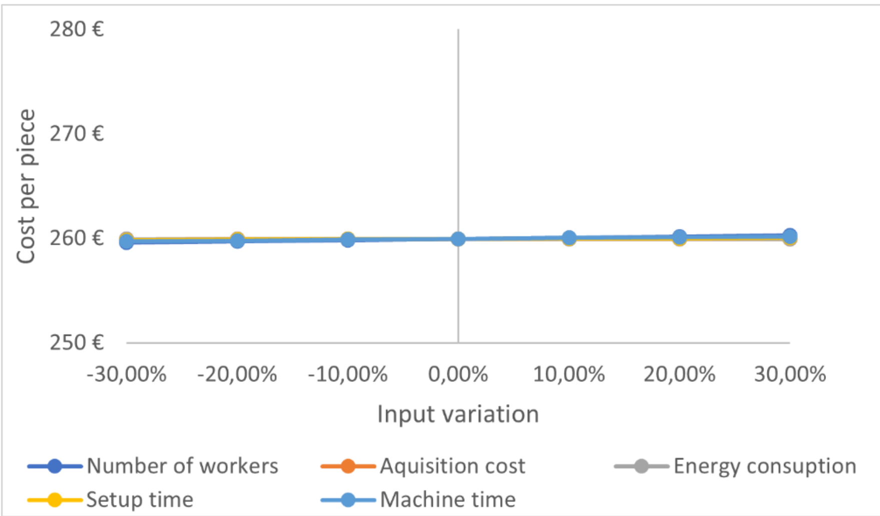

Figure A2-1 Substrate cutting and oxides removal inputs sensitive analysis

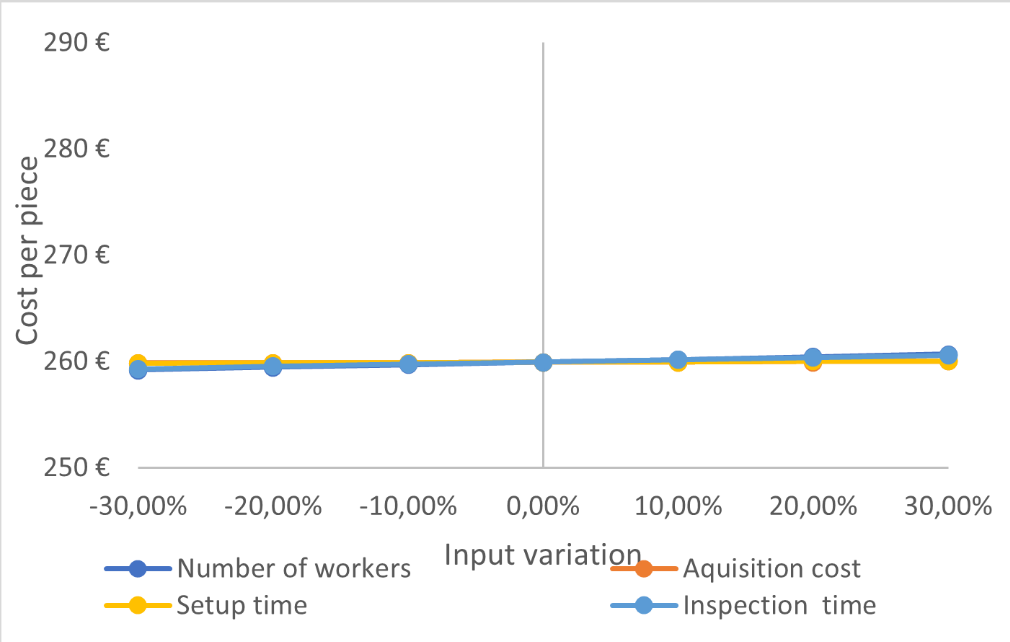

Figure A2-2 Substrate cutting and oxides removal percentage inputs sensitive analysis

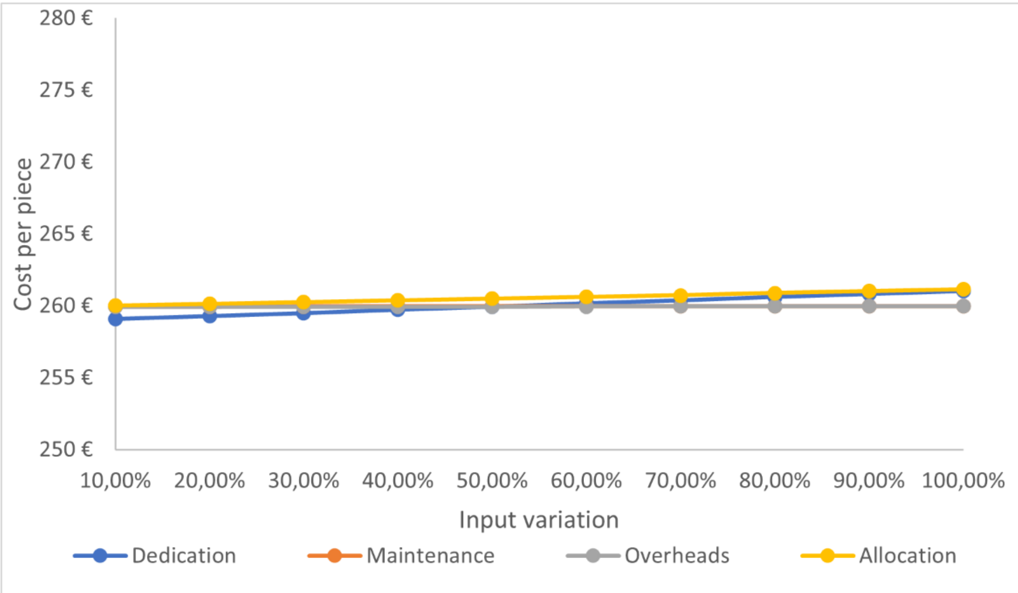

Figure A2-3 Heat treatment inputs sensitive analysis

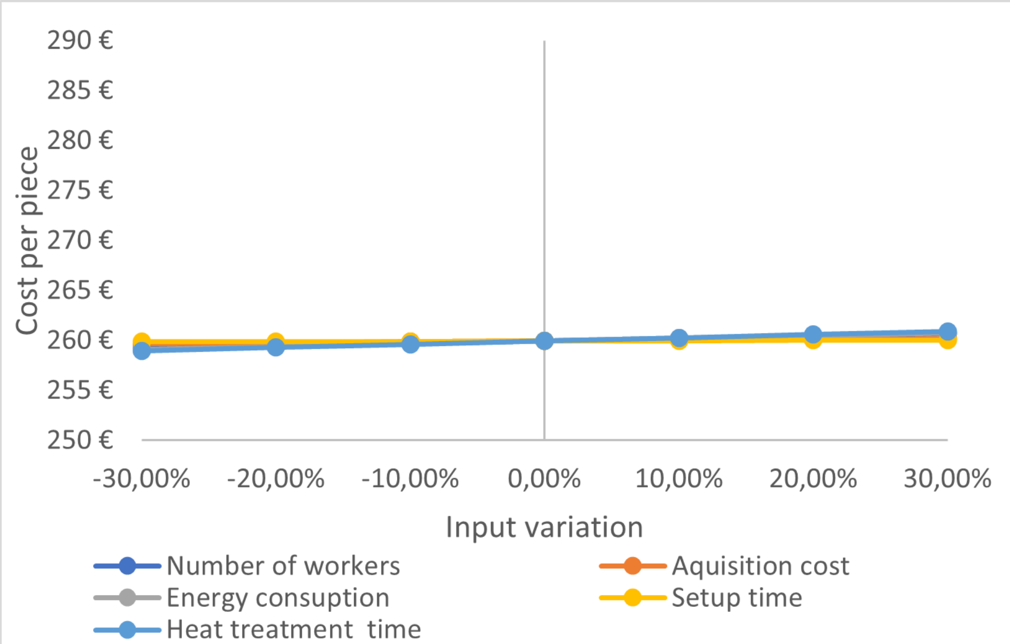

Figure A2-4 Inspection inputs sensitive analysis

2022

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A PROCESS-BASED COST MODEL FOR WIRE AND ARC ADDITIVE MANUFACTURING

NOVA SCHOOL OF SCIENCE & TECHNOLOGY