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NOVA SCHOOL OF
SCIENCE & TECHNOLOGY

DEPARTMENT OF
Mechanical and Industrial Engineering

LIFE CYCLE ASSESSMENT OF PRODUCTS FABRICATED BY WIRE ARC ADDITIVE MANUFACTURING

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BSc in Engineering Sciences and Industrial Management

INTEGRATED MASTER IN INDUSTRIAL ENGINEERING AND MANAGEMENT

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September, 2022



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Life cycle assessment of products fabricated by wire arc additive manufacturing

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ACKNOWLEDGMENTS

In the first place, to Professor Doctor Radu Godina and Ph.D. Candidate Samruddha Kokare for guiding me, for teaching me, for all the suggestions, and above all for always trying to understand my difficulties, during the development of this thesis. My sincere thank you for the effort made and for being an example of professional excellence.

I would also like to express my deep gratitude to all the FCT-Nova community that got me where I am today, all the professors who accompanied me along the way, and all the friends that I made.

To my parents, for trying to give me opportunities that they didn't have and for always doing the best that they could, a big thank you.

To all my family and to all my friends that became family and supported me since day one, and in special, to my grandfather whom I know would love to be here. I promised I would always make you proud.

To all of the experiences and people that I've met in these five years, thank you for making me grow and for letting me become who I am today.

To my boyfriend, for making life lighter and easier to enjoy. I am grateful for having you with me and for sharing this moment with you.

To the past, the present, and the future, thank you.

ABSTRACT

The industrial progress made throughout these years, allowed to obtain great results in terms of producing fast and with good quality. However, the impacts related to that production, whether these are environmental, economic, or social have been, at times, neglected. The manufacturing sector, as one of the most pollutants, felt the urge to adapt to this industrial progress and find ways to produce with a greener mentality without compromising the quality of the final product and the production time.

The industry easily understood that they could only benefit from this approach, given the fact that a greener mentality involves a series of factors that limit the need for reinvestments. Society itself has also become more environmental aware and stricter environmental legislations have been created. Consumers started prioritizing greener products and sustainable productions that comply with those legislations. With this in mind, new sustainable technologies emerge and improvements to the technologies that already exist are made. Additive Manufacturing (AM) is one of the revolutionary technologies that provides alternative and more sustainable paths to the traditional manufacturing.

The proposed work has the intent of recognizing the environmental impacts associated with a particular AM technique for the fabrication of metal parts, the Wire Arc Additive Manufacturing (WAAM). Firstly, a global overview on AM processes is made. Afterwards, WAAM is analyzed with further detail identifying, through literature, the main challenges underlying. In order to validate some of these challenges found, three case studies were conducted considering the Life Cycle Assessment (LCA) methodology. The practical work was based on the production of different complexity metal parts considering an AM process and, for greater context on the subsequent results, a subtractive manufacturing process. The quantification of the environmental impacts not only allowed a comparison between both types of manufacturing but also enabled the identification of the main environmental hotspots and consequently the suggestion of measures to decrease the impacts related to them. The results were obtained for this particular application and it is acknowledged that in order to reach a global understanding relative to this technology's environmental implications, extra research still needs to be made.

Keywords: Additive Manufacturing, Traditional Manufacturing, Industrial progress, New Sustainable Technologies, Wire Arc Additive Manufacturing, Environmental impacts, Life Cycle Assessment

RESUMO

Os progressos industriais realizados ao longo destes anos, permitiram obter grandes resultados em termos de uma produção rápida e de boa qualidade. Contudo, os impactes relacionados com essa produção, sejam estes ambientais, económicos ou sociais, têm sido, por vezes, negligenciados. O sector industrial, como um dos mais poluentes, sentiu a necessidade de se adaptar a estes progressos industriais e encontrar formas de produzir incorporando uma mentalidade mais verde sem comprometer a qualidade do produto final e o tempo de produção.

A indústria facilmente compreendeu que só poderia beneficiar desta abordagem, visto que uma mentalidade mais verde está relacionada com uma série de fatores que restringem a necessidade de reinvestimentos. A própria sociedade também se tornou mais ambientalmente consciente e criadas legislações ambientais mais rigorosas. Os consumidores começaram a dar prioridade a produtos mais ecológicos e a produções que cumprissem essas mesmas legislações. Com estes progressos surgiram novas tecnologias sustentáveis e as tecnologias já existentes foram melhoradas. O fabrico aditivo (FA) é uma das tecnologias revolucionárias que proporciona caminhos alternativos e mais sustentáveis para o fabrico tradicional.

O trabalho proposto tem a intenção de reconhecer os impactes ambientais associados a uma técnica de FA particular, o Fabrico Aditivo através de Arco Elétrico. Em primeiro lugar, é dada uma visão geral acerca dos processos de FA. Posteriormente, o Fabrico Aditivo através de Arco Elétrico é analisado com mais detalhe e, através da literatura, são identificados os principais desafios que lhe estão subjacentes. Com o intuito de validar alguns destes desafios encontrados, foram realizados três estudos de caso considerando a metodologia de Avaliação do Ciclo de Vida (ACV). O trabalho prático baseou-se na produção de diferentes peças metálicas, considerando um processo de fabrico aditivo e, de modo a se conseguir contextualizar os resultados obtidos, um processo de fabrico subtrativo. A quantificação dos impactes ambientais permitiu, não só comparação entre ambos os tipos de fabrico como também permitiu a identificação dos principais pontos críticos ambientais e, consequentemente, a sugestão de medidas para diminuir os impactos relacionados com os mesmos. É de ressaltar que, os resultados foram obtidos para esta aplicação específica e reconhece-se que para se chegar a um entendimento global relativamente às implicações ambientais desta tecnologia são necessários mais desenvolvimentos.

Palavras chave: Fabrico Aditivo, Fabrico Tradicional, Progresso Industrial, Novas Tecnologias Sustentáveis, Fabrico Aditivo através de Arco Elétrico, Impactes Ambientais, Avaliação do Ciclo de Vida

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ACRONYMS

ACV	Avaliação do Ciclo de Vida
ADAM	Atomic Diffusion Additive Manufacturing
AM	Additive Manufacturing
ASTM	American Society for Testing and Materials
CLIP	Continuous Liquid Interface Production
DLP	Digital light processing
DMLS	Direct metal laser sintering
EBAM	Electron Beam Additive Manufacturing
EBM	Electron beam melting
FA	Fabrico Aditivo
FDM	Fuse deposition modelling
FFF	Fused Filament Fabrication
GMAW	Gas Metal Arc Welding
GTAW	Gas Tungsten Arc Welding
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory

LCIA	Life Cycle Impact Assessment
LENS	Laser Engineered Net Shaping
LMD	Laser metal deposition
LOM	Laminated object manufacturing
MJF	Multi Jet Fusion
MJP	MultiJet printing
PAW	Plasma Arc Welding
SJP	Single Jet Passing
SLA	Stereolithography
SLCA	Social Life Cycle Assessment
SLM	Selective Laser Melting
SLS	Selective Laser Sintering
UAM	Ultrasonic Addition Manufacturing
WAAM	Wire Arc Additive Manufacturing
WFR	Wire Feed Rate

INTRODUCTION

This first chapter's main goal is to explain the focal point of the dissertation. The background and motivation, the problem description and objectives, the methodology used, and the structure of the study are described in this section.

1.1 Background and motivation

Over the past years, with industrial progress, there has been intense exploitation of natural resources that have taken drastic proportions and started to cause considerable impacts on the environment, the economy, and society [1]. This has led to a restructuring of society's thinking where environmental awareness is prioritized and the urge to make several changes to achieve a sustainable way of living arises. Apart from the pressure made by the consumers to produce greener products [2], stricter environmental legislation was created to constrain companies to comply with a more sustainable production process [3], [4]. As one of the most pollutants, the manufacturing sector needed to take action and adapt according to these major changes. One of the main challenges of this sector is finding out how to produce faster, using less raw material, and without compromising the quality of the final product [5].

Once industries started to adapt the production processes to a greener mentality (reduction of material waste, consumption of resources, energy, and emissions of CO₂ and other greenhouse gases), realized that, in the long term, could also benefit monetarily from these changes. For example, concepts like the circular economy, where the preservation of natural resources (many of them raw materials) is a priority, start to be implemented and can lead industries to more effective and efficient production, without disregarding the environmental impacts [1], [6]. In this sense, with the need of creating new sustainable technologies and improving the ones that already exist to obtain higher efficiency, the fourth industrial revolution,

also known as Industry 4.0 arises [7]. As one of the key elements of Industry 4.0, AM is seen as a revolutionary technology that incorporates sustainability into manufacturing systems and provides alternative paths to the traditional manufacturing for producing parts or products [1], [4], [7]–[10].

AM consists of the production of physical objects from 3D computer-aided design (CAD) files by building layers of material [3], [5], [7], [10]–[13]. The 3D printing production process has become increasingly popular due to its ability to optimize the production of a product or part through weight reduction, customization, and complex shapes printing, without the need for additional resources [4], [7], [8], [11], [12], [14]. In addition, this technology also allows the reduction of several costs, for example, costs of production, logistics, inventories, development, and industrialization of a new product, and the reduction of time-to-market [4], [12]. Not devaluing the advantages, it is worth noting that this technology also has some problems, mainly in terms of environmental impacts (high energy consumption) and production constraints (non-appropriate for mass production). These limitations need to be further exploited to fulfill the main goal of finding a solution that optimizes the production process, providing not only high-quality products but also reducing the costs and environmental impacts. As such, were developed tools that facilitate analysis and subsequent evaluation of the environmental impacts, being LCA one of them [15]. Therefore, by conducting a LCA on the production of metallic parts through the WAAM process, this dissertation will contribute to the developments in this field.

1.2 Problem description and objectives

With the growing environmental concern in society and the stricter legislation, the manufacturing sector had to suffer some changes. The urgency to find how to lessen the environmental impacts related to the manufacturing of a component led to the development of alternative processes such as AM. Despite proven to be, in some particular applications, environmentally friendlier than Traditional Manufacturing, it is still required further research on that topic. The present study will contribute to that research.

This dissertation has the main purpose of providing a general overview of the environmental issues related to a specific AM process, responsible for the printing of metal parts, WAAM. To give the essay some context, it is also necessary to approach the issues related to Traditional Manufacturing, specifically the issues related to a traditional manufacturing process that equally approaches the production of metal parts. In this sense, the Computer Numerical

Control (CNC) Milling process was considered. The LCA methodology was applied to three particular case studies in order to characterize with greater detail the environmental impacts of both types of manufacturing. With the results obtained, several conclusions relative to their environmental performance were withdrawn, and consequently, measures to decrease their impacts were suggested. The specific objectives of the present study may be summarized in the items below:

- The quantification and comparison of the environmental impacts involved in WAAM and CNC Milling processes by using the LCA methodology
- The identification of the main environmental hotspots in both technologies based on the results of the LCA study
- The suggestion of measures to decrease the environmental impacts related to the main hotspots identified

1.3 Methodology

In order to understand in detail the main topics of this dissertation, a preliminary study was done regarding the manufacturing of metal components through traditional and additive manufacturing processes, as well as the LCA methodology. After an introductory notion of these concepts and a contextualization of their applications, it was possible to initialize, with the correct approach, the proposed case studies. Subsequently, a quantitative and qualitative analysis of the results was obtained and final report with the conclusions and suggestions to be applied was elaborated. **Figure 1.1** is a schematic representation of the methodology used throughout the dissertation.

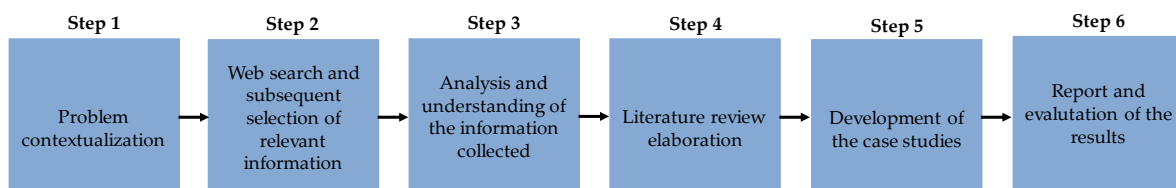


Figure 1.1. Project methodology

The first step, involves understanding the objective of the study and the main topics to be addressed: "what is an LCA? what is the LCA methodology? What benefits does an LCA provide? How is the additive manufacturing process applied to metals? What are the advantages of using additive manufacturing processes instead of traditional manufacturing processes in metal production? Does the LCA methodology already been applied to additive manufacturing products, and if so, what conclusions can be drawn from that application?". In the

second step, a systematic search was conducted, using search engines (e.g. Scopus) to find papers, journals, and book chapters relative to the questions posed previously. The search was made between the months of February and April of 2022, the majority of the publications considered were recent (2017-2022) and had an abstract and/or content regarding Additive Manufacturing, Traditional Manufacturing processes, and Life Cycle Assessment. Given the extent of the application of the LCA methodology, it was also necessary to filter the search by selecting only the publications that are related to the relevant areas for this particular application. The main keywords used in the search were "Life Cycle Assessment", "LCA", "Additive Manufacturing", "AM", " Life Cycle Assessment in Additive Manufacturing", "Life Cycle Assessment" AND "Additive Manufacturing", "Life Cycle Assessment" AND "Wire Arc Additive Manufacturing", "Environmental impacts" AND "Wire Arc Additive Manufacturing", "Traditional Manufacturing Processes for metals" and "Traditional Manufacturing Processes vs Additive Manufacturing", etc. In the third step all the information that has already been collected is reviewed and re-filter, so that only the crucial is referred to in the study. The fourth step enables a summary and an explanation of everything that has so far been considered relevant during the research. Afterward, after studying and understanding all the issues involved, it is initiated the fifth step, the development of the case studies using the LCA methodology. Finally, in the sixth step, all the results obtained are reported and evaluated to conclude and suggest subsequent improvements to the process used.

1.4 Dissertation structure

The present dissertation is structured into **four chapters**.

The first chapter, the **Introduction**, presents the background and motivation of the study, the problem description, objectives, the approaches that were made as well as the contributions and dissertation structure.

The second chapter, the **Literature review**, presents the theoretical background that supports the work developed. This chapter gives a brief notion of one of the most used traditional manufacturing processes related to the production of metals, the Computer Numerical Control (CNC) Milling. Next, there is a sub-chapter dedicated to AM, that contains the characterization of the technology, the challenges and limitations, and a specific part dedicated to a technique that is included in the AM technologies, WAAM since it is the chosen technology for the case studies developed. To finish all the important subjects related to this work, the LCA

methodology is also explained and further detailed, accordingly to ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines [16].

The third chapter, **Case Studies**, has the purpose of characterizing the environmental impacts associated with CNC Milling and WAAM through the conduction of an assessment, considering the requirements and guidelines of the methodology previously approached in chapter two. The LCA methodology was applied to three case studies, whose main difference was the geometry being produced. The specification of the goal and scope of the study along with the assumptions and limitations, of the functional unit, the system boundaries, and the LCI was made. The chapter concluded with some additional observations.

In the fourth chapter, **Results**, it was made a joint analysis of the results obtained that consequently enabled an understanding of the environmental impacts involved in the production of each geometry, for both technologies considered. Final conclusions were withdrawn and based on that, suggestions to decrease the environmental impact associated with WAAM and CNC Milling were elaborated.

The last chapter, **Conclusions**, made a summary of the dissertation's main contributions. Additionally, the limitations of the study were pointed out and future work recommendations were presented.

LITERATURE REVIEW

This chapter presents a theoretical background to support the work developed. It begins with a small introduction to the traditional manufacturing processes and further specifies CNC Milling technology. Afterward, it is done an AM characterization and subsequently an identification of its challenges and limitations. This is followed by an overall view of WAAM. Lastly, the chapter abords the LCA methodology accordingly to ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines [16].

2.1 Traditional Manufacturing Processes

Technologies have been evolving through the years and, as an alternative and/or complement to the traditional manufacturing processes, it appeared AM processes. AM has presented several improvements and started to be considered in the manufacturing industry since it was proven to be a flexible technology that requires minimal post-processing and has a cost-effective good relationship, opposite to subtractive manufacturing [17], [18]. As this thesis is based on the printing of metallic parts, it is important to make a parallel between the normally used processes and the alternative processes that emerged. This chapter has the purpose to give an introductory notion of one of the most used processes in this type of production, the Computer Numerical Control (CNC) Milling.

2.1.1 Computer Numerical Control Milling

Per definition, CNC milling is a machining process that allows the production of a custom-designed part or product through the progressive removal of the material from a single workpiece [19]. **Figure 2.1** schematized the whole production process. In the first place, it is necessary to establish the inputs: the raw material, the CNC machine, the cutting tools, and the machining technology. Afterward, it is essential to define the process parameters and consecutively the milling sequence that leads to the final product. After the process is finished, quality control is made to distinguish the conforming from non-conforming products. When

comparing this traditional manufacturing process with the new emergent technologies, the main disadvantage mentioned in the literature is related to the high energy consumption and low energy efficiency of the process itself. Several mathematical models have been developed and proposed in an attempt to solve these problems, however, still remains the need to exploit them for further application due to the complexity of the characteristics of a CNC machine[20].

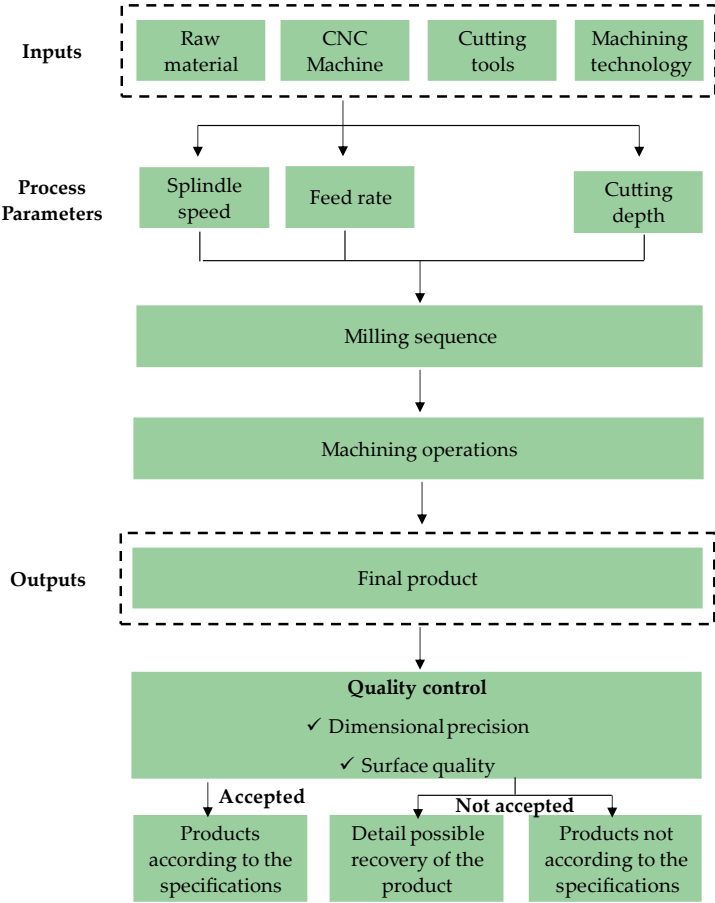


Figure 2.1. CNC process. Adapted from [21], [22]

2.2 Additive Manufacturing

AM emerged as a ground-breaking technology and allowed the industrial sector to produce components or products while taking process sustainability into account [1], [4], [7]–[10]. AM allows the production of a part/product through the building of successive layers of material [3], [5], [7], [10]–[13]. It has become a well-known process due to certain advantages, as such material efficiency, optimization of performance in production, product functionality/flexibility, the extent of the product's life cycle, and reduction of several costs. Nonetheless, further research in this field is required since it still has some limitations regarding the product itself and the environmental impacts that it causes [4], [7], [8], [11]–[14]. In the subsection **AM**

advantages and disadvantages, it will be explained in greater detail the main benefits and challenges of this technique. This technology has several applications throughout the product's life cycle, from the idea conception to the product development and end-of-life, as shown in **Table 2.1**. Thus, given its versatility, it is noteworthy its application in a variety of sectors, including the automotive, biomedical, home appliance, manufacturing, aerospace, maritime, and power generating industries is possible [1], [9]. This new type of approach in production processes led consequently to a diversification of the used techniques. **Table 2.2** enumerates the seven different technique categories that have been established for AM, according to the ISO/ASTM 52900:2015 Additive manufacturing — General principles — Terminology [21], and details the technologies that each category contains, the materials involved, the process itself and main advantages and disadvantages [21]–[25].

Table 2.1. Applications of AM. Adapted from [1], [7], [9], [12], [24]

Applications	Description	Phases of product life cycle
Co-creation	Active participation of customers and suppliers in the product development.	Product idea, product planning
Rapid prototyping	Rapid production of prototypes and consequently, faster time-to-market.	Product planning, product development
Rapid tooling	Production of tools and appliances only for production purposes.	Product development, production
Efficient product	Additional elements that can be incorporated into the product in order to make it more useful.	Product planning, product development
Co-production	Active participation of customers and suppliers in components production.	Product planning, product development, production
Rapid manufacturing	Fast production of components due to an increasing material diversity and to the growth of AM technology.	Production
Spare parts on demand	Production of spare parts whenever its required, avoiding unnecessary stocks and transportation.	Product application and service
Repair of wear parts	Fixing a specific area of the component that needs to be repaired.	Product application and service, reprocessing

Table 2.2. Seven categories of additive manufacturing

Categories	Technologies	Type of material	Process	Advantages	Challenges
Vat Photopolymerization	<ul style="list-style-type: none"> Stereolithography (SLA) Digital light processing (DLP) Continuous Liquid Interface Production (CLIP) 	Polymer <ul style="list-style-type: none"> Filament material Melted material Powder material (liquid) Liquid material Sheet material 	The material is selectively cured by using light activated polymerization.	High Building Speed. Good part resolution.	Overcuring. High cost for supplies and materials.
Material Jetting	<ul style="list-style-type: none"> Polyjet printing (MJP) 	Polymer <ul style="list-style-type: none"> Filament material Melted material Powder material (liquid) Liquid material Sheet material 	The material is selectively deposited in droplets.	Multi-material 3d printing. High surface finish.	Low strength material.
Material Extrusion	<ul style="list-style-type: none"> Fuse deposition modelling (FDM) Fused Filament Fabrication (FFF) Atomic Diffusion Additive Manufacturing (ADAM) 	Polymer <ul style="list-style-type: none"> Filament material Melted material Powder material (liquid) Liquid material Sheet material 	The material is selectively dispensed through a nozzle or orifice.	Inexpensive extrusion machine. Multi-material printing.	Limited part resolution. Poor surface finish.
Binder Jetting	<ul style="list-style-type: none"> Multi Jet Fusion (MJF) Single Jet Passing (SJP) 	Polymer <ul style="list-style-type: none"> Filament material Melted material Powder material (liquid) Liquid material Sheet material 	In order to join powder materials, the bonding material is selectively deposited.	Full-color objects printing. Wide material selection.	Require infiltration during post-processing. High porosities on finished parts.
Powder Bed Fusion (PBF)	<ul style="list-style-type: none"> Selective Laser Sintering (SLS) Selective Laser Melting (SLM) Direct metal laser sintering (DMLS) Electron beam melting (EBM) 	Metallic <ul style="list-style-type: none"> Filament/wire material Powder material Sheet material Ceramic <ul style="list-style-type: none"> Powder and liquid suspension Powder material 	The powder bed is selectively fused by thermal energy.	High accuracy and details. Fully dense parts. High specific strength. Powder handling and recycling.	Powder recycling. Support and anchor structure. High specific strength and stiffness. Fully dense parts.
Sheet Lamination (SL)	<ul style="list-style-type: none"> Laminated object manufacturing (LOM) Ultrasonic Addition Manufacturing (UAM) 	Metallic <ul style="list-style-type: none"> Filament/wire material Powder material Sheet material 	The sheets of material are bonded to form an object.	High surface finish.	Low material, machine, process cost. Decubing issues.

Table 2.2 Continuation					
Direct Energy Deposition (DED)	<ul style="list-style-type: none"> • Laser Engineered Net Shaping (LENS) • Electron Beam Additive Manufacturing (EBAM) • Laser metal deposition (LMD-w) • Wire Arc Additive Manufacturing (WAAM) 	Metallic <ul style="list-style-type: none"> • Filament/wire material • Powder material • Sheet material 	As being deposited, the material is fused by focused thermal energy.	High deposition rate compared to PBF process. Repair of damaged/worn parts. Functionally graded material printing.	Require post-processing.

2.2.1 AM advantages and disadvantages

For a better understanding and a global overview of the main advantages and disadvantages of AM, **Table 2.3** and **Table 2.4** were elaborated.

Table 2.3. Advantages and Opportunities of AM

Advantages and Opportunities	Description	References
Growing environmental concerns and stricter environmental legislation	Due to increasing environmental awareness over the past years, the manufacturing industries were forced to adapt their production according to a more sustainable approach. A company known as environmentally friendly and worried about a greener production will lead to higher customer satisfaction.	[3], [4], [10]
Resource and material efficiency	AM allows the creation of a product by consequent deposition, layer by layer, of materials. Thus, due to this technology no longer exists the need to remove a substantial amount of materials and resort to additional resources (fixtures, cutting tools, and coolants) to obtain the final product. In contrast to the traditional manufacturing processes, there is practically no waste involved in the production, and the time-to-market is reduced.	[3]–[5], [7], [11], [12]
Reduced manufacturing costs	AM enables the production of several components in the same build. This and other factors like the low waste rate and the ability to quickly repair the product without the need of producing a new one might represent a reduction of the manufacturing costs.	[5], [8]–[10], [12], [14]
Longer product life cycle	AM is a very useful technology to apply in techniques that allow extending the product life cycle like, for example, repairing, remanufacturing, and refurbishing. Thereby, thanks to this technology, if the product is damaged, it can be repaired without producing a new product from scratch. Whenever it is needed, new parts can also be added to the product and old parts can be replaced by improved ones. This not only extends the life cycle of the original product as it also allows the optimization of the product performance.	[1], [3], [4], [8], [14],
Reduced supply chains complexity/dimension	AM allows a more customized production using low raw material rates and gives the manufacturing companies more freedom in the design of the product. This shortens the supply chains and leads to more localized production. Consequently, for the whole life cycle of the product, it is verified times and cost savings. There might also be a reduction in the environmental impacts.	[2]–[4], [9], [13], [14], [26]
Production flexibility	AM enables the production of complex geometric shapes in fewer parts and sometimes even in single pieces through simple manufacturing or assembly processes. In other words, AM processes are more flexible than traditional manufacturing processes and allow the production of functional products with added value. Additionally, is also possible to verify its flexibility in terms of production, as the AM machines don't need setup, and issues like production bottlenecks and line balancing are eliminated and no longer considered a problem.	[2]–[4], [11], [14]

Design flexibility and product customization	Currently, there has been pressure from the market to produce more and more diversified and customized products. This technology not only allows more freedom in product design but also makes possible the democratization of production by integrating the customer into the production process. Thus, it is possible to build single products with more complex geometries and lighter components targeted to the needs of the market.	[4], [5], [8], [9], [11], [12], [14]
No overproduction in stocks	As the production is made according to the customers' needs, there is practically no stock constitution.	[5], [9]

Table 2.4. Limitations and Challenges of AM

Limitations and Challenges	Description	References
Size and material restrictions	The 3D printers that are used in AM limit the size of the objects produced since they only can produce objects smaller than their size. It should also be noted that, even if the machine could produce very large objects, their production time would be much higher. The bigger the component is, the higher is the risk of compromising its strength. Consequently, manufacturing companies tend to don't invest in the production of large-sized objects through this technology due to its lack of strength and the higher production time.	[3], [8]
Inappropriate in high-volume production	The AM techniques are more suitable for small to medium batch production since it is a more thorough process and, therefore, has a lower speed of production. For a higher volume production it would be necessary to have several 3d machines working (which would represent unbearable costs) and still, the traditional manufacturing processes would have a higher advantage over the productivity of the process.	[3], [8], [9], [13]
Imperfections/Product Quality	This process is more independent of the operators since the only skills that are required from them are that they know the machine procedures and the materials that should be used in the production. In this sense, the product's quality depends mostly on the process performance of the process. In terms of process performance, it is known that AM has several constraints of material suitability. The materials used lead to lower quality products with poor surface finish and will require greater quality control.	[3], [9], [12]
High costs	The machinery used in the AM production represents a high investment. Nevertheless, with the development of these technologies and their establishment in the market, it is expected a price reduction over the next few years.	[3], [5], [8], [9]
Lack of standardization and reliability	General conclusions about the WAAM performance still cannot be withdrawn. The conclusions reached are mainly case specific, and therefore, non-reliable for all applications.	[9], [27]
Intellectual property issues	As WAAM easily allows design flexibility and product customization, similar products or services regarding this technology might appear, leading to copyright issues.	[9], [28]
Management issues	With the big changes that AM introduces come big challenges, such as the need to introduce operators to this new technology, supplier changes in supply chains due to more localized production, the need for creating new business models, etc.	[4], [9]
Environmental impacts	When compared with traditional manufacturing techniques, it doesn't always present environmental advantages. In addition, it can require higher energy consumption of the process and sometimes involves the emission of gases that are harmful to health.	[1], [2], [9]

2.2.2 Wire Arc Additive Manufacturing

The several categories of AM and the respective existing technologies were previously addressed. Since the main focus of this dissertation is related to a specific AM technology, WAAM, this subsection will give a brief framework on it.

WAAM is a method that enables the creation of three-dimensional shapes through welding the materials, layer by layer, using wire feedstock and standard arc welding equipment [13], [29]. **Figure 2.3** describes the main steps that are required to produce a part by using this technique. The first step involves creating a three-dimensional representation of the part being produced using processes like computer-aided design (CAD). After that, this 3D representation should be saved in a standard format so that it can be used as an input for the slicing software. The software transforms the 3D model into 2D layers, thick enough to be precisely deposited, define the appropriate parameters, and calculates an optimum path for depositing material. It should be noted that the parameters and the programming must be adapted depending on the specific material of the part being fabricated. Next, a computer numerical control (CNC) code with several program instructions is generated. That code will be sent as control information to the machine tool (robotic arm), specifying its motion, speed, and operations. After choosing the parameters and programming the machine, the product finally begins to be additively built layer by layer until the entire component is finished. In the majority of the cases, the part produced still has some quality requirements that need to be improved like low surface finish, and therefore, post-treatment processes are required [30].

Numerous alloys from the welding sector are widely used as feedstock for WAAM applications, primarily because they are readily available, affordable, and allow for multi-millimetre thicknesses for individual layers. Therefore, as approached earlier, the use of this kind of technology is prioritized by sectors including aerospace, automotive, military, nuclear energy, marine, and mould and dies [29]. **Table 2.5** was elaborated according to [30] and presents a summary of all the materials that are used in WAAM processes, as well the respective fields of applications of each one.

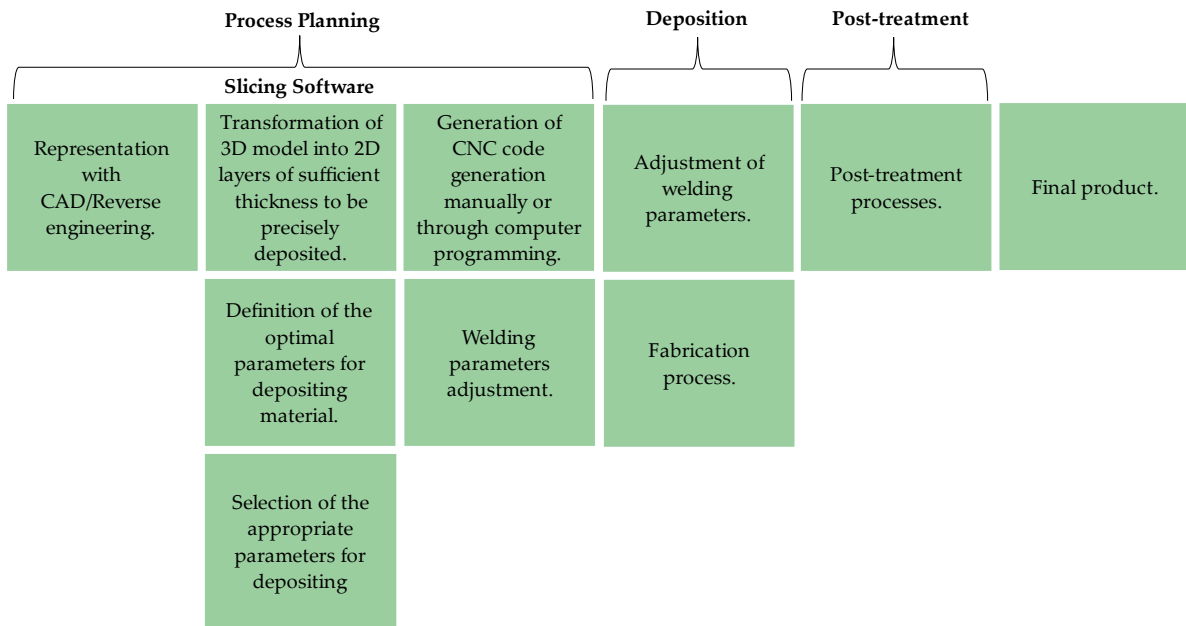


Figure 2.2. WAAM steps to create a part. Adapted from [28]

Table 2.5. WAAM process materials [32]

Materials	Applications
Titanium alloys (Ti-based) <ul style="list-style-type: none"> • The cost of materials is high • Machinability is poor • Strength-to-weight ratio is high (quite dense) • Lack of need of Hot Isostatic Pressing (HIPing) • A better tolerance for damage 	Automotive, Tools and moulds
Aluminium alloys (Al-based) <ul style="list-style-type: none"> • Necessity of post-process heat treatment to improve the mechanical properties and the microstructure • Porosity 	Marine, Corrosion resistance, High temperature, Tools and moulds
Stainless steels (Steel-based) <ul style="list-style-type: none"> • High strength at high temperatures • The yield strength, ultimate tensile strength and elongation of deposited nickel alloy are similar to those for wrought and cast materials 	Aerospace, Corrosion resistance, High temperature
Nickel-based superalloys (Ni-based) <ul style="list-style-type: none"> • High ductility • Corrosion resistance 	Automotive, Marine, Tools and moulds
Bimetal	Marine, Tools and moulds

In addition to a detailed understanding of the different materials, to obtain a high-quality product with good mechanical features, it is also imperative to have knowledge about the main inputs of the process and, to help determine how much room there is for improvement on an

environmental, social, or economic level, about the outputs. In this sense, considering WAAM technology, the main inputs are the shielding gas, electricity and the welding wire and, the outputs are the printed object, the welding spatter (waste) and emissions to air [1]. Likewise, the process parameters must be well established in a first approach and all their implications should be considered. **Table 2.6** presents a quick overview of the process parameters and specifies the important details related to them [1], [30], [31].

Table 2.6. Process parameters of WAAM. Adapted from [1], [32], [33]

Process parameters	Wire feed rate (WFR)/ Wire feed speed (m/min) <ul style="list-style-type: none"> Linear variation with bead height and aspect ratio. Inversely proportional to the wetting angle. The roughness and melt through depth are independent from this parameter.
	Travel speed/ Welding speed (mm/min) <ul style="list-style-type: none"> Linear variation with the bead roughness. Inversely proportional to bead width, wetting angle and melt. The bead height is independent from this parameter.
	Arc current (A) <ul style="list-style-type: none"> Inversely proportional to bead roughness, bead width, wetting angle, and melt through depth (heat input). The bead height is independent from this parameter.
	Voltage (V)
	Arc length (mm)
	Shielding gas flow rate (l/min) <ul style="list-style-type: none"> Not considered to be a critical input variable but necessary to control oxidation of the deposited surface.
	Printing path strategy <ul style="list-style-type: none"> If all layers are deposited in the same direction it is formed a low point at the beginning and a high point at the end of the weld path that is formed. On the other hand, if the layers are deposited by using alternating deposition directions, it is observed a small difference in height.
	Substrate temperature (°C)
	Interlayer temperature (°C)
	Heat input (°C) <ul style="list-style-type: none"> Excessive and insufficient heat input causes consequences. Therefore, depending upon the material and features of part, it is suggested a consecutive reduction of heat input by 5%, 10%, or 20%. This can be achieved if the current applied in the process is constant and if the travel speed increases with each deposited layer.
	Pre-heating (°C) <ul style="list-style-type: none"> It ensures a significant decrease in temperature gradient and consequently in cellular fine grain formation. This means mechanical properties are improved.

WAAM has three different types of processes that must be acknowledged. **Table 2.7** shows the different forms of WAAM processes (Gas metal arc welding, Gas tungsten arc welding, Plasma arc welding) and clarifies their primary distinctions, in terms of materials and features [29], [30],[32].

Table 2.7. The different forms of WAAM processes. Adapted from [24], [32],[34]

Arc based welding	<p>Gas metal arc welding (GMAW)</p> <ul style="list-style-type: none"> • An electric arc is formed between a consumable wire and the metal workpiece. • High material utilization, deposition rate, density, and low cost. • As compared to powder-based raw materials, there is a low risk of contamination and porosity. • Good surface quality. • Low cost equipment. • Need separate wire feed system. • Limited to the minimum wall thickness and surface finish by a relatively large melting pool and heat supply. • Less stable and produces more weld-fume and spatter than the other methods. • The executing unit is CNC. More accurate but expensive.
	<p>Gas tungsten arc welding (GTAW)</p> <ul style="list-style-type: none"> • A weld is produced with a non-consumable tungsten electrode. • High deposition rate. • Variable wire feed orientation. • The executing unit is a robot. More economical, flexible and adaptable.
Plasma based welding	<p>Plasma arc welding (PAW)</p> <ul style="list-style-type: none"> • Produces welding distortions and heat-affected zones three times lower than GTAW welding. • Low heat input. • High arc stability. • Smaller welds. • Lower welding speeds. • The executing unit is a robot. More economical, flexible and adaptable.

From the different WAAM processes presented, the case studies developed in this thesis will be focused on the use of **GMAW technology**. This process initiates with the passage of an electric arc between the consumable electrode and the workpiece. That leads to the melting of the wire electrode and subsequently, along with the movement between the worktable and GMAW torch, to the deposition above the substrate surface. At this stage, the heat that was developed during the process is finally used to melt the substrate and the wire, and the final product, without machining, is obtained [32]. **Figure 2.3** presents a schematic diagram of the GMAW-based additive manufacturing where all the involved subcomponents of the process are identified (power supply unit, wire feeder, shielding gas supply unit, nozzle, and CNC controlled work table).

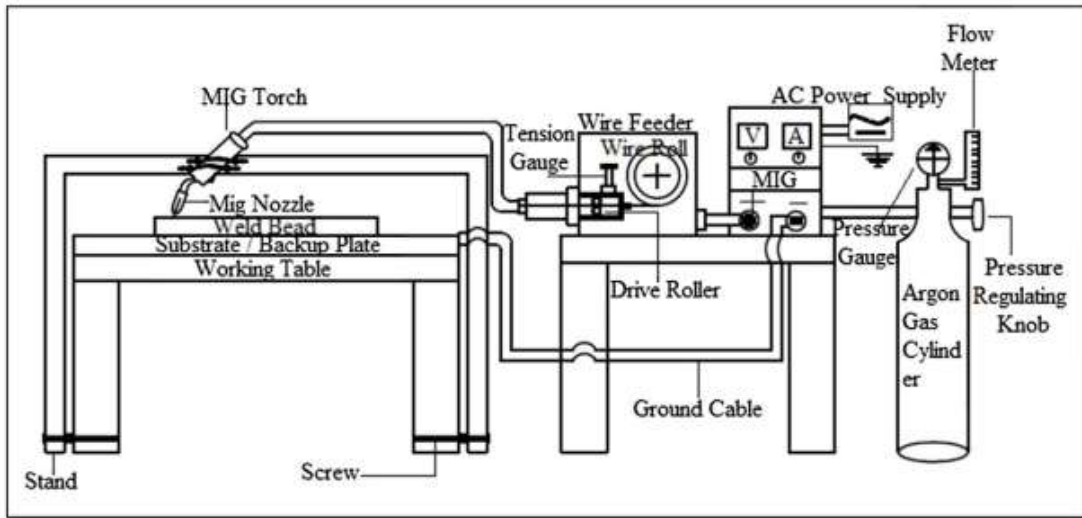


Figure 2.3. Schematic diagram of the GMAW process [34]

In comparison with the other AM techniques, WAAM has proven to have a higher deposition rate and a more viable and cost-effective production due to 100% material utilization and better fusion of layers within parts [29]–[31]. Despite being a very advantageous process, it still presents some challenges that need to be overcome. These were listed in **Table 2.8** according to the information in [29], with the respective consequences and possible solutions to be implemented.

Table 2.8. Challenges of WAAM. Adapted from [24]

Challenges	Implications	Possible solutions
High levels of residual stress (due to high deposition rates and heat inputs)	<ul style="list-style-type: none"> Loss of geometrical accuracy (distortions) and tolerances in the components Humping 	<ul style="list-style-type: none"> Analyze the patterns and sequences that are obtained from the residual stress study, in order to draw conclusions and develop solutions. Elaborate more studies to analyze the influences of process conditions on thermal history, microstructure and resultant mechanical and surface properties of parts.
High periodic heat input	<ul style="list-style-type: none"> Grain growth (reduces hardness and may lead to structural collapses) Limited precision in the deposition process Residual stresses and distortions Delamination, warping and dimensional inaccuracy (particularly for large parts) Low part quality Complex thermal conditions such as higher inter-layer temperature and lower cooling rate Modification of the geometry of the layers and the microstructure of the material Humping Cracking 	<ul style="list-style-type: none"> Before you start working with a material, it is important that you have a good understanding of the various factors that affect its cooling rate. These include the thermal conductivity, the amount of heat that's applied during the process, and the base material's heat. Create strategies for managing potential changes that could happen in the impacted heat zone during the cooling stage based on this understanding.

Table 2.8 Continuation		
Porosity	<ul style="list-style-type: none"> • Low mechanical properties (fatigue, strength, durability, resistance) • Different size and shape distribution • Material performance impaired • Limited commercial applications 	<ul style="list-style-type: none"> • Analyze and elaborate studies relatively to the porosity of each part produced, in order to achieve an reduced and acceptable level.
Operators lack of understanding of the programming of the 3D machines	<ul style="list-style-type: none"> • Deposited parts with poor geometric accuracy and mechanical properties) • Poor programming strategy that may lead to deficient parts production • Unstable weld pool dynamics 	<ul style="list-style-type: none"> • In order to facilitate the printing process for the operator himself, design the part previously, considering factors like part orientation, the slice and path chosen, the process parameters and the geometric characteristics. • Elaborate further studies to establish design rules that inform about the use of the WAAM process in general and demonstrate how to benefit from high-quality product design. • Train the workers and allow an open communication to understand their difficulties regarding the process.
Machine malfunctions	<ul style="list-style-type: none"> • Poor production 	<ul style="list-style-type: none"> • Develop maintenance management plans.
Environmental impacts	<ul style="list-style-type: none"> • Gas contamination 	<ul style="list-style-type: none"> • Develop detailed analyses in order to quantify the environmental impacts of the process. • Study alternatives that allow the reduction of environmental impacts (integration of WAAM with other production processes or with other Industry 4.0 technologies).
Limited design	<ul style="list-style-type: none"> • The build orientation since will influence the quality and performance of the part produced (strength, material properties, surface quality, etc.) • Need to compromise the functionality of the product to make it cost-effective compared to existing traditional methods • Mandatory machining operations, to achieve the required surface finish 	<ul style="list-style-type: none"> • Know the most critical characteristics of the part to be produced and orient it accordingly. • Integrate WAAM with other processes and machines in order to make the production more cost-effective and optimize it.

2.3 Life Cycle Assessment

2.3.1 Life Cycle Assessment characterization

LCA is a methodology that allows characterizing quantitatively and qualitatively the environmental impacts of a product system throughout its life cycle, from the extraction of raw materials (cradle) to the production phases, use, transportation, and end-of-life (grave) [33], [34]. It provides estimations of soil and water acidification, global warming, eutrophication, ozone layer depletion, and abiotic depletion of non-fossil and fossil resources [35]. This is mainly useful in activities such as product development and improvement, strategic planning, public policy making, marketing, and others. Although the cradle to grave interpretation is the one that is most often used, in some cases, it is more useful to conduct a partial LCA, for

example, to analyze a portion of the life cycle upstream from the gate (the cradle to gate), downstream from the gate (the gate to grave) or to analyze the portion of life cycle between two gates (the gate to gate) [11]. According to ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines [16], LCA is a systematic process that contains 4 different phases [9], [33], [35]:

- **The goal and scope definition**

This first step allows an understanding of why the assessment is being performed. The main reasons are the need for industries to comply with regulations, the growing environmental awareness from the customers, and the possibility of a business standing out by "being a role model".

- **Inventory analysis (Life Cycle Inventory-LCI)**

The complete identification and analysis of all relevant inputs and outputs are done.

- **Impact assessment (Life Cycle Impact Assessment-LCIA)**

Afterward, it is critical to assess and categorize the potential environmental impacts that might arise over the course of the product system's whole life cycle.

- **Interpretation of results**

Finally, the data from LCI and LCIA are analyzed according to the previously defined goal and scope to draw a conclusion about the assessment and make recommendations.

A diagram showing the relationship between the four phases can be seen in **Figure 2.4**. The following subsections have the purpose of allowing a better understanding of what each of these phases consist of and the requirements that need to be met, according to ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines [16].

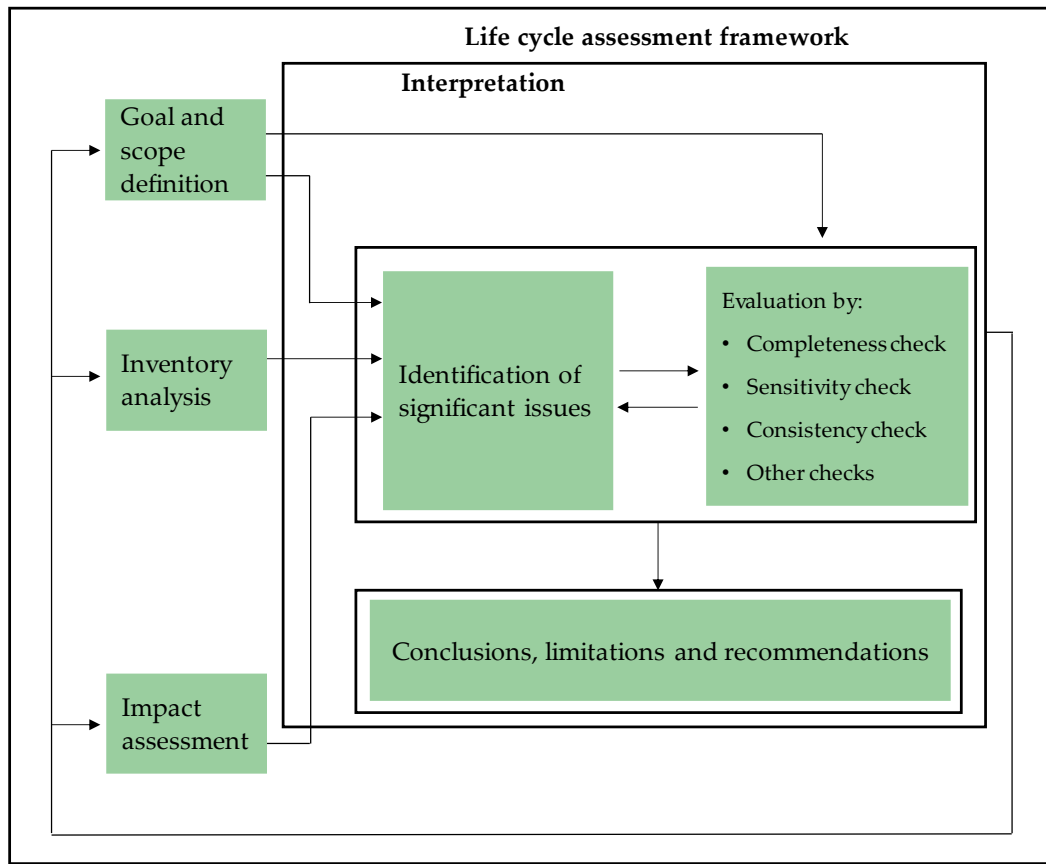


Figure 2.4. Relationship between the four phases of the LCA. Adapted from [16]

2.3.2 Goal and scope definition

As previously mentioned, this first step has the purpose of clearly defining the intent of the application of the LCA. The level of depth and specificity of the LCA should also be established in this phase, to define the system boundaries. The assessment might be more simple and fast, for example in cases of checking alternative options for the materials to be used in production, or more detailed and extended, like the analysis made in the product design phases. The **goal of an LCA** should clearly define the application's intent, the study's objectives, its intended audience, and whether the results are going to be used in comparing claims that are going to be made public. The **scope of the LCA** should consider and clearly describe the product system to be studied and its functions, the functional unit, the system boundaries, the data and data quality requirements, and the considerations concerning the critical analyses (allocation procedures, LCIA methodology, and types of impacts, interpretation to be used, assumptions, limitations, value choices, and optional elements), type of critical review and type/format of the report required for the study. **Table 2.9**, presents in more detail the specific requirements of each of the items that are present in the scope.

Table 2.9. Requirements of the scope items. Adapted from [16]

Item	Requirements
Function and functional unit	<p>The functions or performance characteristics of the system being studied should be specified.</p> <p>The functional unit should be consistent with the goal and scope of the study and be clearly defined and measurable, to normalize the data inputs and outputs. After choosing the functional unit, the reference flow must establish.</p>
System boundary	<ul style="list-style-type: none"> • Specify the unit processes that LCA includes and the depth of detail to which they should be analyzed. • Choosing system boundaries accordingly with the goal of the study. • The criteria used for defining the system boundary should be recognized and described. • Only delete the life cycle stages, processes, inputs, or outputs that do not significantly impact the study's conclusions. • A decision to remove a life cycle phase, process, input, or output must be justified and its consequences explained. <p>Outline the interrelationships between the system's unit processes through a process flow diagram.</p> <ul style="list-style-type: none"> • Define all the unit processes. (where it begins and ends, the type of operations and transformations that take place) • The inputs and outputs should be elementary and the product must flow. • Identification of which unit processes generate inputs and which receive the outputs. Initially created using the information already in hand (information gathered from specific websites or published sources), and further developed as additional data was acquired throughout the course of the study. A sensitivity analysis might be performed.
Allocation procedures	<ul style="list-style-type: none"> • Assumptions, as well as cut-off criteria for inputs and outputs must be specified. • When using mass as a criterion, all inputs that cumulatively contribute more than a defined percentage to the mass input of the product system being modeled in the study must be included. • When using energy as a criterion, the inputs that cumulatively contribute more than a defined percentage of the product system's energy inputs in the study must be included. • The inputs that have higher environmental significance relative to the individual data of the production system must be mentioned. • It must be identified the inputs and outputs data that can be traced to other product systems or even to the environment. In these cases, in the allocation process, flow diagrams should be elaborated.
LCIA methodology and types of impacts	<ul style="list-style-type: none"> • Select, accordingly to the goal and scope of the study, the characterization models, category indicators, and impact categories that will be used in the LCA research.
Types and sources of data	<ul style="list-style-type: none"> • Should be according to the goal and scope of the study. • Estimated, measured, and calculated data might be included.
Data quality requirements	<p>Data quality should be characterized by both quantitative and qualitative aspects as well as by the methods used to collect and integrate those data.</p> <p>Should address:</p> <ul style="list-style-type: none"> • Time-related, geographical, and technology coverage. • The precision: calculate the variability of the data values expressed. • The completeness: address flow's percentage that has been measured or estimated. • Representativeness: perform a qualitative assessment to inquire if the data set reflects the true population of interest. • Consistency: perform a qualitative assessment to understand if the study methodology is applied uniformly according to the various components of the analysis.

Table 2.9 Continuation	
Data quality requirements (continuation)	<p>Should address:</p> <ul style="list-style-type: none"> • Reproducibility: perform a qualitative assessment to recognize if the methodology and data values information allows an independent practitioner to reproduce the results reported in the study. • Sources of the data. • The uncertainty underlying everything approached, meaning data, models, and assumptions defined. <p>* If there any missing data is identified in the unit processes or the reporting locations, it shall be documented and referred to as a "non-zero" data value.</p>
Comparisons between systems	<ul style="list-style-type: none"> • Evaluate if the systems being compared are equivalent. • Definition of the scope of the study enabling the comparison of the system. • The systems should consider equal functional units and equivalent methodological considerations. If between both systems differences are found, they should be reported.
Critical review considerations	<ul style="list-style-type: none"> • Define if a critical review is necessary and, if so, how to conduct it. • Define the type of critical review needed. • Define who would conduct the review, and their level of expertise.

As an iterative process, the study's aim or scope can be amended in response to unforeseen constraints, limitations, or additional information. Documentation and justification are required for such changes.

2.3.3 Life Cycle Inventory

Following the definition of the goal and scope of the study, all the prerequisites are met for LCA's next stage, the performance of a LCI. This phase enables the identification and analysis, within the system boundary, of each unit process inputs and outputs. To perform an LCI it is necessary to follow the operational steps outlined in **Figure 2.5**.

The data collection includes qualitative and quantitative data, whether this is measured, calculated, or estimated. Data may be classified: as inputs (energy, raw material, ancillary), products, co-products, waste, outputs (releases to air, water, and soil), and other environmental aspects. Preparing for data collection is a step that has several features:

- Information gathered from public sources must be referenced.
- Most significant data for the conclusions of the study should be according to the data quality requirements and all the relevant details related to it should be stated, as well as a description of each unit process.
- The product systems should be modelled consistently and uniformly.
 - Drawing of flow diagrams with the necessary interrelationships.
 - Unit processes must be described in detail with the respective inputs and outputs. All the flows and relevant data related to it also must be listed.
 - All the units being used must be listed.

→ The procedure of collecting the data and the calculation techniques used should be consistently applied throughout the study and must be described. Special situations, anomalies, and other things that might be connected to the data provided should be documented with detailed instructions.

For calculating data, in addition to specifying all the procedures involved and the assumptions made, several operational steps should be followed:

1. Validation of the data

Verifies that the data quality requirements for the intended application have been fulfilled, through mass balances, energy balances, and/or comparative analyses of release factors. If there are any anomalies verified from this validation, it must be suggested alternative data that complies with the data selection requirements.

2. Relating data to unit process and functional unit

Each unit process should have a flow associated with it so that, later, a reference flow can be established using the flowchart and the flows between those unit processes. The quantitative input and output data calculated for all the unit processes of the system should be according to the flow established. This calculation should remit system data to the functional unit. The aggregation of the data should be consistent with the goal of the study and it should be done carefully since only equivalent substances and similar environmental impacts should be aggregated. The goal and scope definition phase of the study must clarify additional aggregation rules.

3. Refining system bounding

LCA has an iterative nature so, it allows to make decisions about what data should be included in the study after running a sensitivity analysis and understanding their significance. All the changes that need to be made through the process of revising the previous system boundaries established, must be accordingly to the cut-off criteria previously defined in the scope of the study and should be documented. The sensitivity analysis allows for the exclusion of life cycle stages, unit processes, inputs, and outputs that lack significance to the results of the study and include new ones that demonstrate to be significant.

A process/product system's data is mainly aggregated through a process called allocation, which allows the input and output flow to be divided between products and functions, to

reflect their relationships. Although it is not that common, data can also be aggregated through physical relationships (i.e. kg, m², m³, etc.). **Figure 2.6** illustrates this allocation procedure.

All the procedures related to the allocation must be documented and explained. If an alternative allocation procedure seems applicable, it should always be conducted a sensitivity analysis to understand the changes to be made. As the inventory is based on the balances of the material, the sum of all allocated inputs and outputs of a unit process should be equivalent to the inputs and outputs of that unit process before the allocation procedures, and fundamental input/output relationships and characteristics should be maintained.

The principles and procedures used for the allocation of the process/product system are also applicable in reuse and recycling situations. For that, it is not only important to document all the changes that the materials suffer, but it is also important to identify and explain the system boundary, ensuring that the allocation principles are followed. The shared unit processes should use as a basis for allocation, if possible, physical properties, economic value, or the number of subsequent uses of the recycled material. **Figure 2.7** it is showed how to address allocation procedures for reuse and recycling.

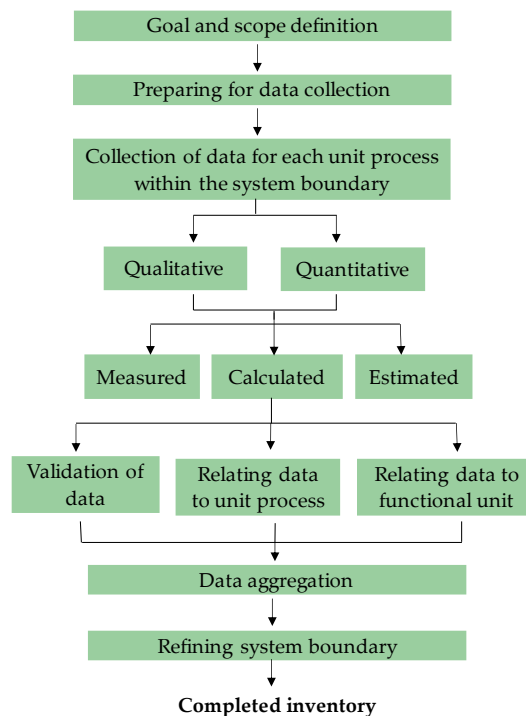


Figure 2.5. Operational steps of a inventory analysis. Adapted from [16]

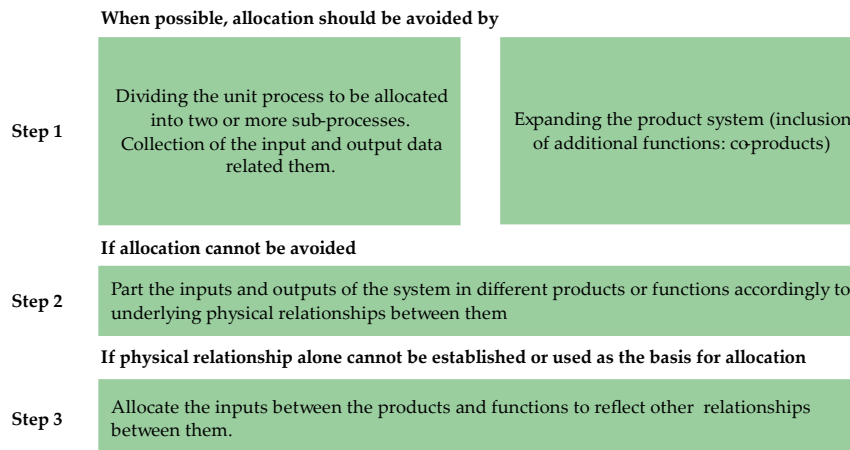


Figure 2.6. Allocation procedure. Adapted from [16]

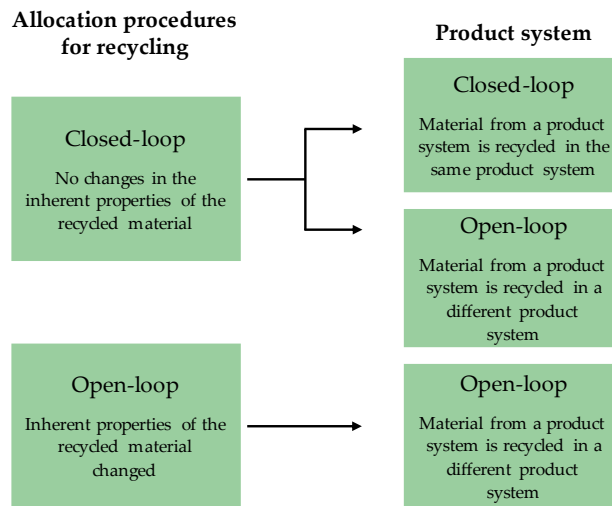


Figure 2.7. Allocation procedures for recycling. Adapted from [16]

2.3.4 Life Cycle Impact Assessment

The LCIA is a unique technique, that might require some information from others like environmental performance evaluation, environmental impact assessment, and risk assessment but still has approach differences since it is based on a functional unit. LCIA must be planned according to the goal and scope of the study and must agree with the other phases to understand possible omissions and sources of uncertainty. In this phase, it is made the LCIA profile for the product system, by putting together a set of indicator findings for several impact categories. Elementary flows not assigned to impact categories and data that isn't an elementary flow must be reported. For a better comprehension of all the elements involved in LCIA, **Table 2.10** and **Table 2.11** present respectively all the information/characteristics related mandatory and optional elements.

Table 2.10. Information related to the mandatory elements. Adapted from [16]

Selection of	
<p>Related information and sources shall be referenced. Justified and consistent with the goal and scope of the LCA. Iterative. Internationally accepted. Value-choices and assumptions should be minimized.</p>	
Impact categories	<ul style="list-style-type: none"> • Accurate and descriptive name • Include all environmental issues relevant to the product system under study • Category indicators representative of the aggregated impacts of the product system on the category endpoint(s) <p>For each impact category:</p> <ul style="list-style-type: none"> ➤ Category endpoint(s) identification ➤ The category indicator for the specified category endpoint(s) must be defined ➤ It should be made an identification of the relevant LCI results to assigned them to the respective impact category, considering the previously identified category endpoint(s) and chosen category indicators ➤ Identification of the characterization model and the characterization factors
Category indicators	<ul style="list-style-type: none"> • Accurate and descriptive names • Specification of the relationship between the category indicators and the LCI results that don't include mass and energy flow data • Should be environmentally relevant • Must, at the very least, qualitatively address the effects of the LCI findings on the category endpoint(s)
Characterization models	<ul style="list-style-type: none"> • Describe the relationship between the LCI results and the category indicators to establish a basis for the characterization factors • The characterization model and the characterization factors must be scientifically and technically valid and the extent to which this happens must be identified. They should be based on a unique identifiable mechanism and reproducible empirical observations • If any data or information are added to the category endpoint(s), it should be stated: the initial condition of the category endpoint(s), the magnitude involved in the change, the spatial aspects, the temporal aspects, the reversibility of the environmental mechanism, and the uncertainty involved
Assignment of LCI results to the selected impact categories (classification)	
<ul style="list-style-type: none"> • Results exclusive to one impact category • Recognition of LCI results relating to more than one effect category, highlighting the differences between parallel mechanisms • Assignment to serial mechanisms 	
Calculation of category indicator results (characterization)	
<p>Depends on the accuracy, validity, and characteristics of the characterization models and characterization factors</p>	
<ul style="list-style-type: none"> • The calculation of indicator results (characterization) involves the conversion of LCI results to common units and the aggregation of the converted results within the same impact category • The approach utilized, along with the value choices and assumptions made, should be identified and documented • Iterative data collection might be necessary if the LCI results are not available or if the quality of the data prevents the LCIA from achieving the study's aim and scope. Alternatively to the iterative data collection, an adjustment of the study's goal and scope might be made 	

Table 2.11. Information related to the optional elements. Adapted from [16]

<p>Normalization Calculation of the category's indicator results in magnitude in concerning the reference information</p>	<p>This allows to:</p> <ul style="list-style-type: none"> • check for inconsistencies • provide and communicate information on the relative significance of the indicator results • prepare for additional procedures, such as grouping, weighting, or life cycle interpretation
<p>Grouping Assignment of the impact categories into one or more groups, accordingly to the goal and scope defined. The processes of sorting and/or ranking might be involved. Note: Value-based choices, therefore the results obtained are not general.</p>	<p>Two possible procedures:</p> <ul style="list-style-type: none"> • The sorting of impact categories on a nominal basis • The ranking of impact categories in a given hierarchy (e.g. high, medium, and low priority).
<p>Weighting Conversion of the indicator results into numbers based on value choices in all impact categories and possible consequent aggregation. Note: Value-based choices, therefore the results obtained are not general.</p>	<p>Two possible procedures:</p> <ul style="list-style-type: none"> • The conversion, through selected weighting factors, of the indicator/normalized results • The aggregation of the converted indicator/normalized results into impact categories
<p>Data quality analysis Comprehension of the reliability of the indicator results collected.</p>	<p>This allows:</p> <ul style="list-style-type: none"> • to determine whether or not there are significant differences • to recognize the results from LCI that are negligible • to provide a base for iterative LCIA process <p>The specific techniques</p> <ul style="list-style-type: none"> • Gravity analysis (e.g. Pareto analysis): Allows to recognize the data with the highest contribution to the indicator result • Uncertainty analysis: Determines how the uncertainties related to data and assumptions can affect the LCIA result's reliability • Sensitivity analysis: Determines how the LCIA results are affected by changes in methodological choices and data.

2.3.5 Interpretation of results

As previously mentioned, an LCA follows a specific procedure and involves several elements. As **Figure 2.4** in the subchapter **Life Cycle Assessment characterization** proves, there is a strict relationship between all four phases of the study. The interpretation phase has some noteworthy particularities:

1. First, the identification of the most important issues based on the outcomes of the other phases, such as LCA and LCI (always considering the goal and scope of the study).
2. A posterior appraisal of the completeness, sensitivity, and consistency checks done to the significant inputs, outputs, and methodological choices.

3. Lastly, the elaboration of the conclusions, limitations, and recommendations.

Besides the particularities that have been referred to, the interpretation should also consider some details related specifically to the goal of the study:

- If the system functions, the functional unit, and system boundary are well defined and are appropriate for the study in question.
- What are the limitations that the data quality assessment and the sensitivity analysis identified?
- All the LCI and LCIA documents must be verified.
- As LCI is related to data inputs and outputs and not to the environmental impacts themselves, uncertainty may be introduced into the results. Due to that, it is important to characterize that uncertainty and, when possible, perform an analysis to endorse the LCI conclusions.

To structure the results that are obtained in the LCI or LCIA phases, it is important to take an additional step and proceed to the identification of significant issues using the correct approaches, methods, and tools. Significant issues might be inventory data (energy, emissions, discharges, waste), impact categories (resource use, climate change), or any significant contributions that came from life cycle stages to LCI or LCIA results (transportation and energy production). This extra phase aids in determining whether everything is in line with the definition of the goal and the scope, as well as interactively with the evaluation element. The interaction with the evaluation element enables the collection of all the data from the earlier stages, including allocation criteria, cut-off choices, impact category selection, category indicators, and model selection. If the results gathered to meet the demands of the goal and scope of the study, to filter only the relevant results, their significance must be determined. Therefore, the evaluation element establishes confidence in the results of the LCA or LCI study. The techniques and procedures that are considered during the evaluation are explicit in the following items.

Completeness check

- Ensures that all pertinent data and information is available and accurate for the study's interpretation.
- If there is any relevant information missing or incomplete, it must be investigated if it is necessary to comply with the goal and scope of the study and/or for determining the significant issues. The relevant information that is missing and is required for determining the significant issues implies the revision of the preceding phases (LCI and LCIA) or the adjustment of the goal and scope of the study. The information that is proven to not be necessary must be justified and excluded from the study.

Sensitivity check

- It allows to understand if the final results and conclusions are affected by any uncertainties and therefore if they are reliable or not.
- Must include all the information established previously in the goal and scope of the study, the results obtained in other phases of the study such as LCI and LCIA, as well as the sensitivity and uncertainty analysis conducted on them, and lastly expert judgments based on previous experiences.
- The level of detail necessary to perform a sensitivity check is established accordingly to the results obtained from the inventory analysis and impact assessment (if conducted).
- The sensitivity check outputs will allow understanding of its extent and therefore, conclude if it is necessary to perform more extensive or precise analysis.
- Conclusions relative to significant differences between two different studies cannot be withdrawn if it is not possible to perform a sensitivity check.

Consistency check

- Determines the consistency, of the assumptions, methods, and data relative to the goal and scope defined.
- The differences relative to the data quality of two different product systems must be consistent with the goal and scope of the study.
- If any regional and/or temporal differences exist, they must be consistent throughout the study.
- The consistency of the elements relative to the impact assessment and the allocation rules of all the production systems shall be approached.

Conclusions, limitations, and recommendations

- Identification of significant issues.
- Evaluation of the methodology.
- Evaluation of all the results obtained in the completeness, sensitivity, and consistency checks and consequent conclusion of its consistency with the goal and scope of the study.
- Elaboration of future recommendations, regarding the study's application.

2.4 Wire Arc Additive Manufacturing and Life Cycle Assessment

The goal of this subsection is to provide a framework of all the developments relative to the application of the LCA methodology in WAAM. As inclusion criteria for this search, it was defined all the research articles that were written in English and contained keywords related to the present study. On the other hand and accordingly, to the purpose of this subsection, it was not considered articles that did not mention on their abstract and/or content the application of the LCA methodology on WAAM, nor articles previous to the year 2017. The search of information was made between the months of February and April of 2022, by using the Scopus indexing database and regarding different combinations of keywords, such as, "Life Cycle Assessment" AND "Wire Arc Additive Manufacturing", "Life Cycle Assessment" AND "Additive Manufacturing", "Environmental impacts" AND "Wire Arc Additive Manufacturing", "Impact assessment" AND "Additive technologies", "Impact assessment" and "Wire Arc Additive Manufacturing". Considering these keywords, a total of approximately seven hundred articles were found from the aforementioned indexing databases. However, the majority of the articles were relative to the keywords "Life Cycle Assessment" AND "Additive Manufacturing", and did not approach directly the application of the LCA methodology on WAAM. Thus, only three studies were considered [13], [36], [37].

Bekker et al. [13] performed an LCA from cradle to gate to characterize the environmental impacts of WAAM-produced stainless steel 308 L. They also approached the CNC Milling and Green Sand Casting techniques to give context to the assessment and draw further conclusions about WAAM's performance. Although the assessment contained sources of uncertainty and it was recognized that the results may vary according to the product being produced, it was concluded that, for this application, the environmental impact of WAAM equals the traditional manufacturing techniques. Stainless steel proved to be the main cause of environmental damage in all three techniques assessed. Therefore, the authors concluded that it would be important to start prioritizing techniques that allow mass reduction, being an example, WAAM. Although WAAM had lower impacts in stainless steel, they were still significant. Thus, it was acknowledged the importance of further research and development in this field.

Gianni Campatelli et al. [36] developed a case study, regarding the production of a steel blade, to point out the main differences in two different approaches of production: WAAM vs a pure milling process. It was performed a cradle-to-gate assessment given those two technologies and considering an end-of-life system boundary. The energy, material, and resource

flows were quantified along the entire life cycle of the component and the results showed that the pure milling process involved a significantly higher amount of material, as well as higher energy demands. The authors concluded that the results obtained were expected since WAAM has a more efficient material usage than the pure milling process. Additionally, they also assumed three end-of-life scenarios, to emphasize the importance of recycling on environmental performance.

Paolo C. Priarone et al. [37] performed a cradle-to-gate life cycle assessment of aluminum alloy parts, considering different size components and different deposition of material, to obtain a comparison between the performance of WAAM and subtractive manufacturing processes. For this comparison, a TOPSIS Multi-Criteria Decision Analysis method considering the manufacturing time, the product cost, the mechanical performance, and sustainability was developed. After its application, the authors concluded that WAAM has an advantage in the subtractive manufacturing processes when the criteria categories were equally important or when the sustainability of the process was prioritized. When time and cost were prioritized, subtractive manufacturing processes had an advantage. Additionally, it was observed that part geometry affects the outcomes of both additive and subtractive manufacturing processes. Although the results obtained are case specific, the authors defend that the methodology developed will serve as a support for process selection in other future studies.

2.4.1 Research gap

Based on the results obtained from the research, it can be observed that the application of the LCA methodology in AM has been much exploited in the last years. However, relative to the application of this methodology on WAAM, a specific AM technology, only three studies were found. Those studies were analyzed and presented above. A research gap common to all of them was the fact they are case specific, meaning that their results may not be extended to other geometries/materials. Therefore, general conclusions about the environmental impacts of WAAM could not be withdrawn. In this sense, further studies regarding this technology and the printing of different geometries need to be carried out. The present dissertation will contribute to this subject.

CASE STUDIES

This chapter introduces the case studies conducted. For each case study, the LCA methodology was followed. Firstly, it was made an identification of the goal and scope of the study, as well as the establishment of the functional unit and system boundaries. Afterward, an inventory analysis is performed and some observations are made.

3.1 Case Study 1

3.1.1 Goal and Scope definition

The present study has the intent of using the LCA methodology to analyse the environmental impacts of an alternative manufacturing process, WAAM, when producing a gear shape part. This geometry is going to be referred to as geometry 1 in the following sections and chapters. To give this study context, the LCA was performed considering as production processes WAAM, representative of AM, and CNC Milling, representative of subtractive manufacturing. The LCA follows the requirements and guidelines of the European standard, ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines [16]. The environmental data was either measured and calculated through specific processes, estimated through findings in literature sources, or provided directly from the Ecoinvent database 3.

3.1.2 Functional unit and system boundaries

The functional unit can be a product, a service, or even a system that is analyzed, categorized and quantified, to be used as a reference unit. This study has as functional unit a one unit part.

The following figure, **Figure 3.1**, exemplifies the phases that are included in the assessment and demonstrates the system boundaries. Although CNC Milling is presented, due to time constraints and the absence of the appropriate tools/machine (carbide cutting tools), it

was not possible to perform it. Thus, data as volume and mass final parts had to be estimated through specific options (such as evaluate and stock manager) provided by the computer-aided design software, SolidWorks. The study comprehends all the product production phases, from the extraction of natural resources to the production of the final part. The use and disposal phases are not included, since this is a cradle-to-gate study. Transportation was also not considered.

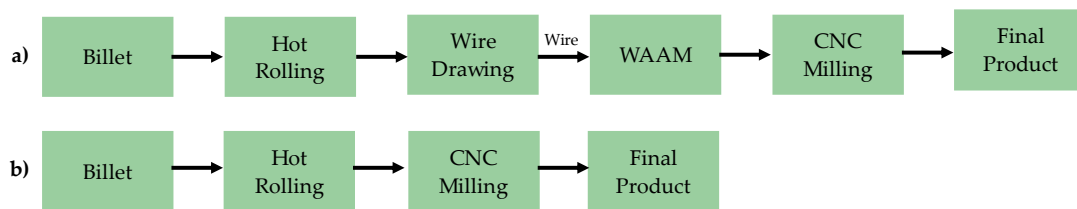


Figure 3.1. System boundaries for a) WAAM b) Pure CNC milling

The assessment was performed considering the ReCipe 2016 (Hierarchical) method that the SimaPro 9.2 software has available. The comparison between both processes was made based on the manufacturing of 0.178 kg of ER90 steel (low alloyed steel). The values available in the Ecoinvent database are relative to 1 kg of steel. As this study is relative to 0.178 kg of steel, the values present in the following subsections that were withdrawn from the database had to be converted. Due to time constraints, was not conducted sensitivity, or uncertainty analysis.

3.1.3 Environmental Inventory Analysis

3.1.3.1 WAAM

To proceed to the inventory analysis of the process it is important to address which inputs are being considered, the stages involved and the final outputs produced. The WAAM process requires as inputs: substrate, ER90 steel wire, energy consumption, and shielding gas, that in this case will be a mixture of 88% Ar and 12% CO₂.

An important factor to consider is that the ER90 steel wire is a final product that results from the transformation of a steel billet. Firstly, to mold the steel billet into the desired shape (a rod), a hot rolling operation should take place. Afterward, the rod shape is exposed to the wire drawing process and the ER90 steel wire is finally obtained. For WAAM to take place, it is necessary to preset the geometry that is to be achieved. Based on that, a G code is generated and a printing path strategy is established. Accordingly, the steel wire is melted and deposited, layer by layer, into the substrate until the envisioned part is completed. All the values referent

to these phases of the ER90 steel wire production were calculated considering the Ecoinvent 3 database. The processes of hot rolling and wire drawing always incur some type of material losses, wherefore, according to it, a loss of 5% and 4%, also based on Ecoinvent 3 database, was assumed respectively.

A final part with no defects and good material properties is essentially due to the parameters established and the strategies used during the manufacturing process. Therefore, all the considerations made during the present case study will be further specified. The mass of the deposited material was 0.302kg. The part was produced by using a CNC milling machine. The voltage of the process was set to be 18 V, the travel speed to be 360 mm/min, and the wire feed speed to be 3 m/min. The flow rate of the shielding gas, an 88% Ar and 12% CO₂ mixture, was monitored to be 16 l/min. For geometry 1 production, it was necessary to 230.4 l of shielding gas. The energy consumption had to be estimated. The LabView software allowed to record of the voltage and current data of the part being produced and thereby making it possible to compute the power consumption of the electric arc regarding the WAAM machine. The power rating obtained was 1.75 kW. Successively, the energy consumed was calculated by simply multiplying the power rating and the process time, obtaining the value of 0.418 kWh. The printing path was established using Prusa 3D slicer software. In some layers, the path followed the clockwise direction, and in other layers followed the counterclockwise direction. This strategy of alternating directions avoids the accumulation of stress in the part being produced. To prevent deformation, it was set at an interlayer temperature of 100 degrees Celsius. This resulted in an interlayer cooling time of 180 seconds. The part was built with 12 layers, the layer height set to be 1.5 mm.

The outputs of the process were the final part, the solid waste, and the pollutant emissions into the air. Due to the lack of specific equipment, the emissions related to the production were not measured. The substrate plate for WAAM was also not considered so that, afterward, a fair comparison with CNC milling process can be made, since it is a subtractive process and only considers as an input a single piece bar. As mentioned previously, the mass of the initial and final parts was estimated in the SolidWorks software. The obtained value for the final product was 0.178 kg. Given the information above and (1), it is possible to compare the mass of the final part produced with the mass of the raw material used. Thus, for this geometry, it was obtained a theoretical buy-to-fly (BTF) ratio of 1.7.

$$\text{Buy to fly (BTF) ratio} = \frac{\text{Input mass}}{\text{Output mass}} \quad (1)$$

The CNC Milling process value, is relative to the quantity of removed material. Therefore, to calculate it, the amount of material deposited (0.302kg) was subtracted from the final product (0.178 kg). The calculated value was of 0.124 kg. For further detail, the final part produced, as well as the CAD model view and the WAAM part preview are represented in **Figure 3.2**.

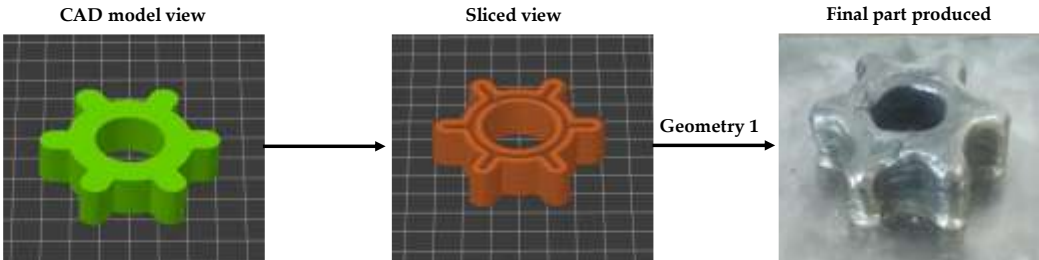


Figure 3.2. CAD representation vs Final part of geometry 1

To summarize all the information specified, the inventory of the WAAM process was depicted in **Table 3.1**.

Table 3.1. LCI of geometry 1 (WAAM process)

Process	Material/Process	Total values	Units	Type of data	Reference
WAAM + CNC Milling	Steel billet	0.329	kg	Calculated	Ecoinvent 3 database
	Shielding gas	230.4	l or dm3	Measured	Measured data
	Hot Rolling	0.329	kg	Calculated	Ecoinvent 3 database
	Wire Drawing	0.314	kg	Calculated	Ecoinvent 3 database
	WAAM Deposition	0.302	kg	Measured	Measured data
	Electricity (WAAM)	0.418	kWh	Calculated	Calculated data
	Electricity (Milling)	0.517	kWh	Calculated	Ecoinvent 3 database
	CNC Milling	0.124	kg	Calculated	Calculated data
	Final Product	0.178	kg	Estimated	CAD representation in SolidWorks

3.1.3.2 CNC Milling

The CNC milling process requires as inputs: the ER90 steel bar, a CNC machine, and the cutting tools and CNC milling machine tool.

Before initiating the machining itself, it is necessary to transform the raw material, i.e the steel billet, into a bar. For that and similarly to the WAAM, it is considered, a hot rolling operation in this stage. Subsequently, the CNC Milling process initiates and the bar is milled until the predefined/desired dimensions are achieved. The values regarding the ER90 steel wire production phases were calculated considering the Ecoinvent 3 database. Also considering Ecoinvent 3 database, a material loss of 5% was assumed for the hot rolling process.

As referred to earlier, it was not possible to execute the CNC milling process due to time constraints and the absence of the appropriate tools/machines. Wherefore, the data relative to compressed air, lubricating oil, water, and electricity was calculated considering the Ecoinvent 3 database, and the data relative to the mass of the final part was estimated in the SolidWorks software.

The initial billet was assumed to be 70 mm in diameter and 17 mm in height. The estimated mass, for the initial billet, was 0.509 kg and for the final product was 0.178 kg. The quantity of removed material has a value of 0.312 kg and it was calculated by subtracting the initial mass of the billet from the mass of the final product. For this calculation, the 5% material losses, must be considered in the initial billet mass. Estimated the mass of both initial billet and final product, (1) was once more used to calculate the theoretical buy-to-fly (BTF) ratio. It obtained a value of 2.86.

All the information mentioned is outlined in the inventory of the CNC Milling process and was represented in **Table 3.2**.

Table 3.2. LCI of geometry 1 (CNC Milling process)

Process	Material/Process	Total values	Units	Type of data	Reference
CNC Milling	Steel billet	0.534	kg	Calculated	Ecoinvent 3 database
	Hot Rolling	0.534	kg	Calculated	
	Compressed Air	0.399	m3	Calculated	
	Lubricating Oil	0.001	kg	Calculated	
	Water	0.005	m3	Calculated	
	Electricity	1.300	kWh	Calculated	
	CNC Milling	0.312	kg	Calculated	Calculated data
	Final Product	0.178	kg	Estimated	CAD representation in SolidWorks

In Case Study 1 a LCA was conducted to the production of a gear shape part, through two different processes, WAAM and CNC Milling. Case Studies 2 and 3 will essentially be identical to this prior case study, the main distinction will be in the part's geometry being manufactured. Therefore, the next sections won't be as detailed and will present only the differentiating characteristics.

3.2 Case Study 2

3.2.1 Goal and Scope definition

The purpose of this study is to investigate the environmental impacts of WAAM in the production of a cylinder shape part, using the LCA methodology. This geometry is going to be referred to as geometry 2 in the following sections and chapters. For a better context of the results obtained, the study considers both WAAM and CNC Milling processes. The LCA follows the requirements and guidelines of the European standard, ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines [16]. The environmental data were either measured and calculated through specific processes, estimated through findings in literature sources, or provided directly from the Ecoinvent database 3.

3.2.2 Functional unit and system boundaries

This study has a functional unit a one unit part. The phases included in the assessment and system boundaries are common to case study 1, being explained previously and exemplified in **Figure 3.1**. The study comprehends all the product production phases, from the extraction of natural resources to the production of the final part. The use and disposal phases are not included, since this is a cradle-to-gate study. Transportation was also not considered. The assessment was performed considering the ReCiPe 2016 (Hierarchical) method that SimaPro 9.2 software has available. The comparison between both processes was made based on the manufacturing of 0.186 kg of ER90 steel (low alloyed steel). Due to time constraints, was not conducted sensitivity, or uncertainty analysis.

3.2.3 Environmental Inventory Analysis

3.2.3.1 WAAM

The WAAM process requires as inputs: substrate, ER90 steel wire, energy consumption, and shielding gas, that in this case will be a mixture of 88% Ar and 12% CO₂. All the values referent to the phases of the ER90 steel wire production (hot rolling and wire drawing), as well as the steel billet value and electricity regarding the Milling process were calculated considering the Ecoinvent 3 database. Also based on Ecoinvent 3 database, a loss of 5% and 4% was assumed, respectively, for the hot rolling and wire drawing processes. The mass of the deposited material was 0.218 kg. The part was produced by using a CNC milling machine. The voltage

of the process was set to be 18 V, the travel speed to be 360 mm/min, and the wire feed speed to be 3 m/min. The flow rate of the shielding gas was monitored to be 16 l/min and for geometry 2 production, it was necessary 238.9 l of shielding gas. The LabView software allowed to compute the power consumption of the electric arc regarding the WAAM machine. The power rating obtained was 1.75 kW. Successively, given the data, the energy consumed was calculated, obtaining the value of 0.436 kWh. The printing path followed the same strategy of alternating directions. The interlayer temperature was set to be 100 degrees Celsius and the interlayer cooling time 180 seconds. The part was built with 32 layers, the layer height set to be 1.5 mm. The outputs of the process were the final part, the solid waste, and the pollutant emissions into the air. Due to the lack of specific equipment, the emissions related to the production were not measured. The substrate plate for WAAM was also not considered so that, afterward, a fair comparison with CNC milling can be made. The estimated value of the final product was 0.186 kg. Considering (1) and the masses of the final and initial part, the theoretical buy-to-fly (BTF) ratio was calculated and a value of 1.17 was reached. The calculated value of the CNC Milling was 0.032kg.

For further detail, the final part produced, as well as the CAD model view and the WAAM part preview are represented in **Figure 3.3**.

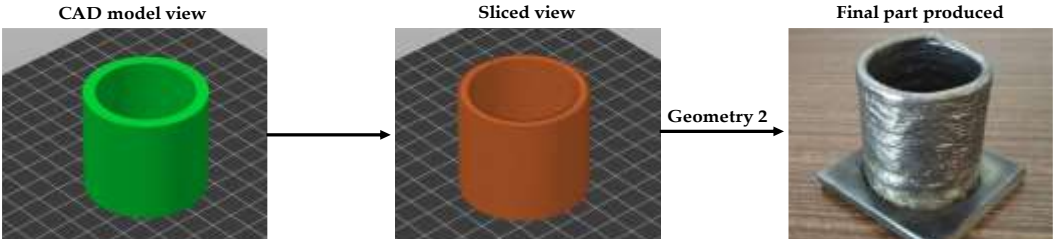


Figure 3.3. CAD representation vs Final part of geometry 2

To summarize all the information specified, the inventory of the WAAM process was depicted in **Table 3.3**.

Table 3.3. LCI of geometry 2 (WAAM process)

Process	Material/Process	Total values	Units	Type of data	Reference
WAAM + CNC Milling	Steel billet	0.238	kg	Calculated	Ecoinvent 3 database
	Shielding gas	238.9	l or dm3	Measured	Measured data
	Hot Rolling	0.238	kg	Calculated	Ecoinvent 3 database
	Wire Drawing	0.227	kg	Calculated	Ecoinvent 3 database
	WAAM Deposition	0.218	kg	Measured	Measured data
	Electricity (WAAM)	0.436	kWh	Calculated	Calculated data
	Electricity (Milling)	0.133	kWh	Calculated	Ecoinvent 3 database
	CNC Milling	0.032	kg	Calculated	Estimated data
Final Product	0.186	kg	Estimated	CAD representation in SolidWorks	

3.2.3.2 CNC Milling

The CNC milling process requires as inputs: the ER90 steel bar, a CNC machine, and the cutting tools and CNC milling machine tool. The values regarding the steel billet, the ER90 steel wire production phases (hot rolling), as well as the data relative to compressed air, lubricating oil, water, and electricity, were calculated considering the Ecoinvent 3 database. A material loss of 5% for the hot rolling process was also assumed based on Ecoinvent 3 database. The initial billet was assumed to be 51 mm in diameter and 51 mm in height. The estimated mass, for the initial billet, was 0.605 kg and for the final product was 0.186 kg. The CNC Milling process has a value of 0.419 kg. Estimated the mass of both initial billet and final product, **(1)** was once more used to calculate the theoretical buy-to-fly (BTF) ratio. It obtained a value of 3.25.

All the information mentioned is outlined in the inventory of the CNC Milling process and was represented in **Table 3.4**.

Table 3.4. LCI of geometry 2 (CNC process)

Process	Material/Process	Total values	Units	Type of data	Reference
CNC Milling	Steel billet	0.635	kg	Calculated	Ecoinvent 3 database
	Hot Rolling	0.6345	kg	Calculated	
	Compressed Air	0.536	m3	Calculated	
	Lubricating Oil	0.002	kg	Calculated	
	Water	0.007	m3	Calculated	
	Electricity	1.746	kWh	Calculated	
	CNC Milling	0.419	kg	Calculated	Calculated data
Final Product	0.176	kg	Estimated	CAD representation in SolidWorks	

3.3 Case Study 3

3.3.1 Goal and Scope definition

The purpose of this study is to investigate the environmental impacts of WAAM in the production of an S shape part, using the LCA methodology. This geometry is going to be referred to as geometry 3 in the following sections and chapters. For a better context of the results obtained, the study considers both WAAM and CNC Milling processes. The LCA follows the requirements and guidelines of the European standard, ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines[16]. The environmental data were either measured and calculated through specific processes, estimated through findings in literature sources, or provided directly from the Ecoinvent database 3.

3.3.2 Functional unit and system boundaries

This study has as functional unit a one unit part. The phases included in the assessment and system boundaries are common to case study 1 and 2, being explained previously and exemplified in **Figure 3.1**. The study comprehends all the product production phases, from the extraction of natural resources to the production of the final part. The use and disposal phases are not included, since this is a cradle-to-gate study. Transportation was also not considered. The assessment was performed considering the ReCipe 2016 (Hierarchical) method that SimaPro 9.2 software has available. The comparison between both processes was made based on the manufacturing of 0.109 kg of ER90 steel (low alloyed steel). Due to time constraints, was not conducted sensitivity, or uncertainty analysis.

3.3.3 Environmental Inventory Analysis

3.3.3.1 WAAM

The WAAM process requires as inputs: substrate, ER90 steel wire, energy consumption, and shielding gas, that in this case will be a mixture of 88% Ar and 12% CO₂. All the values referent to the steel billet and to the phases of the ER90 steel wire production (hot rolling and wire drawing) were calculated considering the Ecoinvent 3 database. Also based on Ecoinvent 3 database, a loss of 5% and 4% was assumed, respectively, for the hot rolling and wire drawing processes. The mass of the deposited material was 0.109 kg. The part was produced by using a CNC milling machine. The voltage of the process was set to be 18 V, the travel speed to be 360 mm/min, and the wire feed speed to be 3 m/min. The flow rate of the shielding gas was monitored to be 16 l/min and for geometry 3 production, it was necessary 200 l of shielding gas. The LabView software allowed to compute the power consumption of the electric arc regarding the WAAM machine. The power rating obtained was 1.75 kW. Successively, given the data, the energy consumed was calculated, obtaining the value of 0.365 kWh. The printing path followed the same strategy of alternating directions. The interlayer temperature was set to be 100 degrees Celsius and the interlayer cooling time 180 seconds. The part was built with 32 layers, the layer height set to be 1.5 mm. The outputs of the process were the final part, the solid waste, and the pollutant emissions into the air. Due to the lack of specific equipment, the emissions related to the production were not measured. The substrate plate for WAAM was also not considered so that, afterward, a fair comparison with CNC milling can be made. The estimated value of the final product was 0.109 kg. Considering **(1)** and the masses of the final

and initial part, the theoretical buy-to-fly (BTF) ratio was calculated and a value of 1.49 was reached. The calculated value of the CNC Milling was 0.053 kg.

For further detail, the final part produced, as well as the CAD model view and the WAAM part preview are represented in **Figure 3.4**.



Figure 3.4. CAD representation vs Final part of geometry 3

To summarize all the information specified, the inventory of the WAAM process was depicted in **Table 3.5**.

Table 3.5. LCI of geometry 3 (WAAM process)

Process	Material/Process	Total values	Units	Type of data	Reference
WAAM + CNC Milling	Steel billet	0.177	kg	Calculated	Ecoinvent 3 database
	Shielding gas	200	l or dm ³	Measured	Measured data
	Hot Rolling	0.177	kg	Calculated	Ecoinvent 3 database
	Wire Drawing	0.168	kg	Calculated	Ecoinvent 3 database
	WAAM Deposition	0.162	kg	Measured	Measured data
	Electricity (WAAM)	0.365	kWh	Calculated	Calculated data
	Electricity (Milling)	0.222	kWh	Calculated	Ecoinvent 3 database
	CNC Milling	0.053	kg	Calculated	Estimated data
	Final Product	0.109	kg	Estimated	CAD representation in Solid-Works

3.3.3.2 CNC Milling

The CNC milling process requires as inputs: the ER90 steel bar, a CNC machine, the cutting tools, and the CNC milling machine tool. The values regarding the steel billet, the ER90 steel wire production phases (hot rolling), as well as the data relative to compressed air, lubricating oil, water, and electricity, were calculated considering the Ecoinvent 3 database. A material loss of 5% for the hot rolling process was also assumed based on Ecoinvent 3 database. The initial billet was assumed to be 62 mm in diameter, 112 mm in length, and 21 mm in height. The estimated mass, for the initial billet, was 0.528 kg and for the final product was 0.109 kg. The CNC Milling process has a value of 0.446 kg. Estimated the mass of both initial billet and

final product, (1) was once more used to calculate the theoretical buy-to-fly (BTF) ratio. It obtained a value of 4.86.

All the information mentioned is outlined in the inventory of the CNC Milling process and was represented in **Table 3.6**.

Table 3.6. LCI of geometry 3 (CNC process)

Process	Material/Process	Total values	Units	Type of data	Reference
CNC Milling	Steel billet	0.555	kg	Calculated	Ecoinvent 3 database
	Hot Rolling	0.555	kg	Calculated	
	Compressed Air	0.571	m ³	Calculated	
	Lubricating Oil	0.002	kg	Calculated	
	Water	0.007	m ³	Calculated	
	Electricity	1.858	kWh	Calculated	
	CNC Milling	0.446	kg	Calculated	Calculated data
Final Product	0.109	kg	Estimated	CAD representation in SolidWorks	

3.4 Additional comments

After understanding the results obtained in the inventory of each case study, some observations regarding the buy-to-fly ratio and the quantity of removed material can be made. In the first place, it is important to acknowledge that the BTF ratio is inversely proportional to the productivity measure, meaning the bigger the BTF ratio, the lower the productivity of the production is and vice-versa. (2) exemplifies that relation. Thus, it was expected that WAAM would have lower values of BTF ratio than the CNC milling process.

$$Buy\ to\ fly\ (BTF)\ ratio = \frac{1}{productivity} = \frac{Input\ mass}{Output\ mass} \quad (2)$$

In addition, it was observed that the BTF ratio was related to the amount of material removed. Lower BTF ratios result in lower values of removed material that consequently translate into higher productivity. **Figure 3.5** and **Figure 3.6** were elaborated in order to demonstrate this relation. In **Figure 3.5**, relative to the WAAM production of each geometry, can be observed that geometry 1 had the highest value of material removal and geometry 2 the lowest. On the other hand, in **Figure 3.6**, relative to the CNC Milling production of each geometry, geometry 3 had the highest value of material removal and geometry 1 the lowest. Thus, it can be inferred that, for the CNC Milling process, better results are obtained the more "filled" the geometries being produced are. For the WAAM process it's the opposite, better results are obtained the less "filled" the geometries being produced are. Although CNC Milling is more suitable for

certain type of geometries, WAAM still proves to have better performance overall. In this sense, by having a higher material efficiency, WAAM will contribute to reduce certain environmental impacts such as material waste.

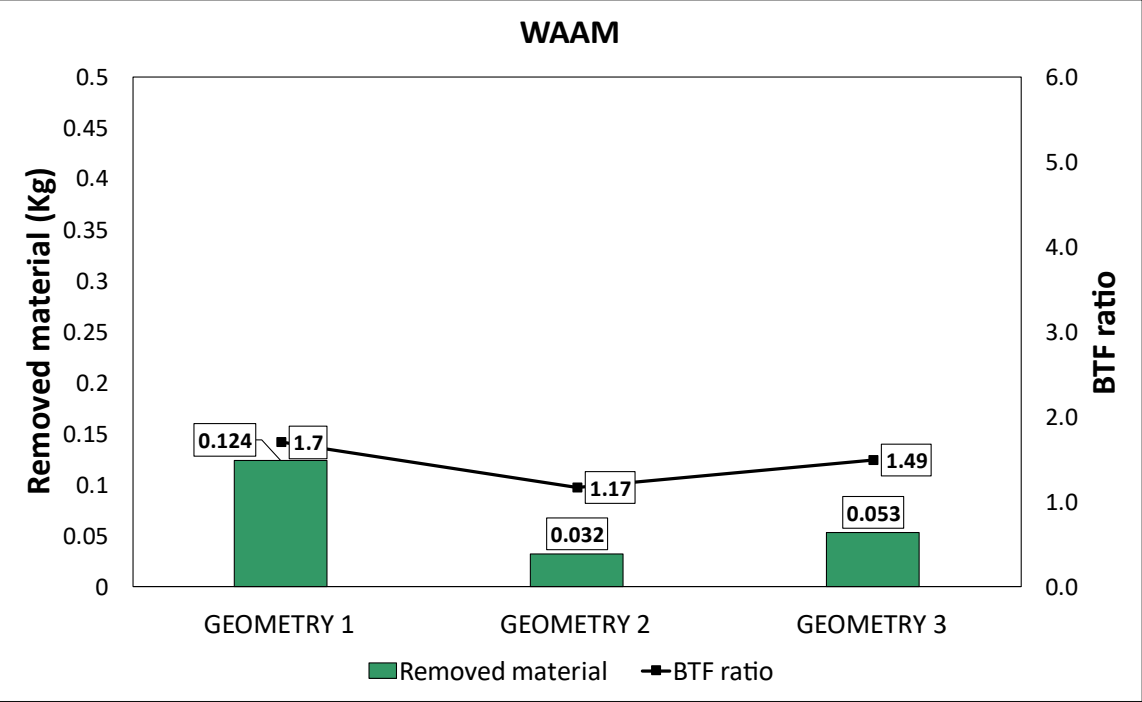


Figure 3.5. Removed material vs BTF ratio for WAAM production

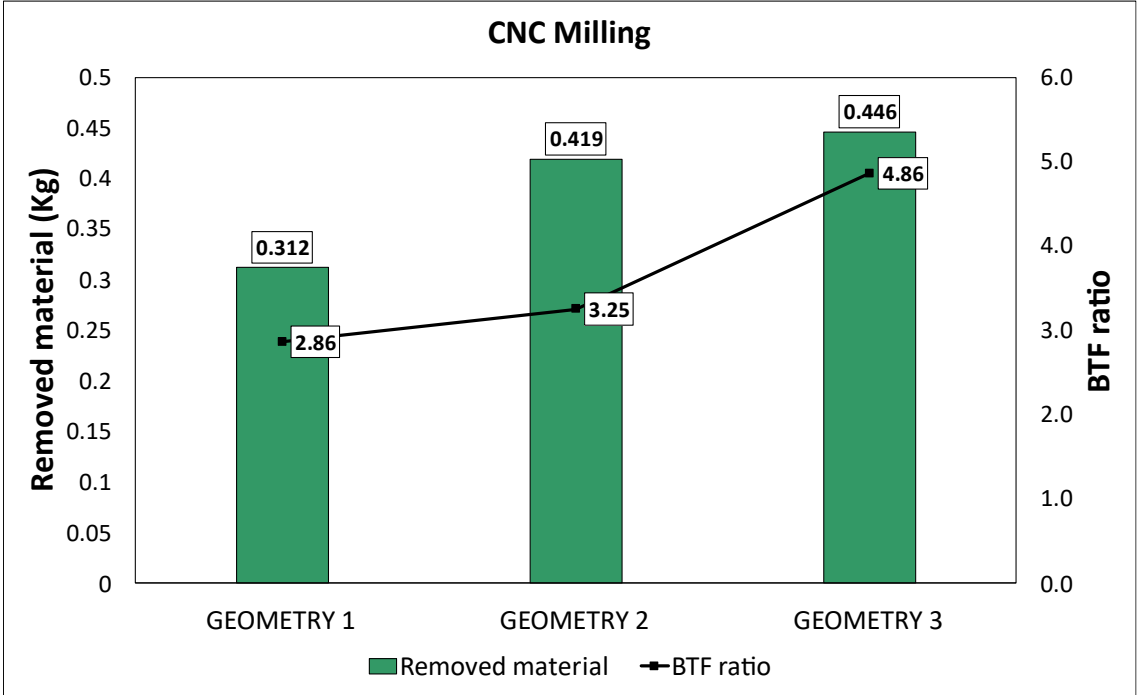


Figure 3.6. Removed material vs BTF ratio for CNC Milling production

RESULTS

The present chapter has the goal to perform a LCIA on the case studies presented. Additionally, conclusions were withdrawn, and suggested measures to implement to decrease the environmental impact associated with WAAM and CNC Milling. The previous chapter approached separately each case study. In this chapter, to facilitate the comparison of the results obtained, a joint analysis of the case studies will be made. The overall impacts of both technologies, as well as the individual impacts, were analysed.

4.1 Interpretation of the LCA results

To carry out an environmental impact assessment it is necessary to choose an impact assessment method. For the case studies considered, the assessment was carried out accordingly to the ReCiPe 2016 (Hierarchist) method. ReCiPe method can either calculate the impacts for one specific environmental problem (midpoint indicators) or calculate aggregate the impacts in levels (endpoint indicators). In this analysis, both were explored.

Table 4.1 represents the results obtained for the 18 midpoint indicators considered. To simplify the interpretation of the results, these midpoint indicators were converted to endpoints through an aggregation process and 3 endpoint indicators were considered: Human Health, Ecosystems, and Resources. The following analysis will be made considering the total impact, meaning the aggregation of these 3 endpoint indicators. Uncertainty was not assumed in the aggregation processes.

Table 4.1. ReCiPe Midpoint Impact Assessment overall results

Impact category	Unit	Geometry 1		Geometry 2		Geometry 3	
		WAAM	CNC Milling	WAAM	CNC Milling	WAAM	CNC Milling
Global warming	kg CO ₂ eq	1.81E+00	1.78E+00	1.44E+00	2.20E+00	1.34E+00	2.07E+00
Stratospheric ozone depletion	kg CFC-11 eq	6.25E-07	5.51E-07	5.01E-07	6.96E-07	4.82E-07	6.78E-07
Ionizing radiation	kBq Co-60 eq	4.21E-01	3.43E-01	3.33E-01	4.52E-01	3.08E-01	4.69E-01
Ozone formation, Human health	kg NO _x eq	3.79E-03	4.00E-03	3.01E-03	4.91E-03	2.86E-03	4.57E-03
Fine particulate matter formation	kg PM _{2.5} eq	2.79E-03	2.95E-03	2.21E-03	3.63E-03	2.08E-03	3.40E-03
Ozone formation, Terrestrial ecosystems	kg NO _x eq	3.95E-03	4.23E-03	3.13E-03	5.19E-03	2.96E-03	4.82E-03
Terrestrial acidification	kg SO ₂ eq	6.03E-03	5.48E-03	4.90E-03	6.84E-03	4.89E-03	6.53E-03
Freshwater eutrophication	kg P eq	1.20E-03	1.16E-03	9.42E-04	1.46E-03	8.61E-04	1.42E-03
Marine eutrophication	kg N eq	9.17E-05	8.28E-05	7.22E-05	1.04E-04	6.50E-05	1.02E-04
Terrestrial ecotoxicity	kg 1,4-DCB	5.45E+00	7.60E+00	4.09E+00	9.13E+00	3.28E+00	8.14E+00
Freshwater ecotoxicity	kg 1,4-DCB	1.21E-01	1.64E-01	8.52E-02	2.04E-01	7.54E-02	1.93E-01
Marine ecotoxicity	kg 1,4-DCB	1.62E-01	2.19E-01	1.15E-01	2.71E-01	1.01E-01	2.56E-01
Human carcinogenic toxicity	kg 1,4-DCB	7.34E-01	1.00E+00	5.38E-01	1.20E+00	4.16E-01	1.06E+00
Human non-carcinogenic toxicity	kg 1,4-DCB	2.05E+00	2.19E+00	1.58E+00	2.74E+00	1.43E+00	2.61E+00
Land use	m ² a crop eq	4.65E-02	4.80E-02	3.61E-02	5.92E-02	3.27E-02	5.56E-02
Mineral resource scarcity	kg Cu eq	4.71E-02	7.51E-02	3.42E-02	8.95E-02	2.57E-02	7.85E-02
Fossil resource scarcity	kg oil eq	4.43E-01	4.30E-01	3.55E-01	5.34E-01	3.39E-01	5.07E-01
Water consumption	m ³	4.26E-02	2.21E-02	3.69E-02	2.81E-02	3.19E-02	2.76E-02

4.1.1 Overall impacts

To represent, the total environmental impact that both processes have in the production of the different geometries, **Figure 4.1** was elaborated. Relatively to the parts produced by CNC Milling, geometry 2 has the highest environmental impact (153.24 mpts), followed by geometry 3 (140.38 mpts) and geometry 1 (125.70 mpts). Relatively to the parts produced by WAAM, geometry 1 has the highest environmental impact (110.05 mpts), followed by geometry 2 (84.76 mpts) and geometry 3 (74.31 mpts). Given the geometries and processes used, the results obtained were expected. CNC Milling is a subtractive process therefore, the higher the need to remove material in the geometry production, the higher the total environmental impact will be. WAAM is an additive process, the higher the need to deposit material to produce the desired geometry, the higher the total environmental impact will be.

WAAM demonstrated to be the process that, overall, has more sustainability potential. When compared to CNC Milling, it had an improvement of 12% in geometry 1 production, 45% in geometry 2, and 47% in geometry 3.

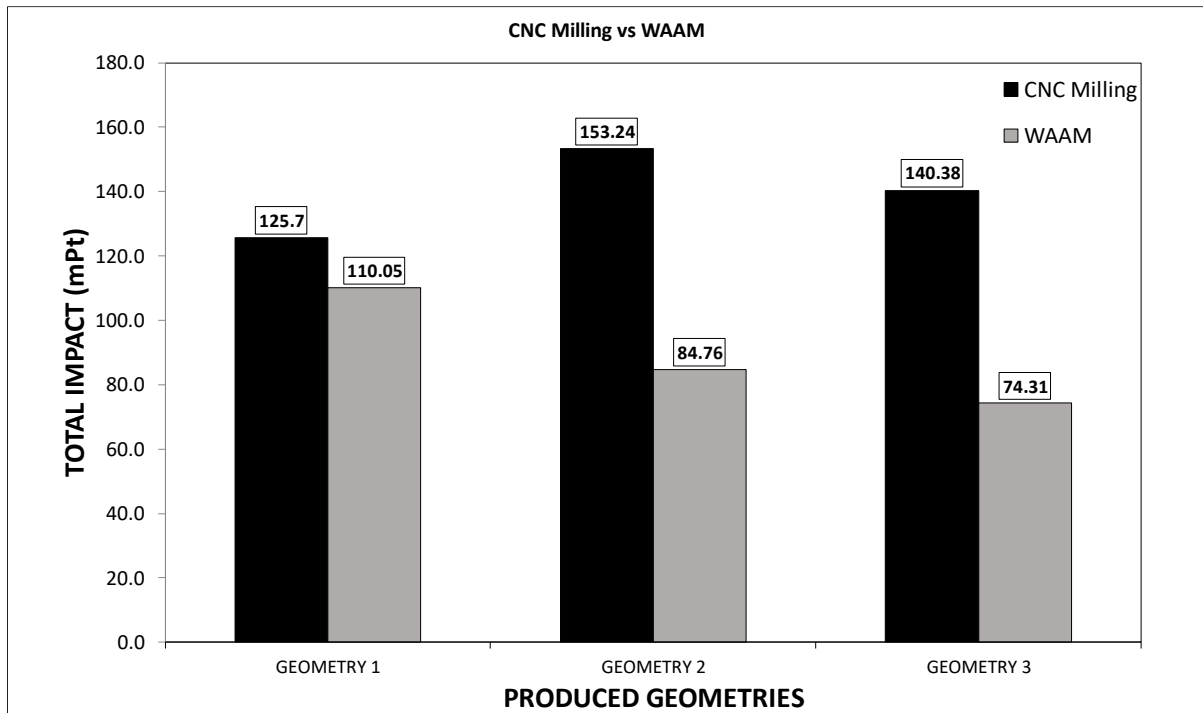


Figure 4.1. Overall environmental impacts CNC Milling and WAAM for each geometry

4.1.2 WAAM impacts

The different contributions of the inventory inputs for the WAAM process were displayed in **Figure 4.2**, to be easily analyzed. The production of the steel billet has proven to be the highest environmental impact for each geometry produced, being responsible for 53% of the total environmental impact of geometry 1, 50% of geometry 2, and 42% of geometry 3. The consumptions of shielding gas and electricity also have significant contributions. The shielding gas contributed 21% for geometry 1 production, 28% for geometry 2, and 26% for geometry 3. The electricity had a contribution of 8% for geometry 1, 11% for geometry 2, and 18% for geometry 3. The remaining contributions are related to the processes of hot rolling, wire drawing, and CNC Milling. Compared with the others, their percentages are relatively low. The hot rolling process generated a 3% impact on the production geometries of all geometries. The wire drawing generated 6% for geometry 1 and 2 part production and 5% for geometry 3. The CNC Milling generated 9% for geometry 1, 3% for geometry 2, and 6% for geometry 3. It is further noted that, for each geometry produced, the hot rolling process is considered the lowest environmental impact. In short, the geometry 1 production presented higher impacts for the different inventory inputs and the geometry 3 production presented lower impacts.

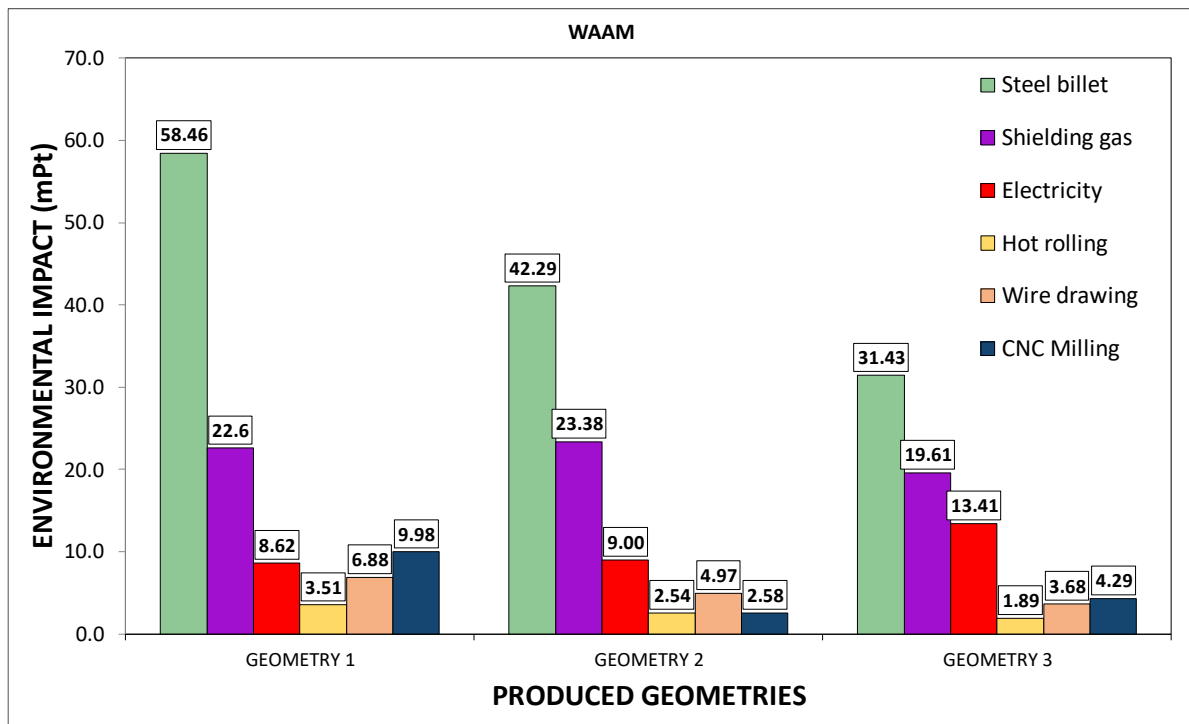


Figure 4.2. WAAM environmental analysis for each geometry produced

4.1.3 CNC milling impacts

The different contributions of the inventory inputs for the CNC Milling process were displayed in **Figure 4.3**, to be easily analyzed. Similarly to WAAM, the production of the steel billet has also proven to be the highest environmental impact for each geometry produced. It accounted for 75% of the total environmental impact for geometry 1, 74% for geometry 2, and 70% for geometry 3. The CNC Milling process also has a significant contribution, generating a 20% impact for geometry 1 production, 22% for geometry 2, and 26% for geometry 3. The remaining contribution is related to the hot rolling process, whose impacts are relatively low, for geometry 1 (5%), geometry 2 (5%), and geometry 3 (4%) productions. To summarize, the geometry 2 production presented higher impacts for the different inventory inputs and geometry 1 production presented lower impacts.

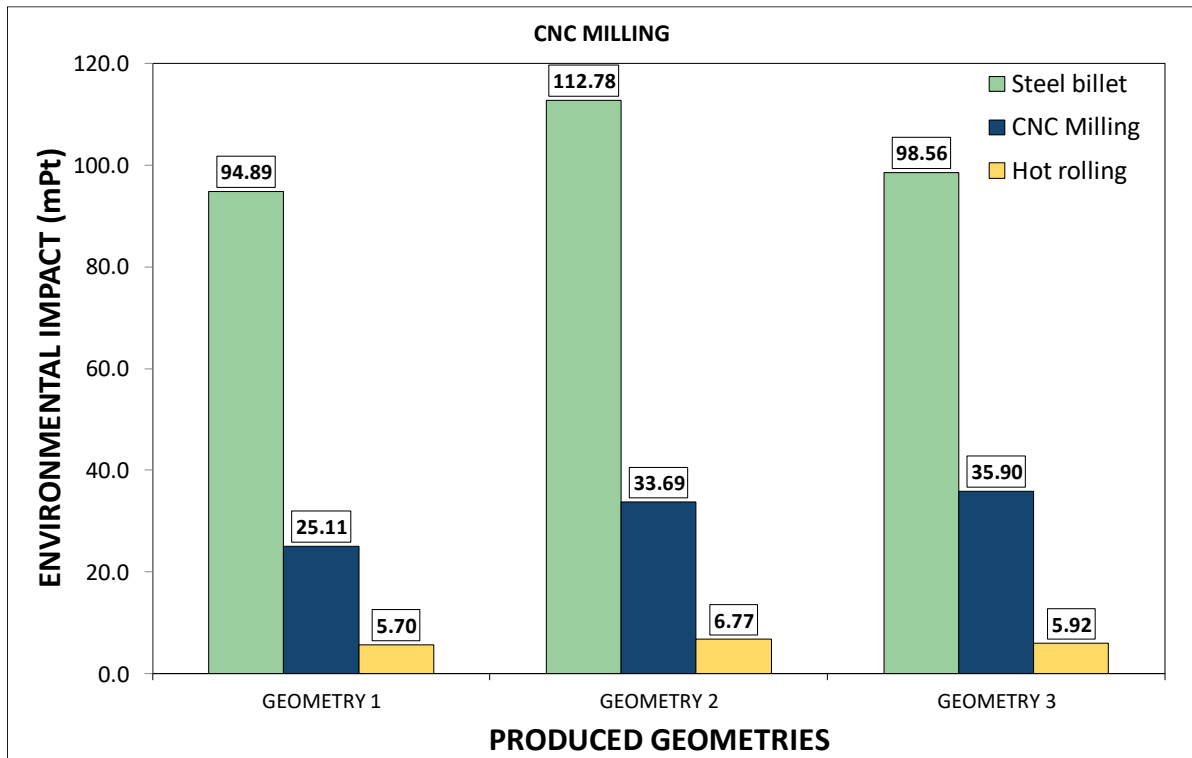


Figure 4.3. CNC milling environmental analysis for each shape produced

4.2 Results discussion

In this particular application and considering all the geometries produced, WAAM has proven to be the best option ecologically. It is notable that, depending on the geometry being produced, the suitability of each process might differ. As previously mentioned, WAAM is an AM process whereas CNC milling is a subtractive manufacturing process. For geometry 1 production, the need to remove material is relatively similar to the need of depositing it, making the differences between using one process or another almost not significant. On the contrary, for geometry 2 and geometry 3 production, the amount of material removed will be significantly higher than the amount of material deposited. In this case, WAAM inevitably has an advantage over CNC Milling.

When analyzing separately both processes, it is possible to get an understanding of which inventory inputs have higher and lower contributions to the total environmental impact. In both processes and for all the geometries considered, the steel billet production was the stage that contributed with the highest environmental impact, being therefore identified as the main environmental hotspot, and the hot rolling process was the stage that contributed with the lowest environmental impact. The production of steel billet is made by continuous casting. This process is connected with certain environmental issues

such as material waste and hazardous emissions, making the results obtained foreseeably. The hot rolling process itself has few environmental implications. But besides that, it is also clear that, to the case studies developed and the technologies used, this process only represents a small stage, whose sole purpose is to mold the steel billet into the desired shape for the input. In this sense, its contribution will be little to the total environmental impact.

The shielding gas and electricity consumptions also had significant contributions to the total impact of all the geometries produced by WAAM. The CNC Milling stage also had a significant contribution to the total impact of all the geometries produced by CNC Milling. This is mainly because these inputs are the main factors involved in each type of manufacturing. Furthermore, it was observed that the WAAM process presented lower individual contributions for the total environmental impact than CNC Milling, proving its higher efficiency.

4.2.1 Suggestions to reduce environmental impact

As previously mentioned, the steel billet production was the stage that contributed more to the total impacts of all the produced geometries. Therefore, this subsection will focus on this subject and further suggest measures for decreasing the impacts related. The steel billet is produced through the continuous casting process. Due to the high temperatures used, this type of production generates not only pollutant emissions but also produces a significant amount of waste that can be translated into gaseous waste, for the most part, and to liquid emissions and solid waste (sand waste, investment casting waste, cleaning room waste, and slag waste) [38].

To help reduce the associated impacts, it is necessary to:

- ✓ Create appropriate treatments to reduce the toxicity of the waste produced allowing it, therefore, to be recycled.
- ✓ Use appropriate machines to prevent gas and liquid emissions. (for example, gas-removing systems [39])
- ✓ Create new processes that combine proper waste management with good performance and efficiency [40].
- ✓ Adopt techniques to recycle the solid waste resulting from the foundry.

Steel can easily be recycled without changing the inherent material properties. This means that scrap can be produced as a high-quality metal [41]. **Figure 4.4** exemplifies the procedure. However, the process of secondary steelmaking still needs some environmental improvements, since it requires high energy consumption and harmful emissions are released.

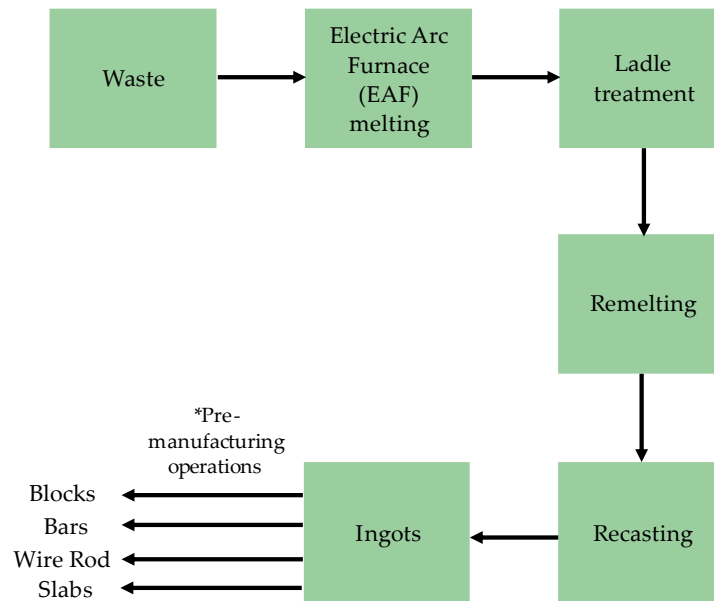


Figure 4.4. Secondary steel making. Elaborated based on [1]

Although the production of steel billet has proven to be the main environmental hotspot, the consumption of shielding gas and the consumption of electricity for the WAAM process and the CNC Milling stage for the CNC Milling process, also showed significant impacts when compared with the other inventory inputs. As for WAAM, a possible solution for the consumption of shielding gas would be to implement new technologies that allow an optimization of the required gas flow for the process. For energy consumption, an option could be the use of renewable energy but that would require further investigation to be implemented. As for CNC and relative to the CNC Milling stage, the main factor that contributes to its significant impact, is the solid material waste caused. Thus, the solutions to be applied are related to waste management processes and recycling techniques (Figure 4.4).

4.3 Further observations

Additional observations can be made if the 3 endpoint indicators were considered instead of the total impact of the analysis. Figure 4.2 and Figure 4.3 are displayed the impacts that each production caused on human health, ecosystems, and resources, for each geometry. The highest impacts, for both processes, are relative to the human health indicator. Analysing it in greater detail in Table 4.2, it is possible to understand that the inventory input that contributes the most to the human health impacts is the production of the steel billet. In the majority of the geometries produced and considering both technologies, this input represented more than 50% of the total human health impacts. As approached earlier, the steel billet is

produced through continuous casting and this process generates a considerable amount of hazardous gases. To address this issue, beyond the suggestions already made, could be added further research on human safety in the continuous casting process.

Table 4.2. Human Health impacts analysis

Inventory Inputs	Geometry 1		Geometry 2		Geometry 3	
	WAAM	CNC Milling	WAAM	CNC Milling	WAAM	CNC Milling
Steel billet	57.345	93.076	41.483	110.628	30.834	96.683
Shielding gas	21.659	-	22.415	-	18.796	-
Electricity	8.251	-	8.615	-	12.843	-
Hot rolling	3.431	5.568	2.482	6.618	1.845	5.784
Wire drawing	6.751	-	4.874	-	3.612	-
CNC machining	9.596	24.144	2.476	32.386	4.125	34.513

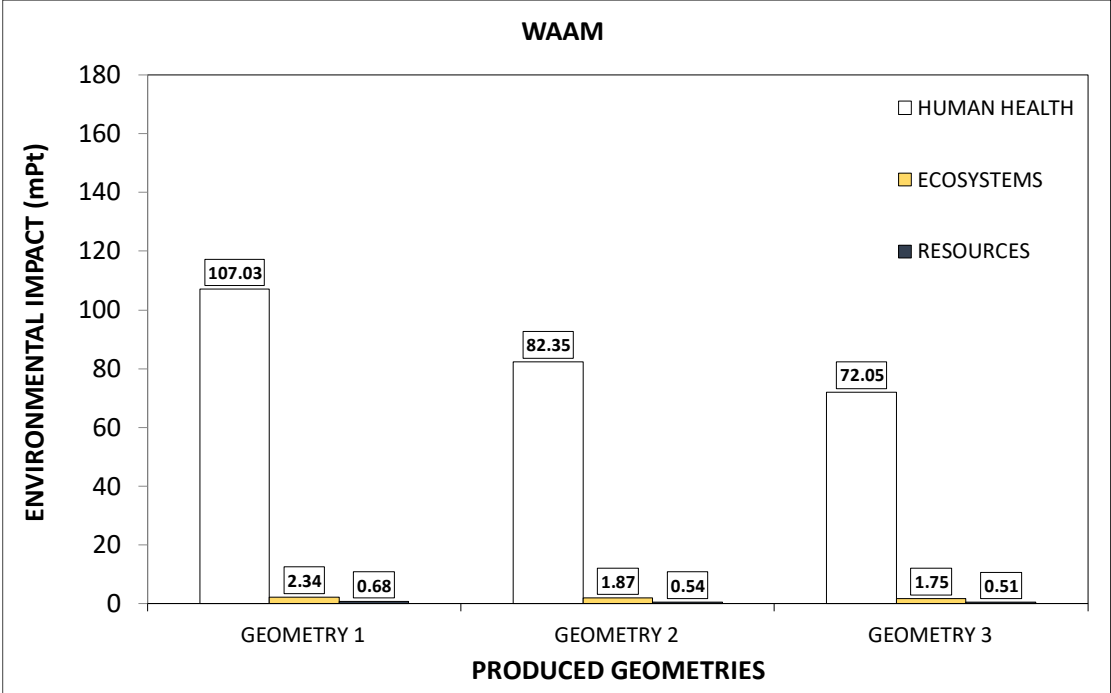


Figure 4.5. Environmental analysis of WAAM, midpoint indicators

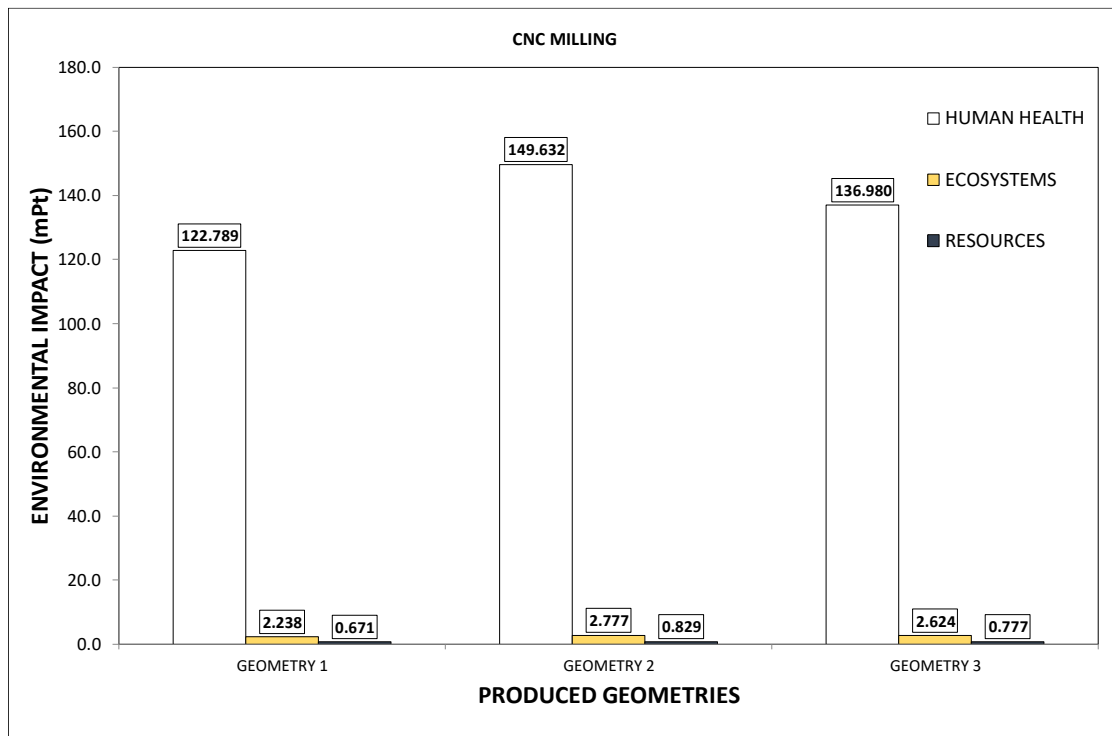


Figure 4.6. Environmental analysis of CNC Milling, midpoint indicators

The last chapter of the dissertation will present a summary of the study's research, to understand its potential contributions and withdraw specific conclusions. Additionally, it outlines the main limitations of the study and makes suggestions for further research.

5.1 Summary

Due to the impacts that the environment has suffered in the last years, the manufacturing sector felt the need to prioritize new sustainable ways of production. In this sense, AM emerged as a revolutionary technology and allowed a change in paradigm relative to the way that products are traditionally manufactured. Through AM technology it is possible to manufacture a part or product by simply depositing layers of material consequently. The present dissertation focused on a particular AM technology that enables the production of metal parts, WAAM. In the first place, it was made preliminary research about this subject. As a result, WAAM's main environmental advantages and disadvantages were identified. Although this technique presents several benefits, mainly in terms of material/resource efficiency, the underlying environmental issues that it has are still a concern. There has been some research made in this field already, however, is not yet possible to draw general conclusions about the environmental performance of WAAM.

The developed study illustrated the environmental impacts of this technology through the application of the LCA methodology in three different case studies. To give the results obtained better context and further highlight this technology's relevance, a traditional manufacturing process normally used for metal parts production, CNC Milling, was also considered in the assessment. The assessment was conducted in the SimaPro 9.2 software, according to the standard ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines [16]. The three case studies were performed under the same

circumstances and having into account the same process parameters, the only differentiating detail was relative to the geometry that was being produced. Case Study 1 approached the production of a gear shape part, Case Study 2 approached the production of a cylinder shape part, and Case Study 3 approached the production of an S shape part. In the case studies assessment and its posterior comparison, those shape parts were referred to as geometry 1, geometry 2, and geometry 3.

For each case study, it was made initially an identification of the goal and scope, as well defined the functional unit and system boundaries. After that, an inventory analysis took place and details such as how the data was collected, the type of data used, the parameters set, etc. were specified. Additionally, during that analysis was observed that the Buy-to-fly ratio, a measure that allows for comparison of the mass of the final product with the mass of the raw material, had a relation to the amount of material removed in the production process. Lower BTF ratios translate into lower values of material removed and consequently into low material waste. CNC Milling proved to have better results in more "filled" geometries, unlike WAAM which had better results in less "filled" geometries. Overall, WAAM proved to have a lesser need to remove material and therefore, to have an advantage relative to the CNC Milling process.

To draw conclusions on the environmental impacts of both WAAM and CNC processes and compare the reached results for each geometry, an environmental impact assessment was conducted. The assessment was carried out considering the total impact caused, i.e., considering the aggregation of the results obtained for the 3 endpoint indicators: Human Health, Ecosystems, and Resources. After elaborating on the necessary graphs and analyzing them in greater detail the results, it was clear that WAAM was the best ecological option for all the geometries produced. However, depending on the geometry being produced its suitability differs. WAAM has an evident advantage relative to CNC Milling when producing geometries like geometry 2 and 3 that imply depositing lesser material than removing it. If the difference between the amount of material deposited and the amount of material removed is not that significant, it is almost indifferent to the technology used for the production, being geometry 1 an example of that. When analyzing WAAM and CNC Milling separately it was possible to understand the inventory inputs that had the highest (environmental hotspots) and the lowest contributions to their total environmental impact. For the geometries and technologies considered, the production of the steel billet presented the highest contributions and the hot rolling process the lowest. These results are mostly due to the nature of the processes involved in the production of the steel billet and hot rolling. Steel billet production occurs by continuous

casting and this is a highly environmentally damaging process because it contributes to material waste and hazardous emissions. On the other hand, the hot rolling process itself has a few environmental implications. With this in mind, certain solutions to apply to the continuous casting process, mainly regarding waste management, recycling options, and complementary equipment to prevent gas emissions, were proposed. Some measures relative to other inventory inputs with significant impacts such as the shielding gas and electricity consumption in WAAM and the CNC Milling stage in CNC Milling were also suggested. These were associated with the creation of new technologies for reaching consumption optimization, the use of renewable energy, and waste management/recycling ideas. Finally, as a curiosity, instead of considering the total impact of the analysis made, the 3 endpoint indicators were considered and additional observations were made. This allowed to verify that, for both processes, the highest impacts were relative to the human health indicator. Within the human health indicator and as expected, due to the issues previously mentioned, the production of the steel billet had the biggest contribution. To address this issue further research on human safety in the continuous casting process must be made.

Through the development of this dissertation, it was possible to have an overview relative to the WAAM process and identify its main advantages/disadvantages over the existing traditional processes. Subsequently, the characterization, quantification, and qualification of the environmental impacts related to this process were made through illustrative case studies. The results obtained from this particular application of WAAM corroborated the hypothesis that this process is less environmentally damaging than the traditional processes. However, once more, the results were obtained for this particular study comparing WAAM with only CNC milling. In addition, it was also necessary to understand what were the main factors contributing to the total environmental impact of the process and suggest improvements. To generalize this conclusions, further research on this topic needs to be made.

The author concludes that while there is already a consensus on using WAAM for certain applications, such as small productions or repairing worn parts, for other manufacturing applications it might not be the least environmentally damaging process. In those cases, maybe the best option would be to implement a hybrid process, incorporating WAAM with another process, to take advantage of both [17]. Another possible solution, but that would imply investigation, would be developing a complementary software that allowed optimization of the process parameters, accordingly to the product being made [42]. Finally, it is worth noting that, this study presented a contribution to the body of knowledge relative to the application of the LCA methodology in WAAM. However, if there were no time constraints or other limitations, it

could have been more in-depth and explored other equally relevant issues of the process. Those limitations, as well as proposals for future work, will be stated below.

5.2 Limitations

The limitations found during the course of this research are outlined next.

- Time constraints. Due to the time available for the dissertation's writing, it was not possible to further elaborate the study and approach other relevant issues related to the process. The proposals for future work will get into greater detail about what could have been done.
- The CNC milling data had to be estimated due to the absence of appropriate machinery equipment (carbide cutting tools) and time constraints.
- There exist several studies relative to the application of the LCA methodology in different sectors, using different AM technologies. However, it was notable a lack of studies relative to the application of this methodology to the WAAM process.
- The research already made in this field, approaching AM and LCA methodology could not be repeated or reused, since the case studies developed in the present dissertation are specific and have different raw materials, part geometries, process parameters, and machine tool types.

5.3 Future Work

The proposals for future work are mentioned in the following items.

- To obtain an overall characterization of WAAM's environmental performance, more comparison evaluations should be conducted, considering other materials, process settings, and geometries [13], [28], [36]. It would also be relevant to compare WAAM with other traditional manufacturing processes besides CNC milling like, for example, green sand casting [43] or even compare WAAM with other AM processes, like Selective Laser Melting.
- The assessment could be conducted considering also the use and disposal phases, as well as transportation. Relative to the use and disposal phases, recycling could be incorporated [33].
- Additionally to the environmental assessment, it could also be done with an economical (Life cycle costing: LCC) and social assessment (Social Life Cycle Assessment: SLCA) to complement the results obtained [42], [44], [45].
- Investigate the environmental impacts of a hybrid process where wire additive manufacturing and a subtractive process are considered [17].

- Development of complementary software to optimize the WAAM's process parameters [42]. The WAAM's process parameters are normally established by the person responsible for the production process. As referred to previously, WAAM's performance highly depends upon the materials and machines used, as well as the geometries produced. Therefore, the parameters must be adjusted according to the production that is being made. The parameters are defined according to the knowledge acquired in previous experimental studies, not being possible a global understanding of what is the most optimal solution for each specific case. In short, developing software that would allow specifying constraints for each production, not only would facilitate the research work for the person that is working with the technology, but it would also allow reaching an optimal solution. For example, if the goal was to optimize the parameters to obtain a high-quality product with low hazardous emissions, material waste, and energy consumption, could be specified the percentage that its acceptable for each one of these impacts. Thus, the sustainability of WAAM would inevitably increase, and these results would cut across all applications of the technology that were made.

REFERENCES

- [1] P. C. Priarone, G. Campatelli, A. R. Catalano, and F. Baffa, "Life-cycle energy and carbon saving potential of Wire Arc Additive Manufacturing for the repair of mold inserts," *CIRP J. Manuf. Sci. Technol.*, vol. 35, pp. 943–958, Nov. 2021, doi: 10.1016/j.cirpj.2021.10.007.
- [2] Y. Shi and J. Faludi, "Using life cycle assessment to determine if high utilization is the dominant force for sustainable polymer additive manufacturing," *Addit. Manuf.*, vol. 35, p. 101307, Oct. 2020, doi: 10.1016/j.addma.2020.101307.
- [3] F. Lourenço, "A social life cycle assessment methodology for additive manufacturing products," *Mestre em Engenharia e Gestão Industrial*, Universidade Nova de Lisboa, 2018.
- [4] R. Godina, I. Ribeiro, F. Matos, B. T. Ferreira, H. Carvalho, and P. Peças, "Impact Assessment of Additive Manufacturing on Sustainable Business Models in Industry 4.0 Context," *Sustainability*, vol. 12, no. 17, Art. no. 17, Jan. 2020, doi: 10.3390/su12177066.
- [5] J. Ma, J. D. Harstvedt, D. Dunaway, L. Bian, and R. Jaradat, "An exploratory investigation of Additively Manufactured Product life cycle sustainability assessment," *J. Clean. Prod.*, vol. 192, pp. 55–70, Aug. 2018, doi: 10.1016/j.jclepro.2018.04.249.
- [6] L. Siva Rama Krishna and P. J. Srikanth, "Evaluation of environmental impact of additive and subtractive manufacturing processes for sustainable manufacturing," *Mater. Today Proc.*, vol. 45, pp. 3054–3060, Jan. 2021, doi: 10.1016/j.matpr.2020.12.060.
- [7] M. Burkhart and J. C. Aurich, "Framework to Predict the Environmental Impact of Additive Manufacturing in the Life Cycle of a Commercial Vehicle," *Procedia CIRP*, vol. 29, pp. 408–413, Jan. 2015, doi: 10.1016/j.procir.2015.02.194.
- [8] D. Böckin and A.-M. Tillman, "Environmental assessment of additive manufacturing in the automotive industry," *J. Clean. Prod.*, vol. 226, pp. 977–987, Jul. 2019, doi: 10.1016/j.jclepro.2019.04.086.
- [9] I. Ribeiro *et al.*, "Framework for Life Cycle Sustainability Assessment of Additive Manufacturing," *Sustainability*, vol. 12, no. 3, Art. no. 3, Jan. 2020, doi: 10.3390/su12030929.
- [10] C. Gao, S. Wolff, and S. Wang, "Eco-friendly additive manufacturing of metals: Energy efficiency and life cycle analysis," *J. Manuf. Syst.*, vol. 60, pp. 459–472, Jul. 2021, doi: 10.1016/j.jmsy.2021.06.011.
- [11] J. Lúcio, "Social Life Cycle Assessment for Additive Manufacturing: A Review," *Mestre em Engenharia e Gestão Industrial*, Universidade Nova de Lisboa, 2017.
- [12] K. Pfähler, D. Morar, and H.-G. Kemper, "Exploring Application Fields of Additive Manufacturing Along the Product Life Cycle," *Procedia CIRP*, vol. 81, pp. 151–156, Jan. 2019, doi: 10.1016/j.procir.2019.03.027.
- [13] A. C. M. Bekker and J. C. Verlinden, "Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel," *J. Clean. Prod.*, vol. 177, pp. 438–447, Mar. 2018, doi: 10.1016/j.jclepro.2017.12.148.
- [14] C. Prakash, S. Singh, H. Kopperi, S. Ramakrishna, and S. V. Mohan, "Comparative job production based life cycle assessment of conventional and additive manufacturing assisted investment casting of aluminium: A case study," *J. Clean. Prod.*, vol. 289, p. 125164, Mar. 2021, doi: 10.1016/j.jclepro.2020.125164.

- [15] Ó. S. Nunes, P. D. Gaspar, J. Nunes, P. Quinteiro, A. C. Dias, and R. Godina, "Life-Cycle Assessment of Dairy Products—Case Study of Regional Cheese Produced in Portugal," *Processes*, vol. 8, no. 9, Art. no. 9, Sep. 2020, doi: 10.3390/pr8091182.
- [16] ISO 14044:2006, "Environmental management — Life cycle assessment — Requirements and guidelines," ISO International Organization for Standardization, Jul. 2006.
- [17] M. Attaran, "The rise of 3-D printing: The advantages of additive manufacturing over traditional manufacturing," *Bus. Horiz.*, vol. 60, no. 5, pp. 677–688, Sep. 2017, doi: 10.1016/j.bushor.2017.05.011.
- [18] T. Pereira, J. V. Kennedy, and J. Potgieter, "A comparison of traditional manufacturing vs additive manufacturing, the best method for the job," *Procedia Manuf.*, vol. 30, pp. 11–18, Jan. 2019, doi: 10.1016/j.promfg.2019.02.003.
- [19] D. Landi, F. C. Zefinetti, C. Spreafico, and D. Regazzoni, "Comparative life cycle assessment of two different manufacturing technologies: laser additive manufacturing and traditional technique," *Procedia CIRP*, vol. 105, pp. 700–705, Jan. 2022, doi: 10.1016/j.procir.2022.02.117.
- [20] L. Li, C. Li, Y. Tang, and Q. Yi, "Influence factors and operational strategies for energy efficiency improvement of CNC machining," *J. Clean. Prod.*, vol. 161, pp. 220–238, Sep. 2017, doi: 10.1016/j.jclepro.2017.05.084.
- [21] ISO/ASTM 52900:2015, "Additive manufacturing — General principles — Terminology," ISO International Organization for Standardization, Dec. 2015.
- [22] A. Nazir, K. M. Abate, A. Kumar, and J.-Y. Jeng, "A state-of-the-art review on types, design, optimization, and additive manufacturing of cellular structures," *Int. J. Adv. Manuf. Technol.*, vol. 104, no. 9, pp. 3489–3510, Oct. 2019, doi: 10.1007/s00170-019-04085-3.
- [23] W. Gao *et al.*, "The status, challenges, and future of additive manufacturing in engineering," *Comput.-Aided Des.*, vol. 69, pp. 65–89, Dec. 2015, doi: 10.1016/j.cad.2015.04.001.
- [24] F42 Committee, "Terminology for Additive Manufacturing Technologies," ASTM International. doi: 10.1520/F2792-12A.
- [25] Z. Lin, K. Song, and X. Yu, "A review on wire and arc additive manufacturing of titanium alloy," *J. Manuf. Process.*, vol. 70, pp. 24–45, Oct. 2021, doi: 10.1016/j.jmapro.2021.08.018.
- [26] R. Jiang, R. Kleer, and F. T. Piller, "Predicting the future of additive manufacturing: A Delphi study on economic and societal implications of 3D printing for 2030," *Technol. Forecast. Soc. Change*, vol. 117, pp. 84–97, Apr. 2017, doi: 10.1016/j.techfore.2017.01.006.
- [27] T. A. Rodrigues, V. Duarte, R. M. Miranda, T. G. Santos, and J. P. Oliveira, "Current Status and Perspectives on Wire and Arc Additive Manufacturing (WAAM)," *Materials*, vol. 12, no. 7, Art. no. 7, Jan. 2019, doi: 10.3390/ma12071121.
- [28] S. Ford and M. Despeisse, "Additive manufacturing and sustainability: an exploratory study of the advantages and challenges," *J. Clean. Prod.*, vol. 137, pp. 1573–1587, Nov. 2016, doi: 10.1016/j.jclepro.2016.04.150.
- [29] D. Jafari, T. H. J. Vaneker, and I. Gibson, "Wire and arc additive manufacturing: Opportunities and challenges to control the quality and accuracy of manufactured parts," *Mater. Des.*, vol. 202, p. 109471, Apr. 2021, doi: 10.1016/j.matdes.2021.109471.
- [30] S. R. Singh and P. Khanna, "Wire arc additive manufacturing (WAAM): A new process to shape engineering materials," *Mater. Today Proc.*, vol. 44, pp. 118–128, Jan. 2021, doi: 10.1016/j.matpr.2020.08.030.

- [31] Y. Li, C. Su, and J. Zhu, "Comprehensive review of wire arc additive manufacturing: Hardware system, physical process, monitoring, property characterization, application and future prospects," *Results Eng.*, vol. 13, p. 100330, Mar. 2022, doi: 10.1016/j.rineng.2021.100330.
- [32] S. Pattanayak and S. K. Sahoo, "Gas metal arc welding based additive manufacturing—a review," *CIRP J. Manuf. Sci. Technol.*, vol. 33, pp. 398–442, May 2021, doi: 10.1016/j.cirpj.2021.04.010.
- [33] D. R. Vieira, J. L. Calmon, and F. Z. Coelho, "Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: A review," *Constr. Build. Mater.*, vol. 124, pp. 656–666, Oct. 2016, doi: 10.1016/j.conbuildmat.2016.07.125.
- [34] J. Fernandes, M. Peixoto, R. Mateus, and H. Gervásio, "Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: Rammed earth and compressed earth blocks," *J. Clean. Prod.*, vol. 241, p. 118286, Dec. 2019, doi: 10.1016/j.jclepro.2019.118286.
- [35] J. Almeida, C. Magro, E. P. Mateus, and A. B. Ribeiro, "Life Cycle Assessment of Electrolytic Technologies to Recover Raw Materials from Mine Tailings," *Sustainability*, vol. 13, no. 7, Art. no. 7, Jan. 2021, doi: 10.3390/su13073915.
- [36] G. Campatelli, F. Montevicchi, G. Venturini, G. Ingarao, and P. C. Priarone, "Integrated WAAM-Subtractive Versus Pure Subtractive Manufacturing Approaches: An Energy Efficiency Comparison," *Int. J. Precis. Eng. Manuf.-Green Technol.*, vol. 7, no. 1, pp. 1–11, Jan. 2020, doi: 10.1007/s40684-019-00071-y.
- [37] P. C. Priarone, E. Pagone, F. Martina, A. R. Catalano, and L. Settineri, "Multi-criteria environmental and economic impact assessment of wire arc additive manufacturing," *CIRP Ann.*, vol. 69, no. 1, pp. 37–40, Jan. 2020, doi: 10.1016/j.cirp.2020.04.010.
- [38] TheMetalCasting.com, "Environmental Issues." <https://www.themetalcasting.com/environmental-issues.html> (accessed Sep. 14, 2022).
- [39] M. Mazur, M. Bogacki, R. Oleniacz, and A. Łopata, "Assessment of ecological effects of the implementation of continuous casting of steel," *Stahl Eisen*, vol. 123, pp. 109–113, Jun. 2003.
- [40] E. C. Gentil, D. Gallo, and T. H. Christensen, "Environmental evaluation of municipal waste prevention," *Waste Manag.*, vol. 31, no. 12, pp. 2371–2379, Dec. 2011, doi: 10.1016/j.wasman.2011.07.030.
- [41] Reliance Foundry Co. Ltd, "How is Steel Made? An introduction to the production and properties of steel alloys," Jul. 02, 2020. <https://www.reliance-foundry.com/blog/how-is-steel-made> (accessed Sep. 14, 2022).
- [42] S. H. Huang, P. Liu, A. Mokasdar, and L. Hou, "Additive manufacturing and its societal impact: a literature review," *Int. J. Adv. Manuf. Technol.*, vol. 67, no. 5, pp. 1191–1203, Jul. 2013, doi: 10.1007/s00170-012-4558-5.
- [43] A. C. M. Bekker, J. C. Verlinden, and G. Galimberti, "Challenges in Assessing the Sustainability of Wire + Arc Additive Manufacturing for Large Structures," 2016.
- [44] B. Naghshineh, A. Ribeiro, C. Jacinto, and H. Carvalho, "Social impacts of additive manufacturing: A stakeholder-driven framework," *Technol. Forecast. Soc. Change*, vol. 164, p. 120368, Mar. 2021, doi: 10.1016/j.techfore.2020.120368.

- [45] G. Rebitzer *et al.*, "Life cycle assessment: Part 1: Framework, goal and scope definition, inventory analysis, and applications," *Environ. Int.*, vol. 30, no. 5, pp. 701–720, Jul. 2004, doi: 10.1016/j.envint.2003.11.005.



2022

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LIFE CYCLE ASSESSMENT OF PRODUCTS FABRICATED BY WIRE ARC ADDITIVE MANUFACTURING