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ENVIRONMENTAL IMPACT OF CONVENTIONAL MANUFACTURING AND ADDITIVE MANUFACTURING IN LIFECYCLE OF TURBINE BLADE

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Declaration of Authorship

I, Sharon Andrea Torres Carrillo, declare that this thesis titled, “ENVIRONMENTAL IMPACT OF CONVENTIONAL MANUFACTURING AND ADDITIVE MANUFACTURING IN LIFECYCLE OF TURBINE BLADE” and the work presented in it are my own.

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Sharon Andrea Torres Carrillo
Monterrey Nuevo León, May 20, 2018

Dedication

To God, for all the blessing that you give in my life.

To my father Jorge and my mother Lorena, whose actions and words full of love and wisdom inspire me to be a better human being, guide me in my path, raise me like a strong woman.

To my brother Ricardo whose affection, jokes and love fill my days with joy.

To my uncle Gabriel, to be like a second father and for always support my dreams and goals.

Thank you, because you are the engine of my life and the main motivation to promote this work.

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ENVIRONMENTAL IMPACT OF CONVENTIONAL MANUFACTURING AND ADDITIVE MANUFACTURING IN LIFECYCLE OF TURBINE BLADE

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Abstract

The exponential growth of additive manufacturing technologies is not only improving production processes to achieve functional requirements for products, but it could also help to minimize environmental impacts. In order to align a green product lifecycle management vision, companies need to implement emerging technologies and define a set of metrics that measure the benefits of the change. Each product requires a particular and optimized manufacturing process plan, and each production phase must achieve a significant reduction of critical metrics for the whole Life Cycle Assessment (LCA).

This study provides a comprehensive and comparative LCA of two manufacturing process plans for the case study of an aircraft engine turbine blade. The first process consists of a combination of Investment Casting and Precision Machining and the second consists in the replacement of Investment casting by Selective Laser Melting as an emergent process for near net shape fabrication. The collected data for the comparison includes Global Warming Potential (GWP), Acidification Potential (AP), Ozone layer Depletion Potential (ODP), Human Toxicity Potential (HTP), Ecotoxicity and Abiotic Depletion Potential (ADP).

List of Figures

List of Tables

Table of Contents

Chapter 1: Introduction

The aerospace sector is continuously adapting and innovating emergent manufacturing processes, towards the creation of new aircraft designs that must accomplish strict weight reduction and regulatory safety requirements. The environmental impact of the assimilation of new processing technologies is always a concern, due to the consumption of energy and the waste generation not considered before of the disruption of this kind of processes. Thus, Life Cycle Assessment in this new scenario becomes more relevant to fully understand the impact that must be addressed before the generalized use of novel fabrication methods.

The environmental burdens associated with a new aeronautic product should be evaluated during all the phases and stages of its lifetime, from the material extraction until its final disposal, including the production and manufacturing, the distribution, and the use of the product as well as its maintenance. In the case of aircraft design and manufacturing, there are different product subsystems with a specific design and functional requirements, for example, the fuselage, the wings, the stabilizers and the engine. In the particular case of this last, one may find many different parts with high mechanical performance requirements that must be designed and manufactured with tight mechanical tolerances.

In order to meet strict product requirements and at the same time higher levels of productivity and performance, advanced manufacturing processes and materials are continuously replacing conventional manufacturing technologies. Once Rapid Prototyping (RP) technologies have reached a maturity state, the emerging technologies in Additive Manufacturing (AM), especially Selective Laser Melting (SLM), have the potential to drive down cost and weight of an aircraft, by achieving acceptable levels in geometric accuracy and leading appropriate mechanical properties, while possibly reducing the environmental impact of the manufacturing cycle as well.

For economic and environmental reasons, the design of new aeronautic parts can take into account the possibility of using AM processes. Several studies show that AM is an exponential technology and will have a boom by the year 2050, some aerospace manufacturers are already implementing it to create jigs and fixtures. In fact, studies have demonstrated the potential of saving weight reduction, energy and greenhouses gas emissions in an aircraft component with the use Selective Laser Melting and Direct Metal Laser Sintering [1]. The work presented here is intended to contribute to environmental Life Cycle Assessment for additively manufactured aeronautic components. The environmental indicators included in the framework are related to the impacts emissions of energy, materials, and fluids.

The study is focused on the Global Warming Potential (GWP) caused by energy consumption. The main directly related indicator with GWP is the carbon footprint that measures all the carbon dioxide (CO_2) thrown into to the atmosphere during the manufacturing process, to calculate the CO_2 is necessary to analyze all energy consumption along the process.

In order to focus the work on a specific component, the research has developed the environmental impact analysis of a turbine blade production. The case of study is applied in a manufacturing facility dedicated to producing several aeronautic components by using a variety of technologies. The study compares the present manufacturing technologies against an Additive Manufacturing technology which is Selective Laser Melting.

1.1. Motivation

"The aerospace industry of our country is growing every day. In the last three years, it has been seeing growth rates above 15% per year. In fact, we are now the sixth supplier to the aerospace industry in the United States of America."

(President of United States of México, 2016)

Mexico is becoming more and more consolidated in the manufacture of aeronautical components worldwide. The installation in Mexico of several world-class companies such as Honeywell, Bombardier, Grupo Safran, EADS, ITR, has allowed the formation of important industrial conglomerates in various regions of the country, mainly in the north and center [2]. According to recent reports from the Ministry of Economy, investment opportunities for the aerospace industry in Mexico focus on completing the final cycle of an aircraft. The Gross Domestic Product (GDP) currently represents the 0.66% of the aerospace industry [3].

The exports level has registered a growth of more than 17.2% in annual average during the period 2004-2014. In 2010, the exports of the industry were 3,266 million dollars, and in 2011, the number of Mexican exports amounted to 4,500 million dollars, with a reached an amount of 6,363 million dollars [4], as it is illustrated in Fig. 1. According to estimates of the "Strategic Industry Program Aerospace 2010-2020" coordinated by the Ministry of Economy, the industry is expected to have exports of 12,267 million dollars by 2021, with average growth of 14%.

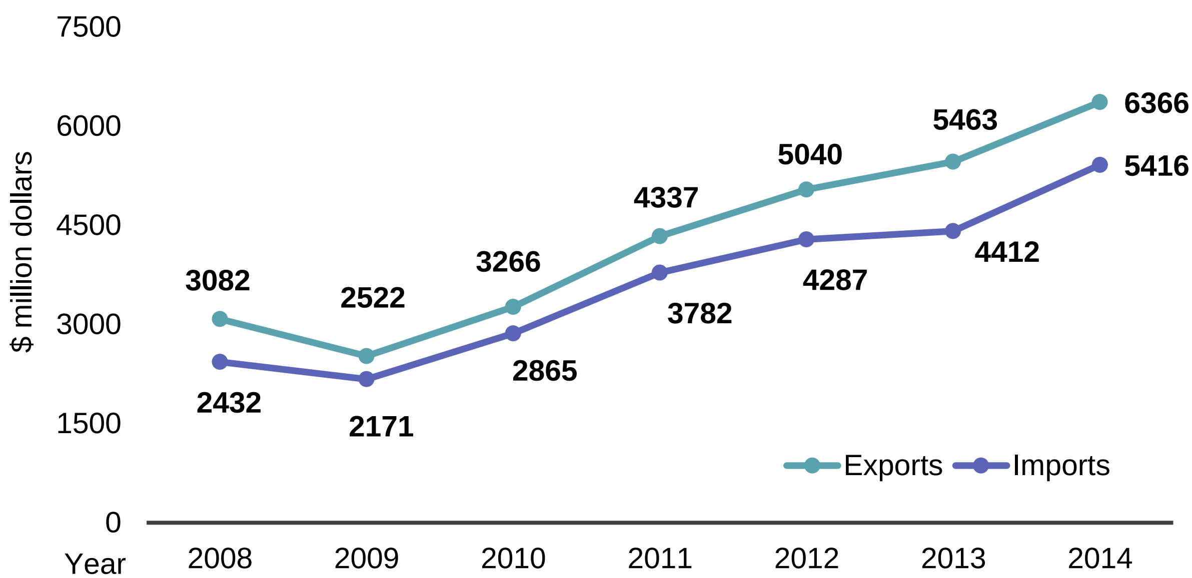

Fig. 1. Mexican exports and imports of the aerospace sector.
(Adapted from Ministry of Economy, 2015).

The analysis of the future market of additive manufacturing and aerospace industry is growing exponentially. In fact, the Wohlers Report, predicts the market for AM products and services will reach $10.8 billion worldwide by 2021 [5] and the Aerospace Additive Manufacturing Market is expected to grow at a CAGR of around 21% during 2016-2021, see Fig. 2. Aerospace demand for advanced, solid, and flexible high-value manufactured metal parts, ought to drive growth in sales of metals and hybrid metals (alloy composition). The key factors driving the growth are weight reduction & fuel consumption, feasible & eco-friendly manufacturing process, growth in utilization and acceptance in the aerospace industry, and ease of manufacturing for complex parts & freedom in design [6].

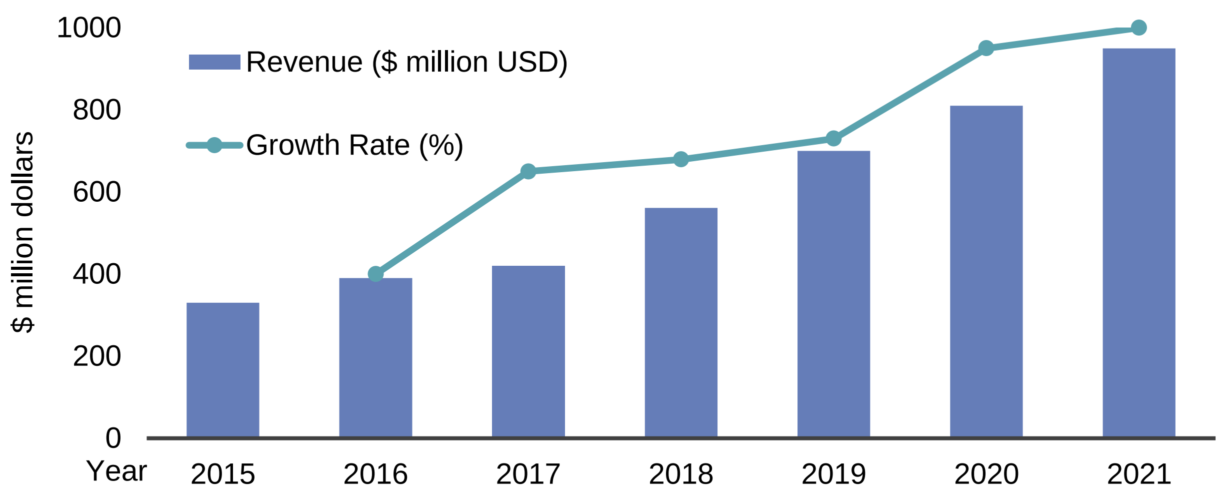

Fig. 2. Global Aerospace Additive Manufacturing Market, 2016-2021 (Adapted from [6]).

In the point of view of innovation and environmental objectives, technology development is progressing, the governments and scientific institutions have been investing more in R&D. The Fig. 3 shows the change in patent applications, for all technologies against the environmental technologies. In countries in the green area, environmental technologies progressed faster than all technologies; in the orange area, they progressed less, the size of the bubble represents the share of environmental technologies among all innovations

[7]. México technology development has growth a 120% regarding environmental technologies in the period of 2000-2002 to 2011-2013.

Fig. 3. Environmental technologies progress around the world from 2000-2002 to 2011-2013 [7].

1.2. Problem Statement and Context

For the economic and environmental proposal, the design of new parts of an airplane will be created by AM process [8]. Those processes are often described as “clean” processes because they only use the exact amount of material to build functional parts limiting scarps production [9]. In the future, this technology could optimize the functional components; in terms of weight, material costs, production time and scrap, leading to a lower environmental impact with a good economic balance, also it would be a solution when the parts are no longer available or discontinued in the market. Additive Manufacturing Technologies have the possibility to optimize the functional components in terms of weight, material costs, production time and scrap, leading to a lower environmental impact with an economic balance, as it is illustrated in Fig. 4 (a), a commercial aircraft uses only 19% of the weight for Payload (the load available as passengers, baggage, and freight), which is what generates profits.

The actual situation confirms, as illustrated in Fig. 4 (b) that the cost of the raw material is the main investment since some of the traction and power components are made by nickel-based superalloys castings and a vast variety of expensive materials. Therefore, any decrease in the casting cost and weight reduction leads to value optimization, which encourages companies to look for lighter and stronger materials.

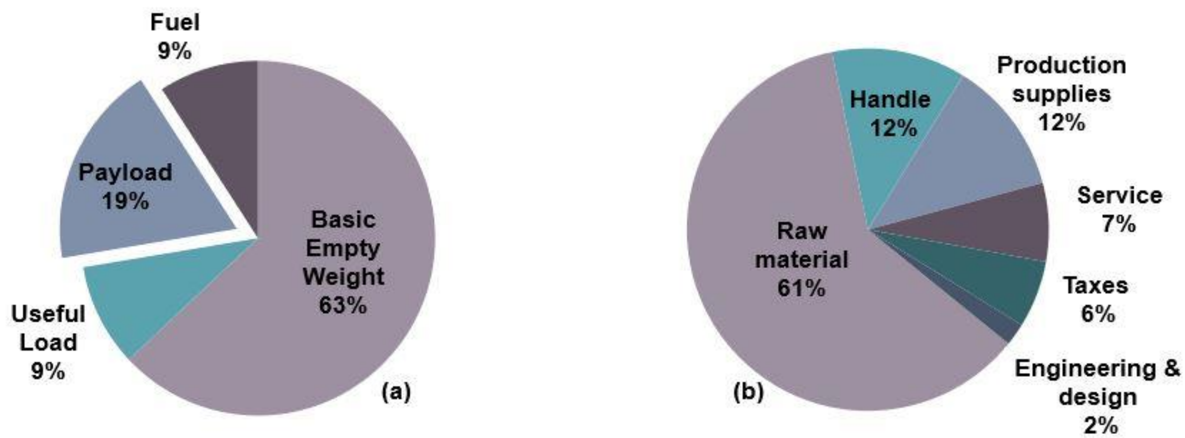

Fig. 4. Aircraft distribution of (a) weight used, and (b) cost production.

Today, the need for developing new technologies to improve the manufacturing process is increasing in many aerospace companies (see Table 1). The researchers of AM are showing great potential with benefits in comparison with CM, because of the possibility to reduce downtime in supply chains of spare part and reduce part inventory more efficiently than Conventional Manufacturing.

Table 1
Overview of aerospace companies in the development of AM against CM [5].

Company	Conventional Manufacturing	Additive Manufacturing
Honeywell	Delivery time for 1000 castings (blade) was 4 to 5 weeks.	Developed a directed energy deposition process called ion fusion formation (IFF) for producing metal parts. The IFF process employs a plasma welding torch to melt and deposit wire or powder metal feedstock.
GE Aviation	In the conventional manufacturing process, as many as 20 metal parts are welded together to achieve a fuel injector assembly. The leading edges are currently forged and machined, a process that takes many hours and results in a 50% scrap rate.	GE is planning to produce the fuel injectors and leading edges for fan blades for its next-generation using metal AM technologies. GE plans on leveraging the technology to build around 85,000 nozzles for use in its jet engine.
Boeing	Before using AM, the company would assemble up to 20 or more parts to produce one air duct assembly. Each of the individual parts that made up the required ducting tooling of some type, and welding and fasteners were often needed.	Boeing and its suppliers are using laser-sintering technology extensively to manufacture ducts for fighter jets, and more recently, for the 787-commercial jet. The company has more than 200-part numbers on 10 production aircraft that are produced using AM. More than 100,000 production parts have been manufactured with AM.
Kelly Manufacturing Company	The world’s largest manufacturer of aircraft instruments. Delivery time for 500 castings was 3 to 4 weeks.	Fortus 900mc: The lead time for 500 units has been shortened to 3 days from order to delivery of parts. Tooling costs have been eliminated, and the cost per piece has dropped 5%.
DST Control	Manufacturing (tooling, welding, and fasteners) and assemble up of 20 or more parts to produce one air duct assembly.	FDM from Stratasys: Produce 20 of the parts into 1 piece. The company realized a cost reduction of 66% and a reduction in production time of seven weeks.

1.3. Research Questions

In the adoption of Selective Laser Melting for the manufacturing of turbine blades and other aeronautic components there are expected hypothesis:

1. Is this process of additive manufacturing competitive in terms of energy consumption in comparison with Conventional Manufacturing processes?
2. Is the impact of the process less harmful in terms of carbon footprint and other environmental indicators?
3. Is the process more competitive in terms of achieving cost, weight and time savings and increase in productivity than the conventional processes?

1.4. Objectives

The specific objectives are:

- Identify the critical parameters, inputs, and outputs in terms of raw material, chemicals, energy and fluids in the production line of a turbine blade.
- Develop a simulation with a Life Cycle Assessment tool by GaBi Software in the production line of turbine blades, working with Conventional Manufacturing and Additive Manufacturing.
- Analyze the results of carbon footprint and environmental impacts in terms of harmful potential.
- Analyze the experimental results in comparison of Conventional Manufacturing and additive manufacturing, as well as emphasize the benefits of AM.

1.5. Research Overview

In order to have a better understanding of this work, a brief literature review about the CM and AM are explained in the following section.

Studies have exhibited benefits in global warming and acidification with Electron Beam Melting against CNC Milling in titanium alloy [10]. Serres et al. have demonstrated in a case study, that a structural airplane component can be manufactured by an AM process (laser cladding) in which manufacturing-related energy demands and CO2 emissions can be lowered by up to 70% in comparison to monolithic titanium alloys machining [11]. The use of AM offers a possibility to reduce downtime in supply chains of spare part and to reduce part inventory more effectively than CNC machining [12].

Table 2
A literature review of LCA and its comparison between AM and CNC manufacturing.

Authors	AM technology	Material	Comparison to CM process	Sector	LCA	Software	Measurement indicators	Environmental methodology	Benefits in AM
Paris et al.,2016	SLS, EBM	Titanium alloy	CNC Milling	Aerospace	Yes	SimaPro	Thermodynamic metrics	CML 2 Baseline 2000	Yes
Wilson et al., 2014	LENS	NiCr20Co18 Ti1	Welding	Aerospace	Yes	SimaPro	Energy consumption	GWP	Yes
Huang et al., 2016	SLM EBM DMLS	Aluminum, Titanium, and Nickel alloys	casting, forging, machining, and finishing	Aerospace	Yes	No	Energy and greenhouse gas emissions	GWP	Yes
Morrow et al., 2007	DMD	H13 tool steel	CNC Milling	Metal parts	Yes	No	Energy consumption	GWP	Yes
Serres et al., 2011	CLAD	Titanium alloy	Machining	Metal parts	Yes	SimaPro	Energy consumption	Ecosystem, Human Health & Resources	Yes
Faludi et al.,	SLM	Aluminum	Milling	Aerospace	Yes	SimaPro	Environmental impacts	ReCiPe points	Yes
Baumers et al. 2010-2013	SLM EBM DMLS	Stainless steel 316L & Ti6Al4V.	No	Metal parts	Yes	No	Energy and cost consumption	No	-
Kellens et al., 2010	SLM SLS	Stainless steel 316L	No	Metal parts	Yes	No	Powder, nitrogen & energy consumption	Eco-Indicator 99	-
Bourhis et al., 2013	DALM	Aluminum	No	CAD model part	Yes	No	Energy, fluids and material consumption	Eco-Indicator 99	-

1.5.1. Life Cycle Assessment

The Life Cycle Assessment (LCA) is the compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its lifecycle [13]. LCA is the only eco-design tool that investigates, quantifies the consumption of resources, and evaluates the environmental impacts, in which results might be valuable contributions to decision-making processes. The LCA methodology used in this work is based on ISO 14044:2006 – Environmental management, Life cycle assessment, Requirements, and guidelines. The analysis of this International Standard is composed of four phases that are shown in Fig. 5 and explained in Table 3.

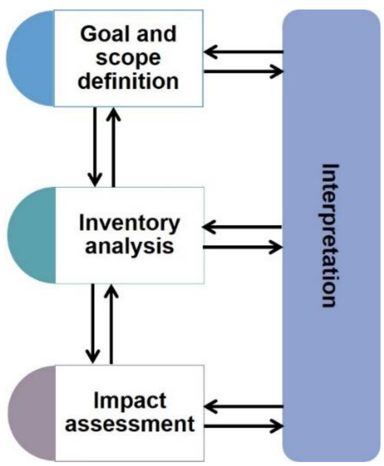

Fig. 5 Framework of Life Cycle Assessment Phases

Table 3
Phases of an LCA (Adapted from [14]).

Phases of an LCA	Definition
Goal and scope	The goal shall show the reasons for carrying out the study and the intended audience. The scope shall be considering the functions of the product system, limitations, and types of impact assessment to be used.
Inventory analysis	This phase involves the compilation and quantification of inputs and outputs, for a given product system throughout its life cycle. The inventory is a method to quantify environmental loads at every stage in the lifecycle.
Impact assessment	The phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system.
Interpretation	The phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are combined consistently with the defined goal and scope in order to reach conclusions and recommendations.

1.5.2. Turbine Blade Manufacturing Process

For the research work presented here, a turbine blade manufacturing process chain is analyzed. The turbine blade is the individual part of an array of curved palettes in a turbomachine for aircraft power engines. The turbine blades are responsible for extracting energy from the combustion chamber, they can divert the current flow to the transformation between kinetic energy, and pressure energy is exposed to the highest temperatures experienced by the engine.

Due to this particular function, the geometry of this part is extremely complex, as it is illustrated in Fig. 6, and the materials for the part are expensive in comparison with other aeronautic alloys. The manufacturing of the turbine blade is a complex process because it is originally performed by using two main manufacturing technologies, Investment Casting and Precision Machining Manufacturing, in order to obtain the required shape and its geometrical and dimensional tolerances.

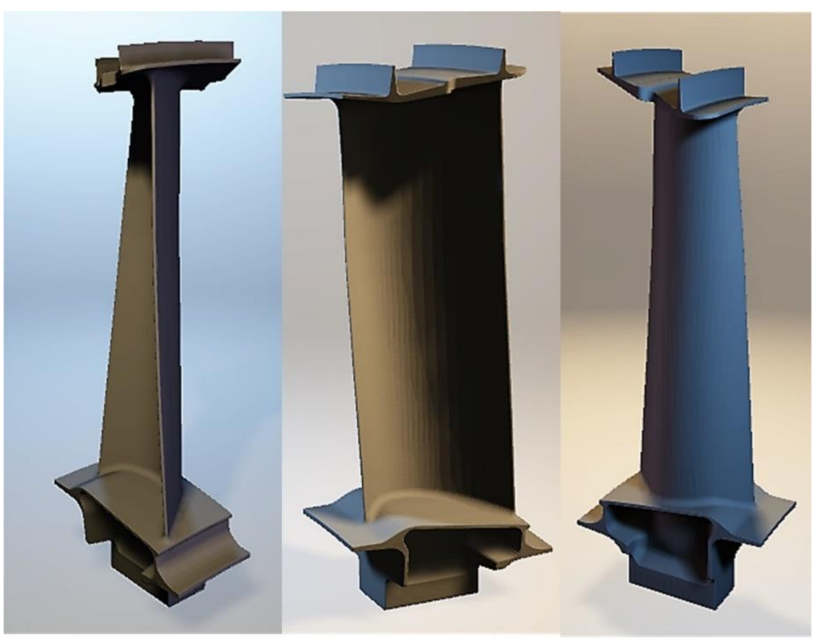

Fig. 6 CAD Model of a turbine blade.

This implies, in our particular scenario, the knowledge and the resources of two different suppliers with a high degree of specialization in their respective area. For the first manufacturing phase, the casting company (Supplier A) performs the investment casting process where the casting is elaborated from raw material with ceramic molds that are filled with high melting point metallic alloys by gravity, pressure, vacuum or centrifugal force techniques [15].

Later, during the second manufacturing phase, the machining company (Supplier B), is in charge of the final stage and transforms the casted preform into a net-shaped turbine blade. The simplified described process of an aerospace turbine blade is shown in Fig. 7. In order to improve the manufacturing process of the part, from the environmental point of view while maintaining its mechanical, functional and geometrical design standards, a deep analysis of each manufacturing technology is performed to compare alternatives.

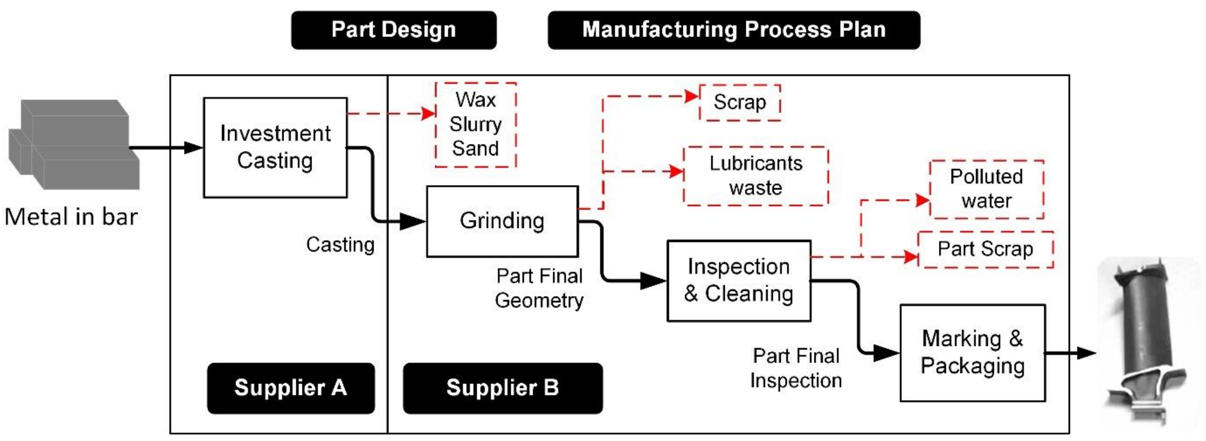

Fig. 7 Conventional manufacturing process of an aerospace turbine blade.

1.5.3. Investment casting

Investment Casting (IC), also known as “lost wax casting,” is known for its ability to produce components of superior surface finish, dimensional accuracy and with high degrees of shape complexity. It is especially useful for making castings of complex and near-net shape geometries, where machining may not be possible or too wasteful. Traditional IC suffers the disadvantage to be an expensive process from high tooling costs for producing wax patterns [16]. The IC technique studied here consists of 5 stages.

The first stage is to produce wax patterns, made by injection or pouring molten wax into the master die under pressure and then the individual wax patterns are adhered to a central wax sprue, the result is a tree pattern model. In the second stage, a ceramic shell is made, the wax patterns are invested with ceramic or refractory slurry, which is then solidified to build a shell around the wax pattern tree. Currently, it takes around 24-72 hr., depending upon the size, quantity, and material of the component. After this stage, the pattern is melted, the mold is hardened and held in inverted form to drain the wax, and this last stage is known as dewaxing.

Once the mold is preheated at high temperatures for the elimination of all the contaminants, which also facilitates the metal flowing into the cavity more easily, the molten metal is poured into the mold by gravity and then solidifies. At the final stage of manufacture, the shell mold is broken away from the solid part, given as a result a raw part that only needs a heat treatment to obtain a casting. The stages and inputs of the investment casting process during this phase are illustrated in Fig. 8.

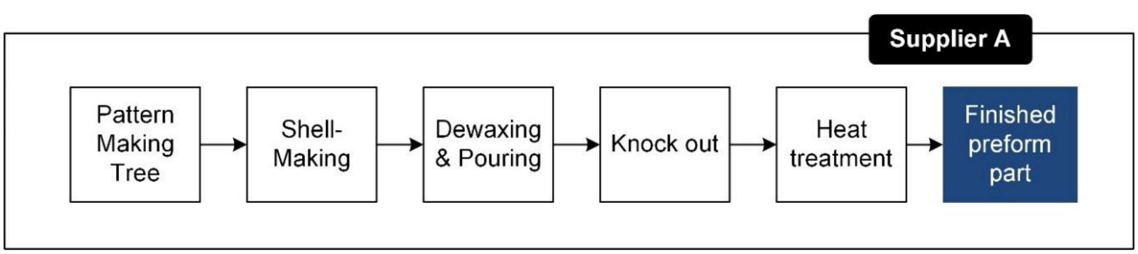

Fig. 8 Investment Casting process.

1.5.4. Precision Machining Manufacturing

The final mechanical process in the manufacturing chain of a turbine blade is Precision Machining Manufacturing (PMM). This phase is divided into 5 stages, and a grinding process composes the first stage. The process consists, basically, in 3 grinding operations that modify the shape of the casted part in order to obtain the final geometry with accurate dimension and to meet dimensional and geometrical tolerances. The first operation is to grind the main slotted geometry of the assembly area, the second operation is the tip/slot grinding of one side of the part, and the third is the grinding operation that machines the cap of the part. After the grinding operations, the casting part goes through three stages of chemical cleaning operations in order to detect anomalies and defects (Fig. 9). The first one is a cleaning operation with nitric acid and deionized water, in which casting parts are submerged into a tank at room temperature with the chemical agents previously mentioned.

In the next stage, the part is dried in a furnace for 1 hour and is taken to fluorescence testing with penetrating liquids and powders (Fluorescent Penetrant Inspection: FPI), to show possible fissures and defects that may become visible under fluorescent light. Consequently, the purpose of this FPI operations is to find any evidence of cracks that could be present in the surface checking in detriment of the surface integrity. The following step is the shot peening operation stage. The shot peen technique is a cold deformation process that generates a uniform layer of compressive stresses in order to analyze any defect that could have the part and prevents failures due to corrosion under stress. Finally, the part is marked and packed in the last stage, and the result is a turbine blade as a finished part.

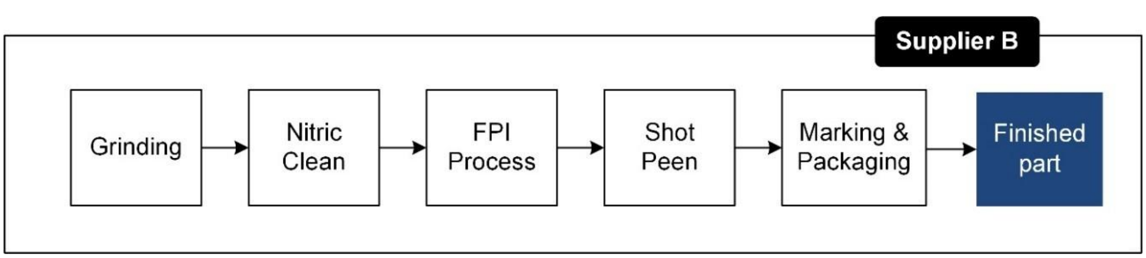

Fig. 9 Precision Machining Process.

1.5.5. Selective laser melting

Selective Laser Melting (SLM), is a particular type of powder bed fusion in the approach of AM technologies, which is one of the processes of interest in the aeronautic industry, due to its versatility, potential cost reduction, and relative productivity [17]. In SLM, fine metallic powder layers (25–50μm) are spread out on a building platform with the aid of a roller or a recoated.

The powder is selectively heated by a high-power density laser beam to its melting temperature, and its energy is calibrated in such a way that each layer of metallic powder is fully molten and joined to the molten particles of the previous layer.

In order to pre-process the geometries, the procedure starts by slicing the 3D CAD file data into layers, from 20 to 75μm, with 1μm increments. The system schematic of this technique is illustrated in Fig. 10**.** The SLM process has the ability to melt the metal material into a solid 3D-dimensional part fully, that is why the process is generally named as 3D metal printing, which is likely to be more competitive than conventional manufacturing when it comes to fabricating products with higher levels of complexity, customization, or a combination of both [18].

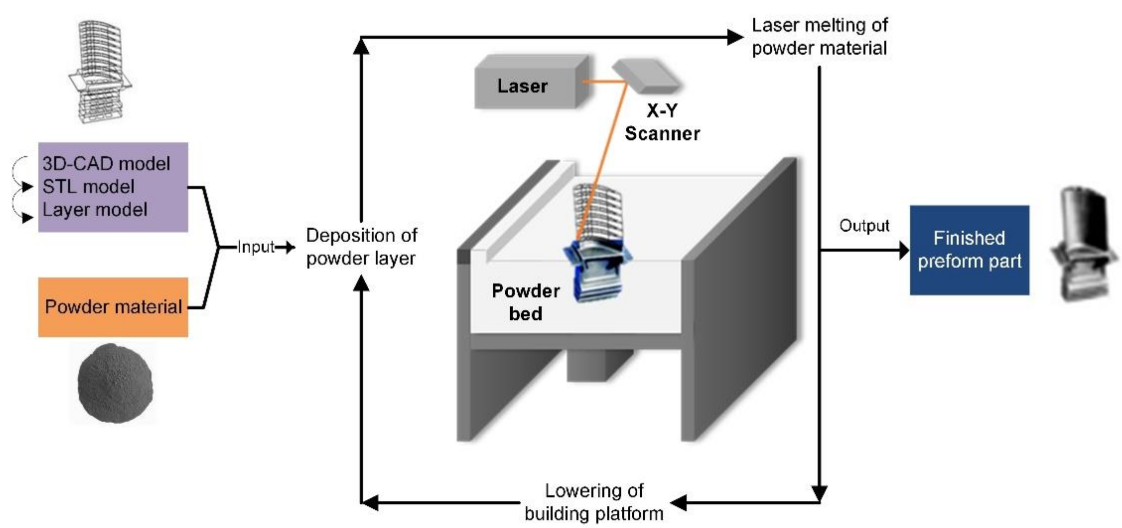

Fig. 10 Selective laser melting system schematic.

Chapter 2: Methodology

The analysis procedure has been divided into four stages, Fig. 11 gives a graphical representation of the methodology. In the first stage, the reasons for carrying out the study and the functions of the system have been defined by the goal and scope of the study. For the second stage, the compilation of inputs and outputs data of each operation and process have been quantified.

The third stage is the understanding and evaluating the magnitude and significance of the potential environmental impacts of a product system by assigning an impact category and modeling the inventory data. Finally, in the last stage, the conclusions and recommendations obtained must be consistent with the goal and scope of the study.

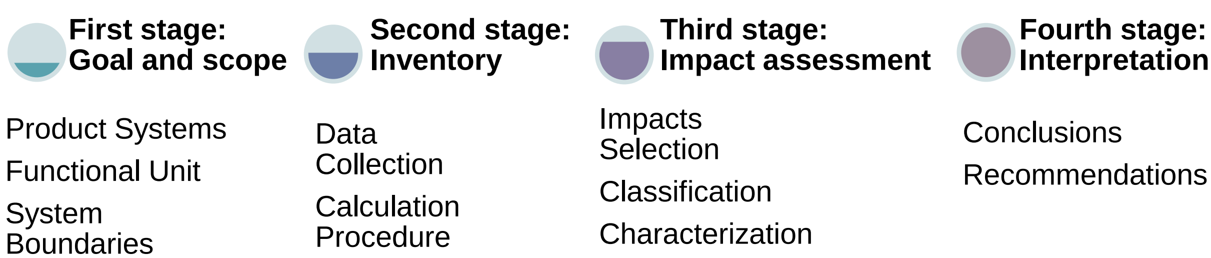

Fig. 11 Analysis procedure stages.

2.1. Goal and Scope

The goal of this research is to analyze the benefits that may be carried out by changing from IC to SLM in the process plan of Turbine Blades Manufacturing and exploring its implications for the whole lifecycle in sustainable metrics including the phase of PMM. This study will be limited to gate-to-gate analysis in the product manufacturing stage in which we will consider the inputs and outputs of the production process. Although LCA implies considering all the transformation stages of the part from cradle-to-grave, the work is going to be focused on the previously described phases.

Within the manufacturing process phases and the described stages, we will consider only the technical factors related to each operation. Factors such as maintenance, human capital, transport and production of secondary materials are out of the scope of this study in order to present a technology-based comparison. Manufacturing data acquisition of SLM and PMM data gathering will be made offline on the shop floor, and IC phase metrics will be complemented with data from the previous literature.

2.1.1. System Boundaries

The LCA is classified into three different measuring range; these are gate-to-gate, cradle-to-gate and cradle-to-grave [19]. The analysis of cradle-to-grave is the full life cycle assessment from resource extraction until final disposal phase, cradle-to-gate it is an assessment of a particular product lifecycle from resource extraction to the product manufacturing, and gate-to-gate is a partial LCA taking into account only one value-added process in the entire production chain, as it is illustrated in Fig. 12. This study will be limited to gate-to-gate analysis in the product manufacturing stage in which we will consider the inputs and outputs of the production process.

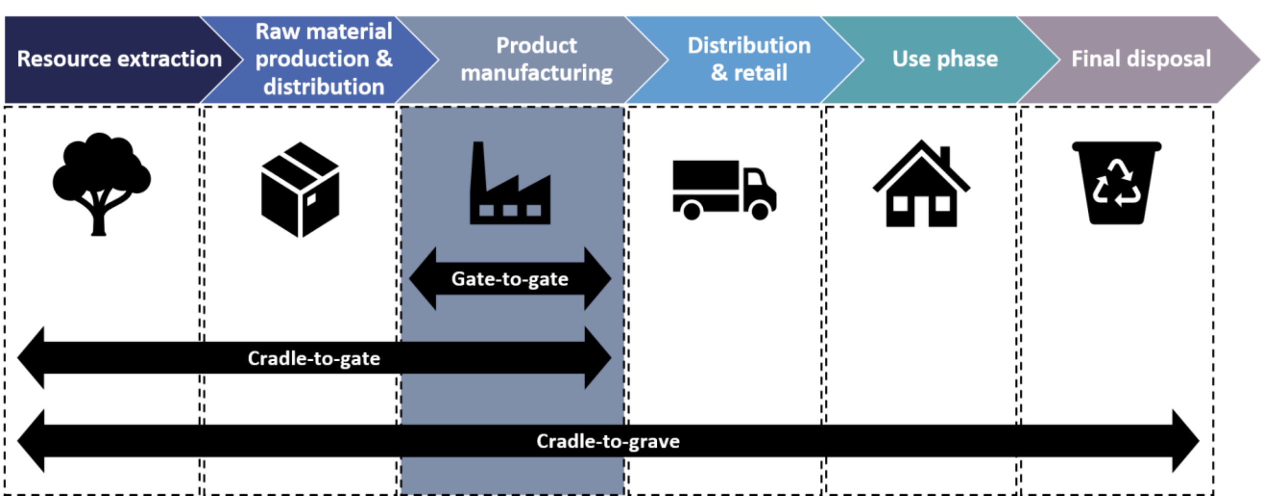

Fig. 12 Classification of the analysis to define a lifecycle.

Although LCA implies considering all the transformation stages of the part from cradle-to-grave, the work is going to be focused on the previously described phases. Within the manufacturing process phases and the described stages, we will consider only the technical factors related to each operation. Factors such as maintenance, human capital, transport and production of secondary materials are out of the scope of this study in order to present a technology-based comparison.

2.1.2. Product Systems

The conceptual comparison of alternative manufacturing processes between Conventional Manufacturing (Investment Casting plus Precision Machining Manufacturing) and Additive manufacturing (Selective Laser Melting plus Precision Machining Manufacturing) is represented in Fig. 13.

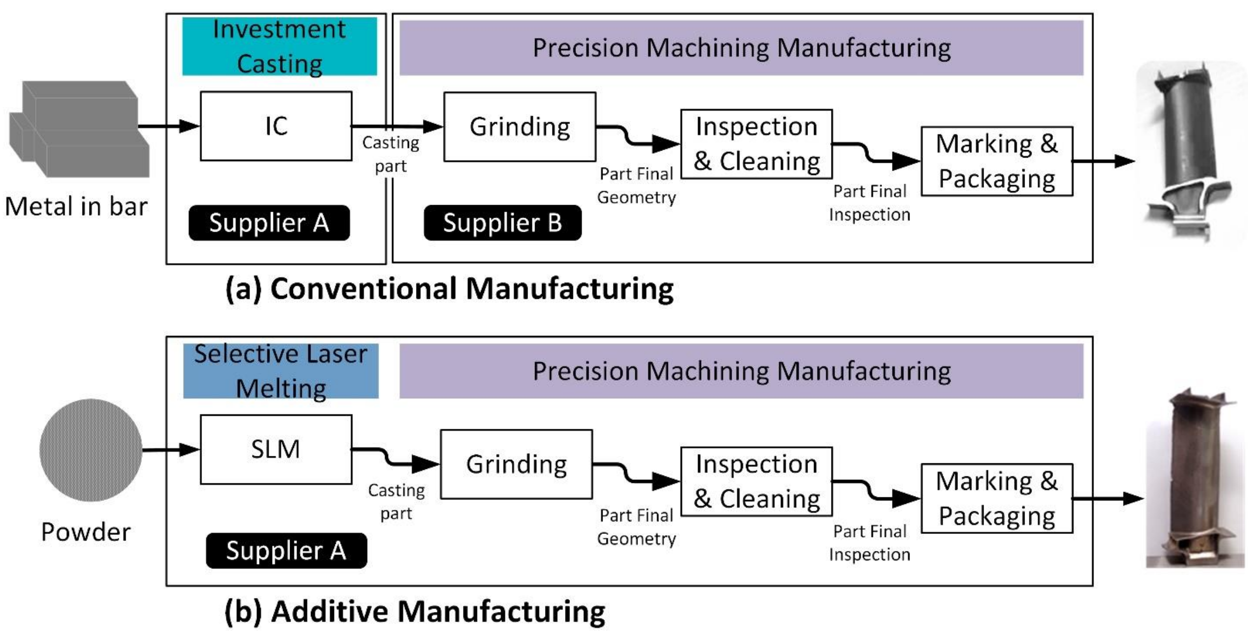

Fig. 13 Schematization of the case study to be compared, (a) CM, and (b) AM.

Although the PMM is the common process between the two-process chain to be evaluated, it might be possible that technical parameters could slightly vary in this process since the metallographic structures could be different due to the technology change and the slight material composition change. However, this difference may be neglected due to its minor impact on the general perspective of this study.

Both processes shall be compared using the same functional units and similar methodological considerations, such as performance, system boundaries, data quality, allocation procedures, and decision rules on evaluating inputs and outputs and impact assessment. Any differences between measurements regarding these parameters shall be identified and reported.

2.1.3. Functional Unit

The functional unit is approached by the size of the production and its monitoring of parts manufactured; the batch size was selected according to the bottleneck and the maximum capacity operation of the entire system of the precision machining process. The batch size was 600 parts as a standard measurement of the IC, PMM and SLM processes. The environmental performance may be affected by the batch size due to the production capacity and machine hours worked of each operation along the turbine blade manufacturing process.

2.1.4. Environmental Approach

From the sustainability point of view, adverse environmental impacts can be caused by emissions to air, discharges into water, generation of solid wastes and many others very difficult to measure. The number of metrics can be vast, and we must define and select the correct ones for an accurate sustainability comparative analysis. For the case study for a turbine blade of an aircraft engine, it is proposed to select the most critical indicators in the manufacturing period of its lifecycle, in which General Life Cycle

Assessments are focused on Carbon footprint. The Carbon footprint stands for a certain amount of gaseous emissions that are relevant to climate change and associated with human production or consumption activities [20]. The emissions of this indicator are released into the atmosphere, therefore is used as a generic synonym for carbon dioxide (CO_2) emissions or greenhouse gas (GHGs) emissions, but individually, these emissions have different meanings. GHG emission is a general topic if it is compared with the carbon dioxide emission which is specific for the CO_2 emissions and emissions equivalents. There are total 24 greenhouse gases for the ozone layer and for global warming phenomenon which are grouped into 6 harmful types: CO_2, CH_4, N_2O, SF_6, PFCs, and HFCs [21]. In order to have a better understanding of GHGs emissions, CO_2 emissions and Carbon footprint, a diagram in Fig. 14 has been presented. The factors estimate emissions of CO_2, CH_4, and N_2O are expressed together as carbon dioxide equivalent (CO_2-e) [22].

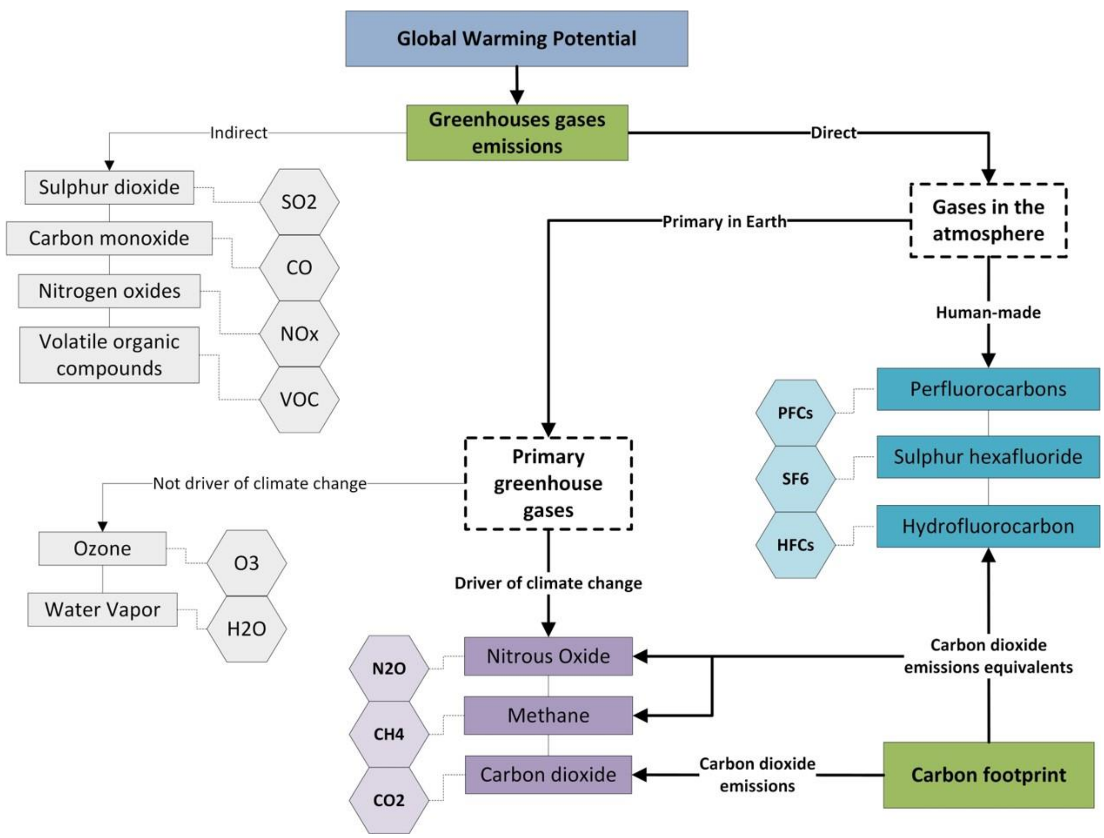

Fig. 14 Classification of greenhouses gas emissions.

2.1.5. Casting requirements

In the manufacture of turbine blades, should be used materials that withstand the high temperatures as well as the mechanical efforts to which they are subjected. If the combustion is analyzed we can see that the temperature of these reaches values of 1700°C to 1900°C, temperatures are too high for the blades of the turbines, making it necessary to work with excess air to lower the temperature to values of the order 750°C at 950°C. Special alloys are required for blades and housings that can withstand not only the temperature without being destroyed but also the harmful effects that this entails, such as the increase of sediments from oxidation and corrosion. The high temperature also favors the formation of nitrogen oxides (combustible liquids), which are expelled by the exhaust gases.

Table 4
Thermal and mechanical properties of a turbine blade

Thermal Properties	Min	At	Max	At	Units
Melting point	1 265	N/A	1335	N/A	°C
Max. service temperature	843.33	2/3 of melt temp.	890	2/3 of melt temp.	°C
Min. service temperature	21.11	N/A	21.11	N/A	°C
Thermal conductivity	10.32	21.11°C	24.27	1 148.88°C	W/m°c
Specific heat capacity	451.85	21.11°C	852.13	1 148.88°C	J/kg°c
Thermal expansion coeff.	13.09	21.11°C	18.63	1 148.88°C	µstrain/°c
Mechanical Properties	**Min**	**At**	**Max**	**At**	**Units**
Weight density		7.75037			G/cm^3
Young's modulus	138	1 148.88°C	209	21.11°C	Gpa
Yield strength	791	23.88°C	861	593.33°C	Mpa
Tensile strength	1.012	23.88°C	1.036	593.33°C	Mpa
Elongation	10.106	593.33°C	12.699	23.88°C	%
Shear modulus	53	1 148.88°C	80	21.11°C	Gpa
Bulk modulus	115.329	1 148.88°C	174.3875	21.11°C	Gpa
Poisson's ratio	0.3	21.11°C	0.3	1 148.88°C	N/a
Hardness	199	21.11°C	361	982.22°C	Vickers

From the considerations of original aerodynamics, we have that several criteria establish the aerodynamic behavior of the blade. Namely, any deviation of the aerodynamic behavior of blades may result in overheating, i.e., a slight change in the angle of discharge to the blade, increases the flow temperature, reducing the design life. For the material selection, it must take into consideration the requirements of the piece. The material properties specification that must be in a turbine blade appears in Table 4.

2.1.5.1. Material selection

According to the functional requirements and mechanical properties specifications for turbine blades of an aircraft engine hot chamber, the most suitable materials for their construction are Nickel based alloys, due to their mechanical performance in high-temperature environments [23]. The material properties were consulted in order to have enough information of the right material chosen. The data of the comparison between the materials selection appears in Appendix B: Materials for metal additive manufacturing in Aerospace Industry. In the particular case of Investment Casting, the alloy taken into account for the comparison is Nickel alloy 100 (Inconel 100), and in the case of SLM manufacturing process, the material selected is the Nickel alloy 718 (Inconel 718). It is assumed that both alloys are comparable in terms of their processing and near net-shaping, due to their similar chemical composition (see Table 5). Some properties of Nickel alloy 718 are shown in Appendix B.

The values in these tables will vary slightly, depending on the composition and condition of the specimen tested. They are typical but are not suitable for specification purposes. Mechanical properties of metal parts manufactured by SLM are usually higher than cast metal and sometimes comparable with wrought materials [24]. Nickel-based superalloys are currently used in many high-end applications such as aerospace and nuclear industries [25]. Inconel 718 has been chosen to be used for the selective laser melting technique; this material has the high-temperature strength and excellent corrosion resistance needed for components such as jet engines, gas turbines, and rocket motors [26]. The wide range of environments in these critical applications points towards a need for high mechanical properties at extreme environments. In order to understand the mechanism for the powerful mechanical properties, one must discern key constituents in the Inconel 718 chemistry [25].

Table 5
Chemical composition of Nickel Alloys using in IC and SLM process.

INCONEL 718	Min	Max	INCONEL 100	Min	Max
Ni	50.00	55.00	Al	5.00	6.00
Cr	17.00	21.00	Cr	8.00	11.00
Fe			Fe	-	1.00
Nb	4.75	5.50	Mn	-	0.20
Mo	2.80	3.30	Ni	Bal*	
Ti	0.65	1.15	Si	-	0.20
Al	0.20	0.80	C	0.15	0.20
Co	-	1.00	Ti	0.40	5.00
C	-	0.08	V	0.70	1.20
Mn	-	0.35	Zr	0.03	0.09
Si	-	0.35	P	-	0.02
P	-	0.02	S	-	0.02
S	-	0.02			
Cu	-	0.30			
B	-	0.01			

2.1.5.2. **ASTM F3055-14a Standard Specification**

"Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion"

This specification covers additively manufactured UNS N07718 components using full-melt powder bed fusion such as electron beam melting and selective laser melting. The components produced by these processes are used typically in applications that require mechanical properties similar to machined forgings and wrought products. Components manufactured to this specification are often, but not necessarily, post-processed via machining, grinding, electrical discharge machining (EDM), polishing, and so forth to achieve desired surface finish and critical dimensions [27].

This specification is intended for the use of purchasers or producers, or both, of additively manufactured UNS N07718 components for defining the requirements and ensuring component properties. Users are advised to use this specification as a basis for obtaining components that will meet the minimum acceptance requirements established and revised by consensus of the members of the committee [28].

2.1.5.3. **Chemical composition analysis**

In order to verify that the powder material used for this case of study accomplish the requirements specified by the ASTM F3055-14a Standard Specification for Additive Manufacturing Nickel Alloy (UNS N07718) with Powder Bed Fusion a chemical composition analysis has been made. To obtain the results, it is taken the average of the data analyzed of four different points in a 3D prototype turbine blade. These results were obtained with an SEM Microscope. The data used can be seen in Appendix C: Results of analysis SEM. The principal elements such as nickel and chromium are in the range specified by the ASTM standard.

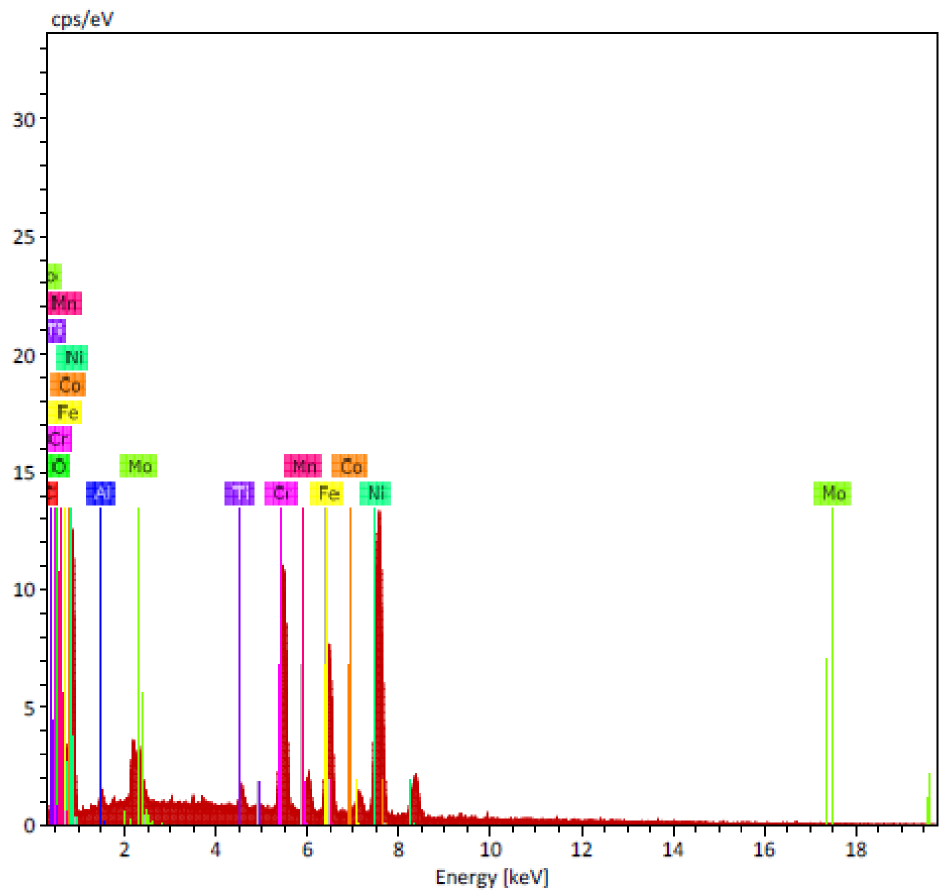

Fig. 15. General graph of result from the chemical analysis

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2.2. Life Cycle Inventory Analysis

2.2.1. Qualitative Data Collection

In work presented, the material flow analysis models must be identified and quantified for its assessment analysis. All input flows (energy, material, fluids) and the resulting outputs (emissions, waste), as shown in the following section, must be identified qualitatively in order to have a perspective of the product system. The material and the resulting outputs such as emissions and wastes of the whole Turbine Blade Manufacturing are shown in Fig. 16. From the sustainability point of view, these inputs and outputs may include the use of resources, air emissions, water and ground pours and energy consumption associated with the product system [14]. Input and output models have been shown to be useful for sustainability analysis; materials flow analysis and energy through industrial processes [1],[29],[30].

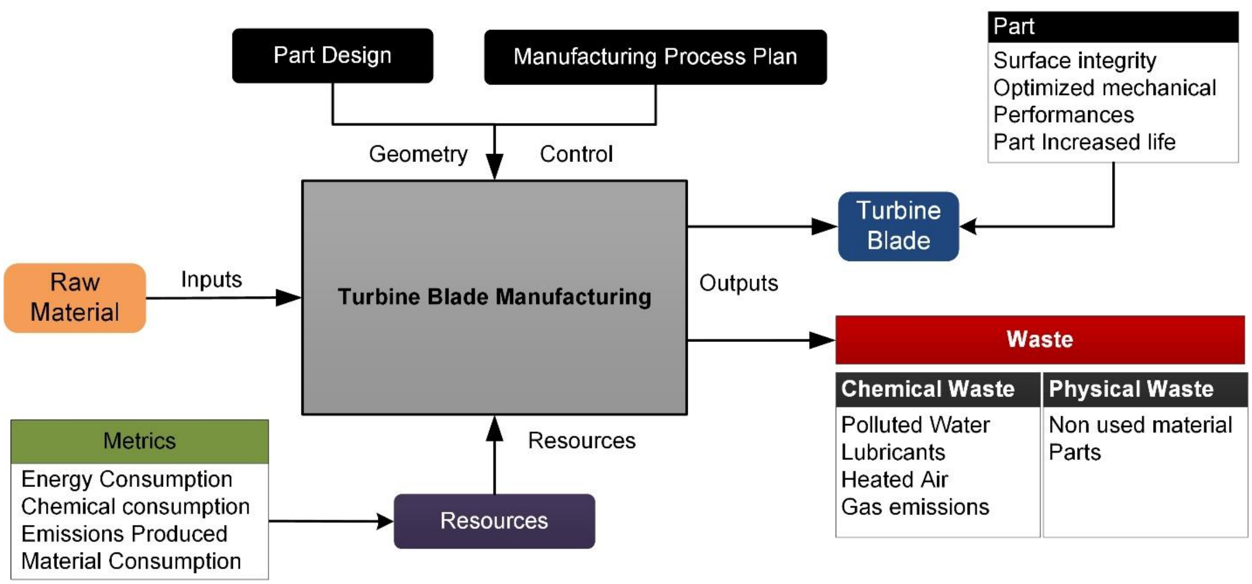


Fig. 16. Sustainability analysis of Turbine Blade Manufacturing.

2.2.1.1. **Investment Casting**

As it has been explained in Fig. 8, the Investment Casting phase includes several discrete operations. Some operations require repetitive cycles that necessitate a considerable amount of time and energy apart from the material and wastes that shall be monitored carefully. A general vision of the sustainability analysis for this manufacturing process can be seen in Fig. 17, which shows the inputs, outputs and proposed metrics for the research. The collection of the qualitative data of IC is shown in Table 6.

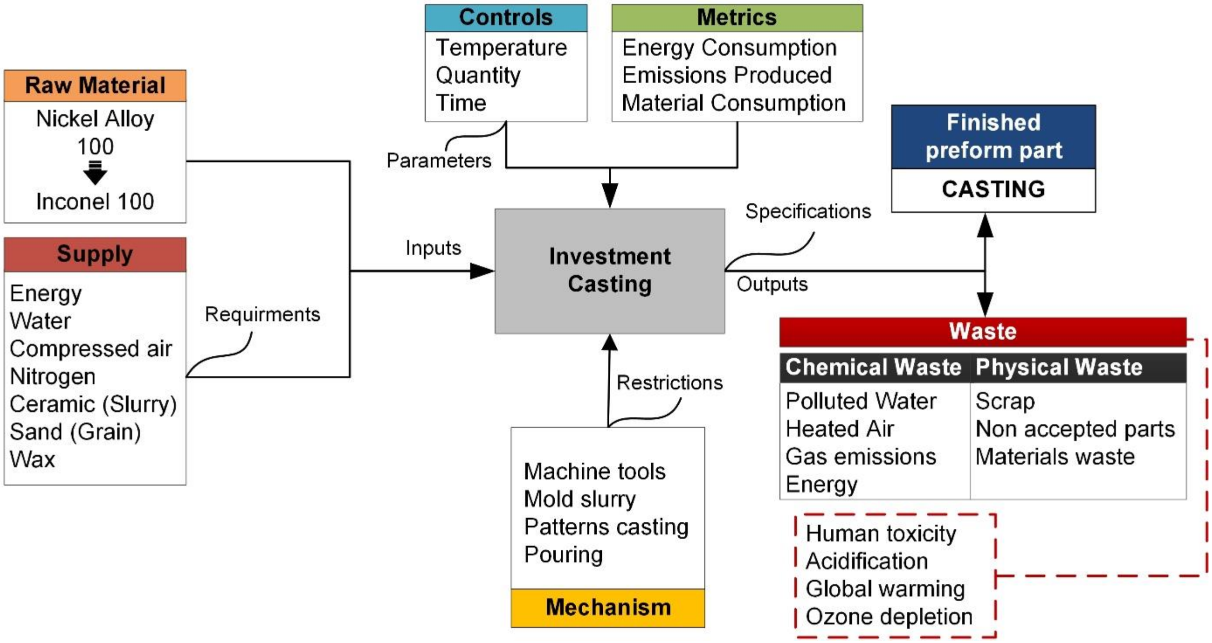


Fig. 17 Sustainability analysis of Investment Casting process.

The data obtained for Investment Casting Life Cycle Inventory (LCI) comes from literature and data mining from the process. Due to the fact that some stages are not yet equipped with a sensor, a rigorous analysis of Pattern Making, Shell Making and Knock Out stages was made from literature and similar machinery data estimation. The estimation of the molten metal in the pouring stage was obtained from a report of Energy and Environmental of metal casting industry [22].

In the same way, the data from the fabrication of raw material (metal in bar stock form) was taken from specialized literature [29].

Table 6
Qualitative data of Investment Casting

Investment Casting	Inputs	Outputs
Metal bar Inconel 100	Material	Scrap
Refractory Materials	Material	Material waste
Wax	Material	Material waste
Electricity, production mix	Energy	Gas Emissions
Water (desalinated; deionized)	Fluid	Polluted water
Compressed air	Fluid	Gas Emissions
Nitrogen	Fluid	Gas Emissions

2.2.1.1. **Precision Machining Manufacturing**

The second main phase of the first case study is the Precision Machining Manufacturing (PMM) stage. For the Grinding, heavy machinery is used due to the high requirements of forces and energy inherent in these machining operations. Here we find the most relevant impact in energy consumption measured, along with the quantities of chemical, lubricants, and fluids, which will be determined per their concentration percentage in each cleaning operation and inspection area. It is important to specify that the data of energy and fluids consumption were calculated per batch of 600 parts (48.06 kg) as a standard measurement. To show a general vision with all the inputs and outputs the sustainability analysis is illustrated in Fig. 18.

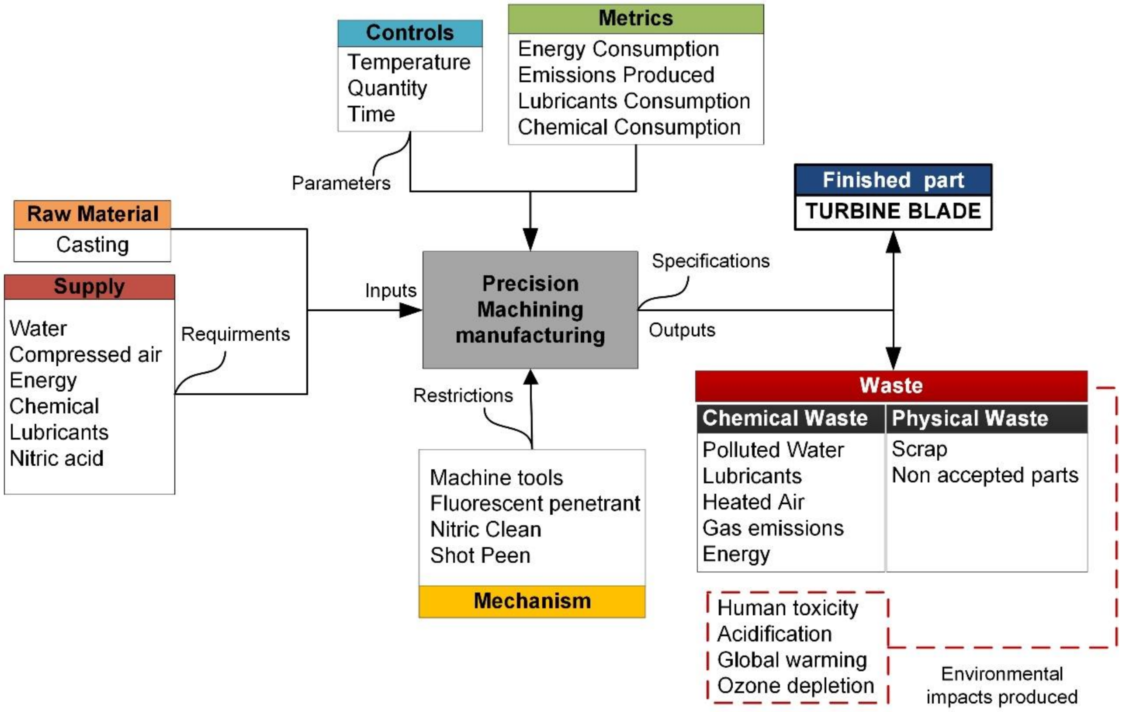


Fig. 18 Sustainability Analysis of Precision Machining Manufacturing.

Regarding the consumption of fluids, in the PMM stage, the fluid is CIMTECH 320 (cooling oil), compound by triethanolamine (30%), neodecanoic acid (13%), nonanoic acid (5%) and mono isopropanol amine (5%). During the Nitric Clean (NC), the fluids used are OAKITE (65% of sodium hydroxide), ECOMATE (89% of dihydrogen monoxide) and Nitric Acid. Another part of the process consists of quality inspection, in which the use of Fluorescent Penetrant liquids is mandatory for detecting cracks and defects in the machined area of the blade. In penetrating impregnation, dry powder developer (pentaerythritol 60% and manganese in alloy 30%) is used for detecting fine, tight discontinuities in safety-critical components and revealing the cracks. In the Prewash area, the blades are immersed in hydrophilic emulsifier (ethoxylated 60%), and finally, in the Emulsifier tank, fluorescent penetrant powders (isodecyl diphenyl phosphate 60%) is used as a high sensitivity dry powder developer for penetrant inspection. It is supplied ready to use and forms a thin film on parts which enables it to enhance indications of ultra-fine discontinuities. The collection of the qualitative data of PMM is shown in Table 7.

Table 7
Qualitative data of Precision Machining

Precision Machining Manufacturing	Inputs	Outputs
Casting Nickel alloy	Material	Scrap
Cast Steel Shot	Material	Scrap
Electricity, production mix	Energy	Gas Emissions
Incandescent light	Energy	Gas Emissions
Fluorescent light	Energy	Gas Emissions
Water (desalinated; deionized)	Fluid	Polluted water
Penetrant Liquids (ZR-10B, ZP-4B & ZL-37)	Fluid	Polluted water
Lubricants (CIMTECH 320 & 610)	Fluid	Polluted water
Chemical (Nitric Acid, Oakite & Ecomate)	Fluid	Polluted water

2.2.1.2. **Selective Laser Melting**

For the alternative solution analysis, a similar procedure has been followed. In this process, we have slightly different inputs and outputs. First, the material is now powder Inconel 718, the calculation of powder fabrication was taken from the literature of gas atomization process for metal powder fabrication. Furthermore, the amounts of material, energy, water, and argon were own measurements taking into consideration the time and temperature of the building process. These are the main parameters to analyze for the identification of environmental indicators considering the lifecycle approach. The metric units are presented as a result of the impacts produced in the waste of energy, water pollution, and gas emissions. In addition, we have taken into account the technical data of the Selective Laser Melting machine [31]. In order to cool the laser system embedded in the machine, an external water/air cooling system is supplied, and a general power supply of 400 volts, 50/60 Hz, 3 phases and 32A is used. Furthermore, in the process chamber requires inert gas (Argon) for enabling an inert atmosphere, the consumption in the process is less than 2 l/min. The pressure for cooling unit (3.5 bar) and energy consumption for internal air dryer (230 volts) must be considered to estimate emissions. The sustainability analysis of SLM is represented in Fig. 19.

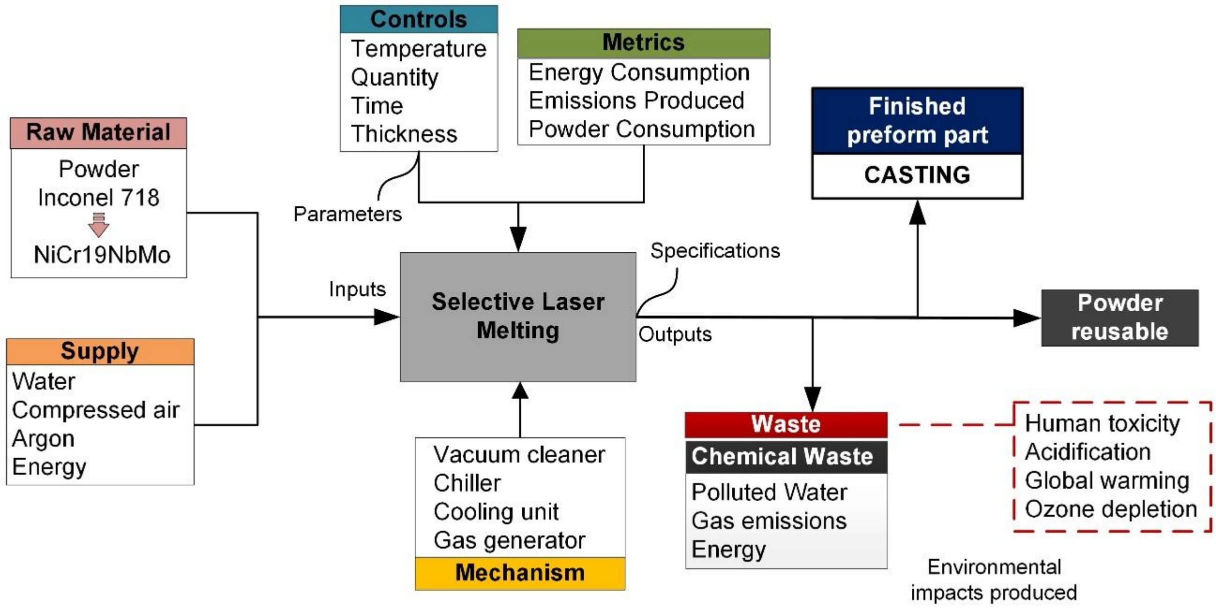


Fig. 19 Sustainability analysis of Selective Laser Melting process.

The sustainability analysis of the preceding technologies must be evaluated with the same unit metric: energy consumption, emissions produced and material consumption. The qualitative data collection of SLM is shown in the table below.

Table 8
Qualitative data of Selective Laser Melting Process

Selective Laser Melting	Inputs	Outputs
Powder Inconel 718	Material	Reusable powder
Electricity, production mix	Energy	Gas Emissions
Water (desalinated; deionized)	Fluid	Polluted water
Compressed air	Fluid	Gas Emissions
Argon	Fluid	Gas Emissions

2.2.2. Calculation procedure

The qualitative data of energy, material, and fluid along the turbine blade manufacturing process must be quantified by calculations using the equations below. Taking into account the system boundaries of each process x, y, z as PMM, IC and SLM respectively from cradle to gate for a given turbine blade.

(1) $$E_{CM} = E_x + E_y$$

(2) $$E_{AM} = E_x + E_Z$$

(3) $$F_{CM} = F_x + F_y$$

(4) $$F_{AM} = F_x + F_Z$$

(5) $$M_{CM} = M_x + M_y$$

(6) $$M_{AM} = M_x + M_z$$

(7) $$\mathrm{CM}= \Sigma\ (\mathrm{x}(\mathrm{E_{input}}+\mathrm{F_{input}}+\mathrm{M_{input}}+\mathrm{E_{output}}+\mathrm{F_{output}}+\mathrm{M_{output}}))+ (\mathrm{y}(\mathrm{E_{inputs}}+\mathrm{F_{inputs}}+\mathrm{M_{inputs}}+\mathrm{E_{output}}+\mathrm{F_{output}}+\mathrm{M_{output}}))$$

(8) $$\mathrm{AM}= \Sigma\ (\mathrm{x}(\mathrm{E_{input}}+\mathrm{F_{input}}+\mathrm{M_{input}}+\mathrm{E_{output}}+\mathrm{F_{output}}+\mathrm{M_{output}}))+(\mathrm{z}(\mathrm{E_{inputs}}+\mathrm{F_{inputs}}+\mathrm{M_{inputs}}+\mathrm{E_{output}}+\mathrm{F_{output}}+\mathrm{M_{output}}))$$

Where E is energy consumption, M is material consumption, F is fluid consumption, CM is conventional manufacturing, AM is additive manufacturing, x is the precision machining process, y is the investment casting process and z is, the selective laser melting process.

2.2.2.1. **Energy consumption**

Its power factor defines the efficient in the energy consumption of every machine; the power factor is the ratio between the energy applied in kilowatts hour (kWh) and the total power in kilovolt-amperes (kVA). The ideal value of the power factor is 1; this indicates that all the energy consumed by the appliances has been transformed into work and the optimum value used in power factor is 0.9 that means the 90% of efficiency. By contrast, a power factor less than unity means more energy consumption needed to produce useful work. This ratio measures the efficiency of the load in a three-phase system. In the equation, the square root of three takes into account in a three-phase system. Otherwise, if the machine is single-phase system the square root of three is not considered, just the power factor. The calculation of energy consumption (1) and power factor (3) was in the following the equations.

(9) $$E_{total} = \left(E_{kWh} * t_m\right)$$

(10) $$E_{kWh} = \left(\left(\sqrt[3]{V}\right) A * 2PF\right)$$

(11) $$PF = \left(\frac{kW}{(\mathrm{kVA})\left(\sqrt[3]{1}\right)}\right)$$

Where E is the energy consumption, PF is the power factor, t_m is the manufacturing time, kVA is the kilovolt-ampere, kW are the kilowatts, V are the volts and A are the amperes.

2.2.2.2. **Volume percent concentration**

In this section, the volume concentrations of fluids are calculated, they include the penetrant liquids, the chemicals, and the lubricants. The concentrations take into account in an exact way the proportions between the amounts of solute and solvent that are being used in a solution. Volume percent concentration is defined as:

(12) $$v/v\,\% = \frac{(v_{s_1})}{(v_{s_3})} * 100\%$$

(13) $$v_{s_3} = v_{s_1} + v_{s_2}$$

Where v_{s_1} is the volume of solvent, v_{s_2} is the volume of solute and v_{s_3} is the volume of solution.

The chemical concentration (cc) of the solutes [v_{s_2}] are 15 liters for ZL-37, 10 liters for ZR-10B and 2.5 kg for ZP-4B. These penetrant liquids are dissolved in 150 liters of water [v_{s_1}]. Meanwhile, in Nitric Clean, each tank has an average capacity of 577.51 liters of water [v_{s_1}] and 115 liters of chemicals [v_{s_2}]; The Oakite and Ecomate chemicals are added as a solvent (see Table 9). Finally, in the grinding stage, Grind Root Form machine needs 250 liters of water, is the only one that used the lubricant CIMTECH 320 (12 liters). The Tip/slot grinder (188 liters), Z form grinder machine (206 liters) and HASS (20 liters) used the lubricant CIMTECH 610 (11 ± 2 liters). The lubricants are added to the grinder machine on an alternative day of the week, expressed on Table 9 as X_1 and X_2.

Table 9
The volume concentration of fluids

FPI PROCESS			
Flow	**wt [%]**	**cc. [l* or kg**]**	$v/v\,\%$
ZL-37*			
Petroleum distillates (PD)	36.8	5.52	90.90→Solvent 9.09→ Solute
Alcohol ethoxylated	5.02	0.753	
PD, hydrotreated light	5.01	0.751	
Triphenyl phosphate	2.50	0.375	
1H-Benz[de]isoquinoline-1,3(2H)-dione	1.01	0.151	
Dioxane	0.1	0.015	
Others (unknown)	49.56	7.434	
ZR-10B*			93.75→Solvent 6.25→ Solute
Nonylphenol ethoxylate	59.9	5.99	
Hexylene glycol	40	4.00	
Ethylene Glycol	0.1	0.01	
ZP-4B**			
Penta-erythritol	42.22	1.05	98.36 →Solvent 1.63→ Solute
Carbonic acid, magnesium salt	22.67	0.56	
Silica	5.24	0.13	
Aluminum oxide	4.63	0.11	
Others (unknown)	25.24	0.63	

NITRIC CLEAN			
Flow	**wt [%]**	**cc. [l]**	$v/v\,\%$
Oakite			
Sodium Hydroxide	65	74.75	83.39→Solvent 16.60 → Solute
Sodium Carbonate	20	23	
Silic Acid	30	34.50	
Ecomate			
Coconut oil	2	2.30	83.39→Solvent 16.60 → Solute
2-Aminoethanol	4	4.60	
Dihydrogen Monoxide	89	102.35	
Tall oil Fatty Acid	5	5.75	
GRINDING & HF			
Flow	**wt [%]**	**cc. [l]**	$v/v\,\%$
Cimtech 320			
Triethanolamine	30	3.6	95.41→Solvent 4.58→ Solute
Monoisopropanolamine	3	0.36	
Nonanoico acid	3	0.36	
Others (unknown)	64	7.68	
Cimtech 610			
Triethanolamine	30	3.3	96 ± 1→Solvent 4 ± 1→Solute
Neodecanoic acid	8.8	0.968	
Diaminopolypropylene glycol	5	0.55	
Monoisopropanolamine	3	0.33	
Nonanoico acid	3	0.33	
Methylisothiazolinone	0.2	0.02	
Others (unknown)	50	5.5	

2.2.2.1. **Additive Manufacturing consumption**

In terms of additive techniques, the water and gas consumption depends on the AM system, the raw material, and type of inert gas. The following equation shows the volume consumption of water (6) and argon (7).

(14) $$v_{water} = d_{water} * t_m$$

(15) $$v_{argon} = \frac{1}{P} * \int_0^t d_{argon}$$

Where d_{water} is the water flow rate (l/s), d_{water} is the gas flow rate (kg/s), t_m is the manufacturing time and P is the gas density.

2.2.2.2. **Environmental Impact emissions**

The total amount of carbon footprint emissions produced over the lifecycle of a turbine blade from cradle to gate was taken as the sum of the carbon emissions generated in energy consumption. The gas emissions in tonnes of $CO_{2\text{-eq}}$ attributable to the quantity of electricity used may be calculated by the following equation [32].

(16) $$C = \sum_{i,j,k} E_{i,j,k} * EF_{i,j,k}$$

(17) $$EF_{i,j,k} = C_k * \eta_{i,j,k}$$

Where C is the amount of carbon emissions, E is the energy consumption, and EF is the emission factor. i is the industry and region, j is the equipment and technology used, k is the type of energy source used, C_k is the carbon content, and $\eta_{i,j,k}$ is the oxidation rate.

In this particular case, it is not necessary to calculate the emission factor because GaBi Software has its own library specialized data with this information taking into account factors such as region and energy source. Otherwise, to quantify the environmental impact of the process, inputs, and outputs data must be multiplied with its indicator listed in the Handbook on LCA operational guide [33].

Abiotic Depletion Potential

(18) $$ADP_i = \frac{DR_i}{(R_i)^2} * \frac{(R_{ref})^2}{DR_{ref}}$$

Where:

DR_i is extraction rate of resource i.
R_i is the ultimate reserve of resource i.
R_{ref} is the ultimate reserve of the reference resource (antimony) expressed in kg.
DR_{ref} is the extraction rate of R_{ref}.

Acidification Potential

(19) $$AP_i = \frac{\eta_i}{\eta_{SO_2}}$$

Where:

η_i represents the number of H^+ ions that can potentially be produced per kg of substance i
η_{SO_2} is the number of H^+ ions produced per kg SO_2. The emission-effect curve is a straight line through zero.

Eutrophication Potential

(20) $$EP_i = \frac{\nu_i / M_i}{\nu_{ref} / M_{ref}}$$

Where:

ν_i and ν_{ref} are the potential contributions to eutrophication of one mole of substance i and ref (i.e. PO_4^{3-}).

M_i and M_{ref} (kg.mol^{-1}) are the mass of i and ref (i.e. PO_4^{3-}). The reference substance PO_4^{3-} used to create eutrophication potentials.

Ecotoxicity

This impact category covers the impacts of toxic substances on aquatic, terrestrial and sediment ecosystems. The area of protection is the natural environment.

(21) $$ETP_{i,ecomp} = \sum_{fcomp} F_{i,ecomp,fcomp} * E_{i,ecomp,fcomp}$$

Where:

$ETP_{i,ecomp}$ is the contribution to ecotoxicity of a unit emission of substance i, to emission compartment $ecomp$. Most methods distinguish several subcategories, such as TETP for terrestrial ecotoxicity, and MAETP and FAEP for aquatic ecotoxicity.

$F_{i,ecomp,fcomp}$ is a fate factor, representing intermedia transport of substance i from emission compartment $ecomp$ to final (sub)compartment $fcomp$, and degradation within compartment $ecomp$.

$E_{i,ecomp,fcomp}$ is an effect factor, representing the toxic effect of exposure of a given ecosystem to substance i in compartment $fcomp$.

Global Warming Potential

(22) $$GWP_{T,i} = \frac{\int_0^T a_i c_i(t)dt}{\int_0^T a_{co_2} c_{co_2}(t)dt}$$

Where:

GWP_i is the global warming potential of the substance.
i is the substance.
a_i is the radiative forcing per unit concentration increase of greenhouse gas i.
$c_i(t)$ is the concentration of greenhouse gas i at time t after the release and T is the time over which integration is performed (yr).

This integration of the process of global warming involves a number of simplifications. GWPs depend on the time horizon T to which integration is performed.

Human Toxicity Potential

(23) $$HTP_{i,ecomp} = \sum_{fcomp} \sum_r F_{i,ecomp,fcomp} * T_{i,ecomp,fcomp} * I_r * E_{i,r}$$

Where:

$HTP_{i,ecomp}$ is the Human Toxicity Potential, the characterization factor for human toxicity of substance i emitted, to emission compartment $ecomp$.
$F_{i,ecomp,fcomp}$ is a fate factor, representing intermedia transport of substance i from emission compartment $ecomp$ to final (sub)compartment $fcomp$, and degradation within compartment $ecomp$.
$T_{i,ecomp,fcomp}$ is the transfer factor, the fraction of substance i transferrred from $fcomp$ to exposure route r
I_r is an intake factor, representing human intake via exposure route r
$E_{i,r}$ is an effect factor, representing the toxic effect of intake of substance exposure route r.

Ozone Layer Depletion Potential

$$ODP_i = \frac{\delta[O_3]_i}{\delta[O_3]_{CFC-11}} \quad (24)$$

Where:

$\delta[O_3]_i$ Represents the change in the stratospheric ozone column i the equilibrium state due to annual emissions of substance i (flux in kg·yr $^{-1}$).

$\delta[O_3]_{CFC-11}$ is the change in this column in the equilibrium state due to annual emissions of CFC–11.

Photochemical Ozone Creation Potential

$$POCP_i = \frac{a_i/b_i}{a_{C_2H_4}/\, b_{C_2H_4}} \quad (25)$$

Where: a_i is the change in ozone concentration due to a change in the emission of VOC i, and b_i the integrated emission of VOC i up to that time, with the denominator containing these parameters for ethylene (the reference substance).

2.2.3. Quantitative Data Collection

The quantitative data involves a collection of procedures information to quantify relevant inputs and outputs of a production system. The main input flows such as energy, solid material, and liquid materials (fluids) are shown in this section.

Energy

The data collection in terms of energy consumption of the Turbine Blade Manufacturing process is specified in the following tables: Table 10 for Investment Casting, Table 11 for Precision Machining Manufacturing and Table 12 for Selective Laser Melting. The consumption details of each machine are shown in Appendix E: Energy Consumption.

For SLM, the measurement of production time and the amount of energy consumed for a batch number of 600 pieces printed was calculated according to the time of one production run. The total building time of one production run is 11 hours and 40 minutes for a batch of 2 blades that were printed simultaneously in the building platform. The estimated times of the internal processes were in accordance with the process principle: preheating the process chamber and creating the inert atmosphere (always 30 minutes), exposure (i.e. selective scanning by the laser), recoating a new powder layer, and final cooling down and part/powder extraction (cleaning) [34].

Table 10
Quantitative Data Collection of electricity in IC.

Stages	Machines	kWh	kWh 600pz
Raw Metal	Fabrication of raw metal		**5202.07**
Patterns making tree	Wax model design	N.C	**443.93**
	Wax mold fabrication	4.93	
	Wax injection	4.93	
	Pattern assembly	4.93	
Shell-making	Refractory slurry and grain	43.05	**4842.89**
	Dry	118.38	
Pouring	Dewaxing	336.48	**3230.97**
	Firing	632.81	
	Pouring	351.11	**1187.83**
Cleaning & Finishing	Knock out / shakeout	1.25	**8.69**
	Cleaning rotatory system	1.25	
	Cut off	2.27	
	Grinding	3.92	
		TOTAL	**14916.4**

Table 11
Quantitative Data Collection of electricity in PMM.

Stages	Machines	kWh	kWh 600Pz
Grinding and HF	Blohm 8-1: Grind Root Form	19.876	1490.7
	Blohm 8-2: Tip/slot	19.876	1490.7
	Blohm 8-3: Z Form	19.876	1490.7
	HASS	0.597	8.53
	CMM	5.269	263.46
	Hand Finish	0.982	73.66
Nitric Clean Line	Furnance	36.45	145.78
	Pumping system		
	Scrubber VIRON		
	Feeding boards		
	Tanks (10 tanks)		
FPI Process	Penetrating impregnation	14.83	59.31
	Prewash		
	Emulsifying tank		
	Postwash		
	Resistance drying furnace		
	Revealed cabin		
	FPI Inspection		
Final Operation	Shot Peen	4.44	22.19
	Part Marking	0.23	6.75
	Finish Visual Inspection	0	0
	Nitric Clean Second Line	14.58	116.63
	Packaging	0	0
	TOTAL	**136.99**	**5168.41**

Table 12
Quantitative Data Collection of electricity in SLM.

Machine	kWh	kWh 600pz
Feeding boards	28.141	**8442.43**
Chiller	1.552	**465.58**
Powder Sieving Station	0.030	**9.07**
Inert Gas-Generator	0.515	**154.56**
EdNiCon Workbench	0.016	**4.89**
Atomization of powder		**45.83**
TOTAL	**30.26**	**9122.36**

Material

The materials considered along the turbine blade manufacturing process are grouped in Table 13. It is added the raw material, the refractory slurry materials, wax for the injection models, the cast steel shot for the shot peen operation and the lost weight of the preform part. Based on several experimentations, the SLM process operate with a total powder mass of 4.103 kg of which 0.1584 kg correspond to the 3D pieces and 0.0766 kg correspond to the supports of building. The resultant powder (3.87 kg) returns to the Powder Sieving Station.

Table 13
Quantitative Data Collection of materials in Turbine Blade Manufacturing.

Area	Operation	Material* (kg.)
	***Raw Material**	
IC	Metal in bar	67.12
PMM	Casting	48.06
SLM	Powder metal	70.51
	***Refractory Slurry**	
Shell Making	Ceramic	16.66
	Slurry	16.66
	***Wax**	
Pattern making tree	Wax injection	2.40
	***Casting Weight**	
Grinding and HF	Grind Root Form	48.06
	Grind wire	44.34
	Grind Z Form	43.68
	HASS	43.32
	Finished Part	43.26
	***Cast Steel Shot**	
Shot Peen	Shot Peen	4.25

Fluids

The fluids have been divided into 3: lubricants, chemical and penetrant liquids. The amount of liquids concentration and water proportion necessary to the Turbine Blade Manufacturing process is specified in the following Table 14.

Table 14
Quantitative Data Collection of fluids in PMM

Area	Operation	Water (L)	Fluids* (L)
	***Lubricants**		
Grinding and HF	Grind Root Form	250	11.88
	Tip/slot	187.5	7.50
	Z Form	206.25	14.09
	HASS	20	2
	CMM	0	0
	Hand Finish	0	0
	***Chemicals**		
Nitric Clean Line	Tank #101	577.51	115
	Tank #102	577.51	0
	Tank #103	577.51	0
	Tank #104	577.51	115
	Tank #105	577.51	0
	Tank #106	577.51	0
	Tank #107	577.51	115
	Tank #108	577.51	0
	Tank #109	577.51	0
	Tank #110	577.51	0
	***Penetrant Liquids**		
FPI Process	Penetrating impregnation	0	15
	Prewash	150	0
	Emulsifying tank	150	10
	Postwash	150	0
	Resistance drying	0	0
	Revealed cabin	0	2.5
	FPI Inspection	0	0

Material capacity

To determine the functional unit along the process, the material capacity planning must be done, taking into account the batch size, processing time, available machine capacity and energy consumption. In Table 15, the results are shown.

Table 15
Material capacity based on real and calculate data.

Process	Data from Honeywell*			Pieces per hour worked		Weight per 1 hour worked		Quantity respect to weight		Time respect to pieces worked		
	CT(min) x pcs	CT(hr) x pcs	Batch	Pcs x hr*	Pcs x hr	Gr x hr	Kg x hr	Pcs x kg	Pcs x ton	hr x kg	hr x ton	hr x 600 pcs
Blohm 8-1	6.25	0.10	1	8	9.6	640.8	0.64	12	12484	1.3	119850	75
Blohm 8-2	6.25	0.10	1	8	9.6	591.2	0.59	13	13531	123	129905	75
Blohm 8-3	6.25	0.10	1	8	9.6	582.4	0.58	13	13736	132	131868	75
Hass	1.41	0.02	1	42	42.5	3032.4	3.03	13	13850	589.3	589379	14.3
CMM	22	0.37	1	2	2.73	144.2	0.14	13	13869	37.8	37826	50
HF	6.25	0.10	1	8	9.6	576.8	0.58	13	13869	133.2	133148	75
NCL	120	2.00	OL	150	-	10815	10.8	13	13869	6.9	6935	8
FPI	50	0.83	OL	150	-	10815	10.8	13	13869	16.64	16643	4
Shot Peen	1	0.02	2	120	120	8652	8.65	13	13869	832.2	832177	5
Part Marking	3	0.05	1	20	20	1442	1.44	13	13869	277.4	277392	30

CT: Cycle time
OL: Order lot
** Real data*

2.3. Life cycle impact assessment

Once linked all the materials, fluids, and energy flow, a collection of the data about inputs and outputs was done for the Investment Casting process. These data and information were used to feed the GaBi Software that simulates the process and gives sustainability information about specific metrics. The previously modeled process was used to define what the GaBi Software calls a *"Process Diagram."* The results of the simulation of the Investment Casting process are shown in Fig. 20**.** In the same way, the results of Precision Machining Manufacturing process are in Fig. 21, and finally, a simulation of the Selective Laser Melting process was done defining the process diagram of inputs and outputs, as it is illustrated in Fig. 22.

In Appendix F: Process diagram using GaBi, it is shown the process diagram of each step in the Precision Machining Manufacturing process.

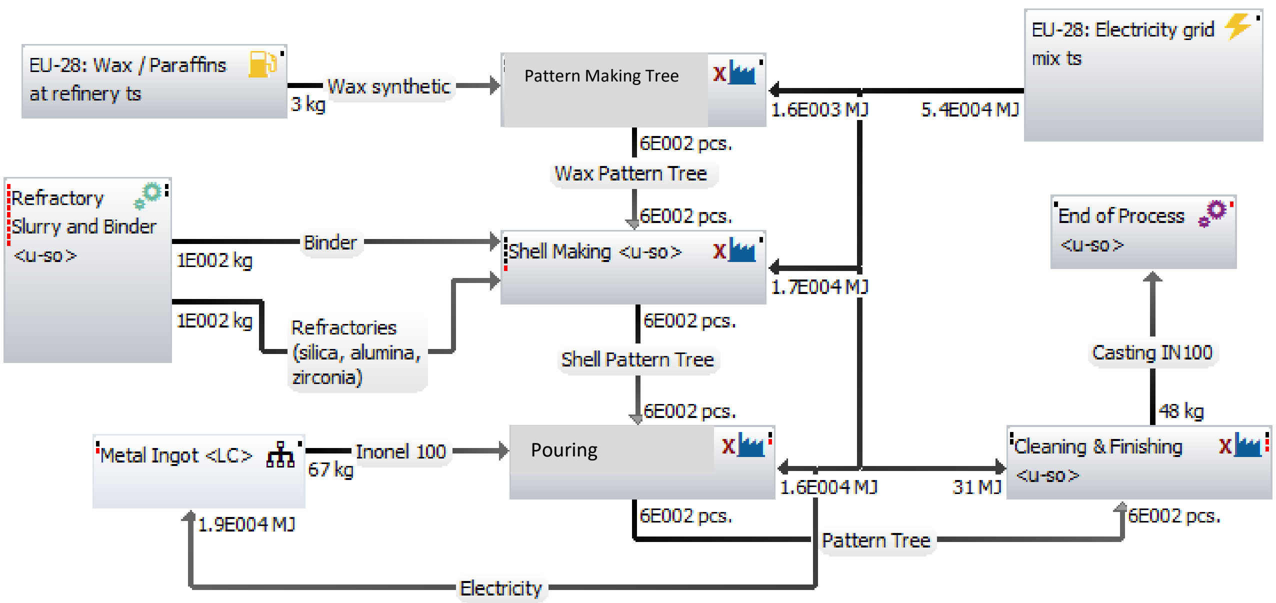


Fig. 20 Process diagram of Investment Casting process (GaBi Software).

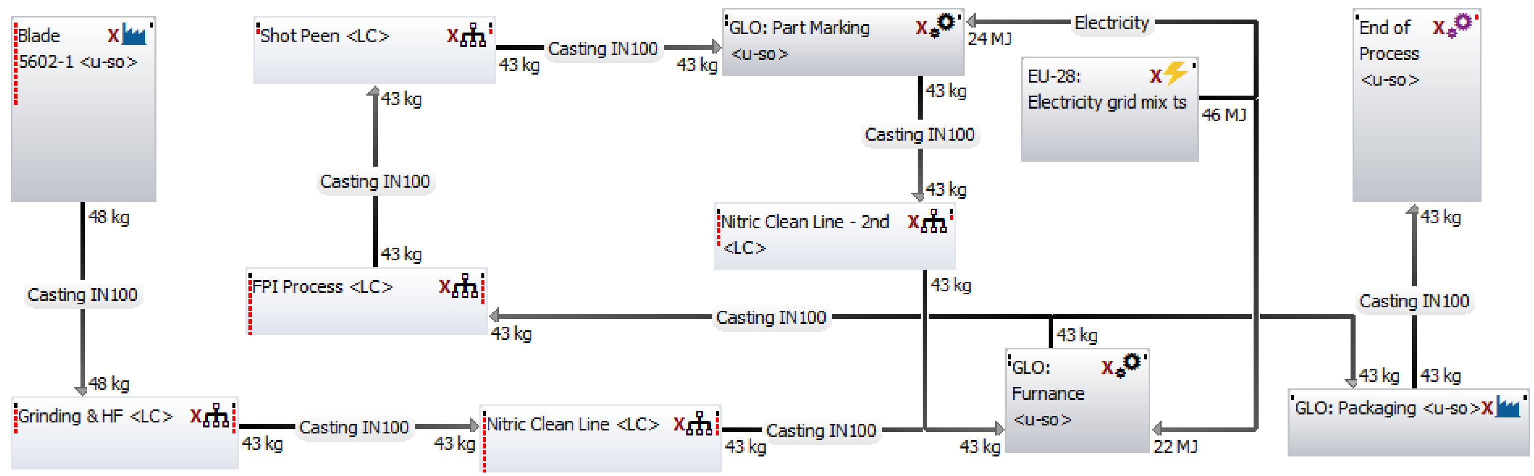


Fig. 21 Process diagram of Precision Machining Manufacturing (GaBi Software).

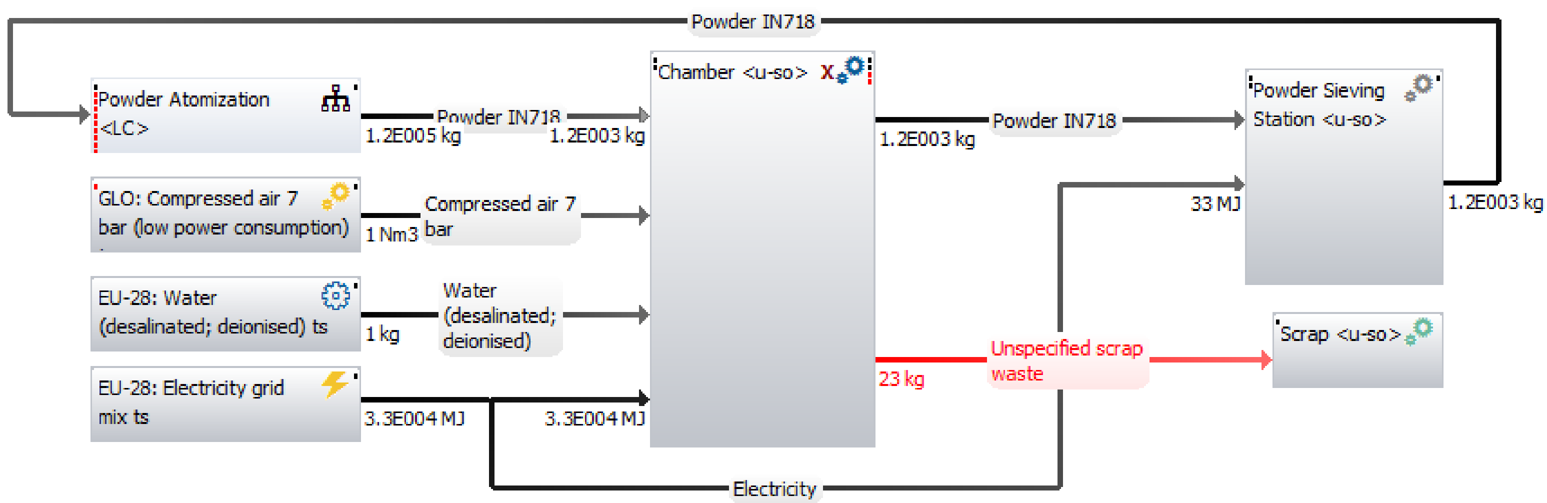


Fig. 22 Process diagram of Selective Laser Melting process (GaBi Software).

2.3.1. Selection of Impact categories

In the Impact assessment phase, the results of the Inventory analysis are translated into contributions to relevant impact categories. The relevant impact categories must be considered according to those categories relevant to the goal and scope of the particular study. These indicators are estimated following the methodologies of CML 2001 and USEtox.

The CML 2001 is an impact assessment method developed by the Institute of Environmental Sciences of the University of Leiden (CML), which quantify the emissions of the cause-effect chain and the results of impact categories are grouped into midpoint categories. On the other hand, the USEtox methodology is an environmental model for the characterization of human and ecotoxicological impacts, which is defined by the factors of carcinogenic and non-carcinogenic with the measurement of CTU_h.

From the perspective of sustainability, the indicators can help to have a general view of the impacts categories; the goal and scope of this particular study are the damage categories of climate change, human health, and ecosystem quality. Mainly, it is the focus on the carbon footprint indicator that measures the global warming; the associated metric can be defined as Global Warming Potential (GWP).

Carbon dioxide, while a relatively weak greenhouse absorber, is the primary climate driver because it remains a gas under all Earthly surface temperatures and pressures, it is expressed in kilograms of CO_2 equivalents as a functional unit. The selection of impact categories are listed in Table 16; they are classified as Midpoints and Endpoints (damage category).

Table 16
Environmental impact indicators.

Impact Categorie	Midpoint Categorie	Unit indicator	Emissions	Endpoint Categorie
Global Warming	Greenhouse gases emission	Perfluorocarbons	PFCs	Climate change
		Sulfur hexafluoride	SF_6	
		Hydrofluorocarbon	HFCs	
		Chlorofluorocarbon	CFC	
	Carbon Dioxide emissions	carbon dioxide	CO_2	
		Nitrous Oxide	N_2O	
		Methane	CH_4	
Ozone Layer Depletion Potential	Stratospheric ozone depletion	Trichlorofluoromethane	R11	Human Health
Human Toxicity	Human Toxicity Potential	Dichlorobenzene	DCB	
	Human Toxicity, cancer effects	Comparative toxic unit for human	CTUh	
	Human Toxicity, non-cancer effects		CTUh	
Ecotoxicity	Freshwater Aquatic Ecotoxicity Potential	Dichlorobenzene	DCB	Ecosystem Quality
	Photochemical Ozone Creation Potential	Hydrochlorofluorocarbon	HCFCs & Ethene	
	Terrestic Ecotoxicity Potential	Dichlorobenzene	DCB & VOC	
	Marine Aquatic Ecotoxicity Potential	Dichlorobenzene	DCB	
	Acidification Potential	Sulphur dioxide	SO_2, NOx	
	Eutrophication Potential	Phosphate	Phosphate & BOD	
Abiotic Depletion	Abiotic Depletion elements	Antimony	Sb	
	Abiotic Depletion fossil	Megajoules	MJ	

2.3.2. Classification

This step refers to the classification of every substance or resource extraction added to the process into compartment groups of resource, air, freshwater, seawater, agriculture soil and industrial soil. The classification data of this compartment are listed in the operational guide of ISO 14044 from the handbook of LCA. The principal substance used in this study are listed and classified in Table 17.

Table 17
Classification of substance.

Substance	Group	Initial emission or extraction	unit
Argon (Ar)	Element	Resources	Kg
Nickel (Ni)	Element, Metal, Inorganic	Resources, agric. and indus. soil, fresh water, sea water	Kg
1,4-dicholobenzene	Halogincated aromatic	Air, fresh water, sea water, agric. and indus. soil	Kg
Carbon dioxide	Inorganic	Air	Kg
CFC-11	Haloginated nonaromatic	Air	Kg
Ethylene	Nonaromatic (alkene)	Air	Kg
Ethylene Glycol	Nonaromatic (ester)	Air	Kg
HCFC	Haloginated nonaromatic	Air	Kg
Methanol	Nonaromatic (alcohol)	Air	Kg
Sulfur dioxide	Inorganic	Air, fresh water	Kg
Nitrogen Dioxide	Inorganic	Air	Kg
Nitric Acid	Inorganic	Air, fresh water, sea water, agric. and indus. soil	Kg
Phosphate	Inorganic	Air, fresh water, sea water, indus. soil	Kg
Dichloromethane	Haloginated nonaromatic	Sea water, indus. soil	Kg

According to the classification step [33], the emissions are classified into 4 categories: the emissions that may theoretically contribute to more than one impact category but in practice contribute only to one (parallel) e.g., an emission of Sulfur dioxide which may have either toxic or acidifying impacts; The emissions with more than one damage category (Serial) e.g., emissions of heavy metals which may first have ecotoxicological impacts and subsequently, via food chains, impacts on human health; The emissions that have a primary impact that in turn lead to one or more secondary impacts (Indirect) e.g., nickel toxicity induced by acidification, or methane contributing to photo-oxidant formation, with the ozone produced contributing to climate change, which in turn may contribute to stratospheric ozone depletion; And emissions that have a mutual influence on each other's impact (Combined) e.g., NOx and VOC, both of them are required for photo-oxidant formation. Table 18 and the figures below, show the general inputs and outputs emissions data of the processes according to the amount substance classification.

Table 18
Classification of general emissions data.

IC	Inputs	Outputs
Emissions to sea water	20	1.20E+05
Deposited goods	0	3.10E+04
Emissions to air	0	1.90E+05
Emissions to fresh water	0	3.50E+07
Emissions to agricultural soil	0	-0.0053
Emissions to industrial soil	0	0.078
SLM	**Inputs**	**Outputs**
Emissions to sea water	0	7.39E+04
Deposited goods	0	1.96E+04
Emissions to air	42	1.48E+05
Emissions to fresh water	2.5	2.1E+07
Emissions to agricultural soil	0	-0.0034
Emissions to industrial soil	0	0.048
PMM	**Inputs**	**Outputs**
Emissions to air	71	9.90E+03
Emissions to fresh water	75	6.10E+04
Emissions to industrial soil	92	0.027
Deposited goods	0	4.50E+02
Emissions to sea water	0	3.80E+04
Emissions to agricultural soil	0	-0.0017

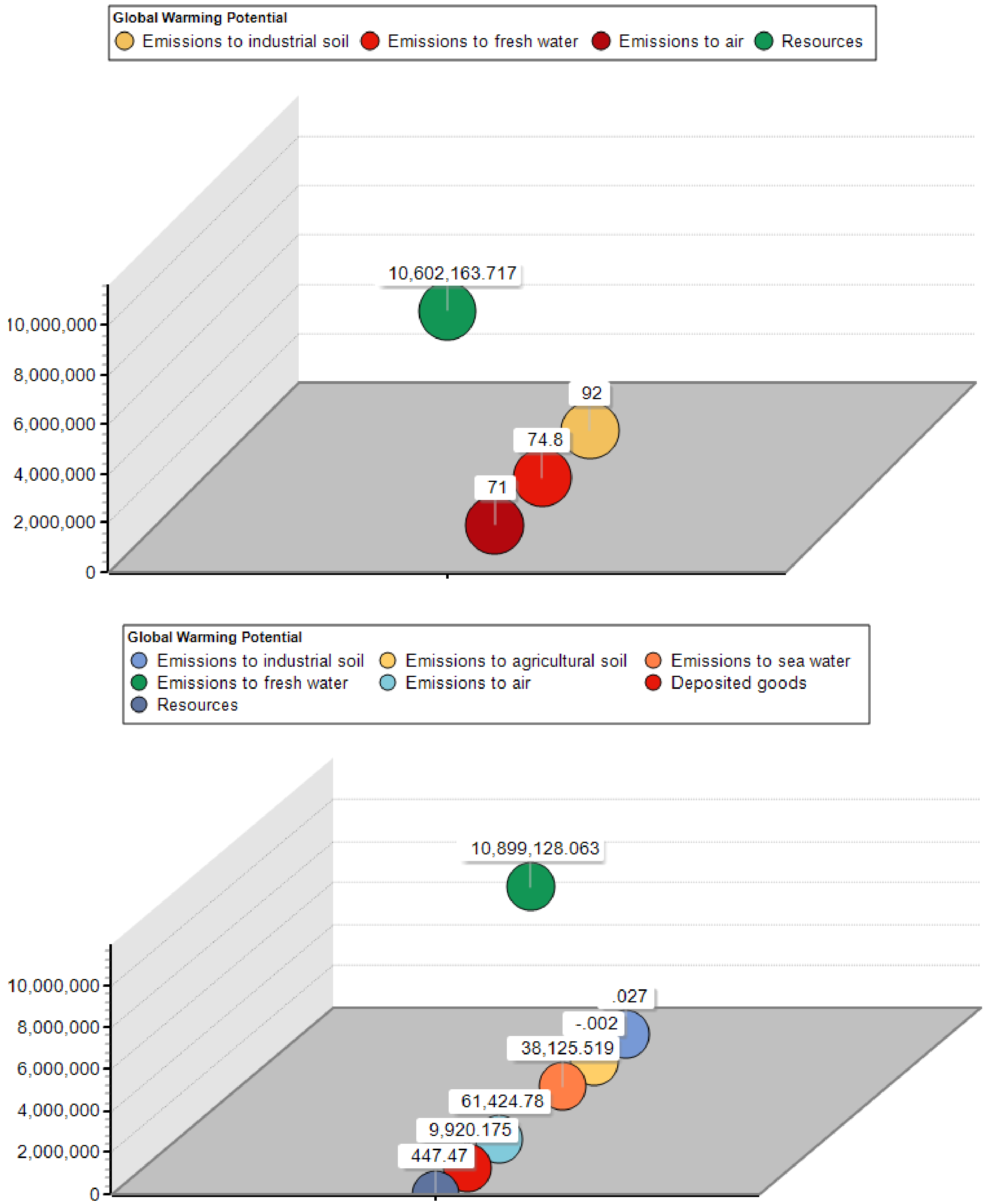


Fig. 23. Inputs – Outputs of global warming emissions in PMM process.

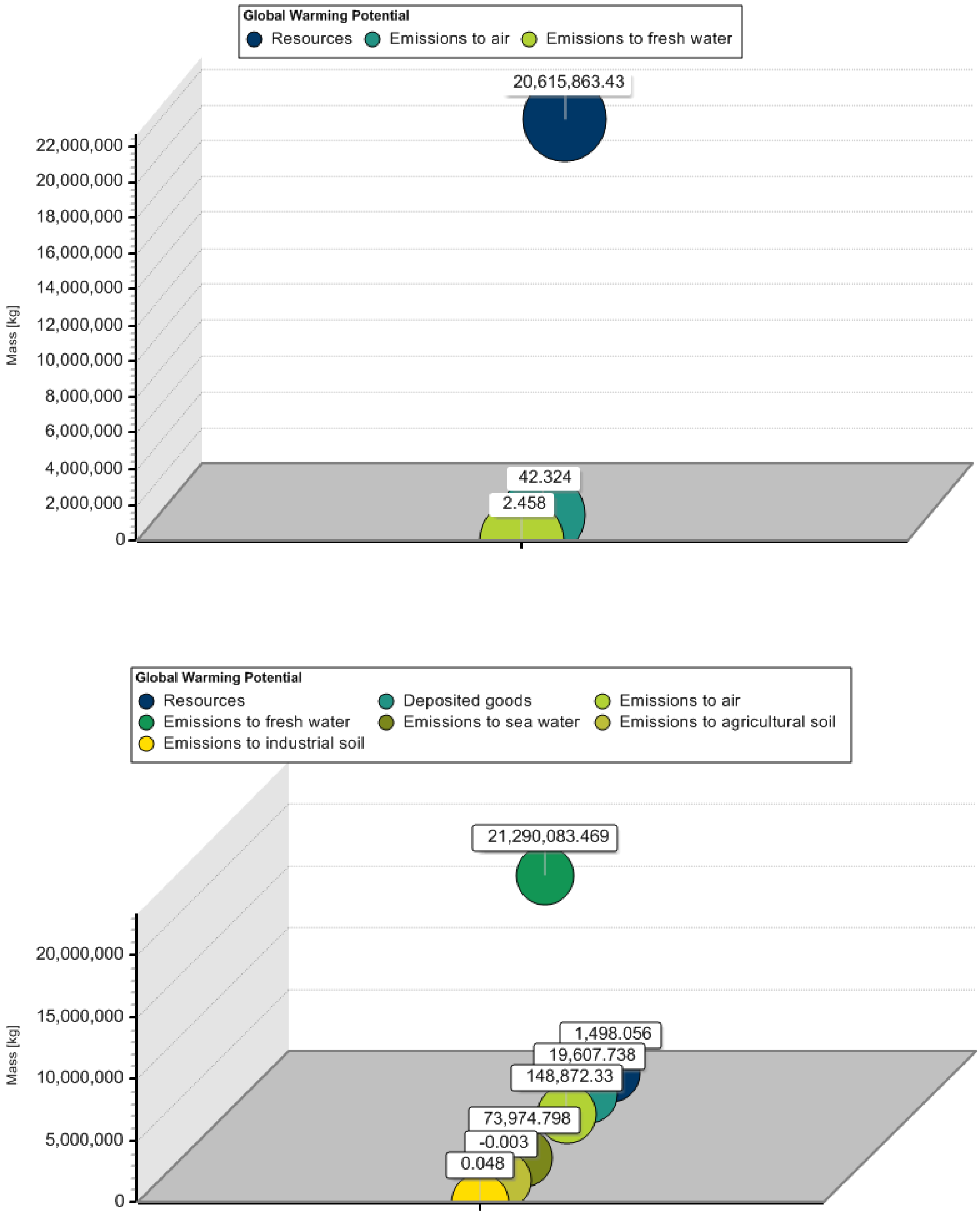


Fig. 24. Inputs – Outputs of global warming emissions in SLM process.

2.3.3. Characterization

For the characterization step of the impact assessment, the environmental indicators listed in Table 16 are translated into scores for each impact category, following the measurement with the indicators. To calculate the environmental impact of the process, the flows must be quantified and multiplied with their specific eco-indicator [35]. In this LCA was used the baseline characterization methods developed by Guinée et al. 2001. In the characterization step of Impact assessment, the environmental impacts assigned qualitatively to a particular impact category in classification are quantified in terms of a common unit for that category [33], following the equation below.

$$I_c = \sum_s CF_{c,s} * m_s$$

Where I_c is the indicator result for impact category, CF is the characterization factor, c is the stand for the impact category, s is the substance emission or resource extraction and $m,$ is the amount emitted expressed in kg.

For each impact category, the indicator result is calculated by multiplying the relevant interventions by their corresponding characterization factors. The value of characterization factor is listed in the Handbook on LCA: Operational annex. Together, the inventory analysis and the results after characterization constitute the 'environmental profile' given in Table 19. As it was specified previously, the study will focus on the emissions of Carbon Footprint, for that reason, the classification and characterization of this indicator are deeply analyzed and shown in this work.

Emission factors for calculating direct emissions are expressed in the form of a quantity of a given GHG emitted per unit of energy (kg CO2-e /MJ). Emission factors are used to calculate GHG emissions by multiplying the factor with activity data. The Global Warming Potential (GWP) convert relevant masses of different greenhouse gases into carbon dioxide gases equivalent (CO2-e) by multiplying the quantity of the gas by its equivalent metric in the same warming effect over a 100 year period [21]. In the Appendix F: , it is listed the table of characterization factor of GWP, the characterization factors of the other environmental impacts are listed in the “Handbook on LCA: Operational annex”.

Table 19
Environmental profile results.

Methodology	Impact category	Amount		Unit
		CM	AM	
CML 2001 - Jan. 2016, World, Year 2000	Abiotic Depletion elements	9.156	6.35	kg of Sb eq.
	Abiotic Depleiton fossil	108 114.67	73 932.78	MJ
	Acidification Potential	27.404	19.344	kg of SO_2 eq.
	Eutrophication Potential	2.629	1.792	kg of PO_4 eq.
	Freshwater Aquatic Ecotoxicity Potential	19.258	13.58	kg of DCB eq.
	Global Warming Potential	9 772.58	7 010.77	kg of CO_2 eq.
	Marine Aquatic Ecotoxicity Potential	1 092 214.36	776 538.36	kg of DCB eq.
	Ozone Layer Depletion Potential	4.23E-7	2.95E-7	kg of R11 or CFC-11 eq.
	Photochemical Ozone Creation Potential	1.757	1.243	kg of Ethene eq.
	Terrestic Ecotoxicity Potential	6.781	4.79	kg of DCB eq.
	Human Toxicity Potential	432.654	304.945	kg of DCB eq.
USEtox North America	Human Toxicity, cancer effects	7.71E-6	5.45E-6	CTUh
	Human Toxicity, non-cancer effects	3.12E-5	1.94E-5	CTUh

Chapter 3: Discussion of Results

3.1. Life Cycle Interpretation

3.1.1. Environmental Impacts

Measurement of environmental impacts is the first step in this process of technology changed to reduce the toxicity potential. According to the interpretation stage of the LCA standard, the inputs and outputs for each manufacturing process are quantified in order to obtain the sustainability indicators. The results of the simulation with GaBi Software determine which stage of each manufacturing process has the worst ecological impact in terms of quantity of greenhouse gas emissions among other emissions. Focusing on gas emissions, Table 20, shows the environmental impact for each manufacturing process analyzed and measured, as well, the reduction achieved using the process plan that considers AM against CM for a batch size of 600 parts.

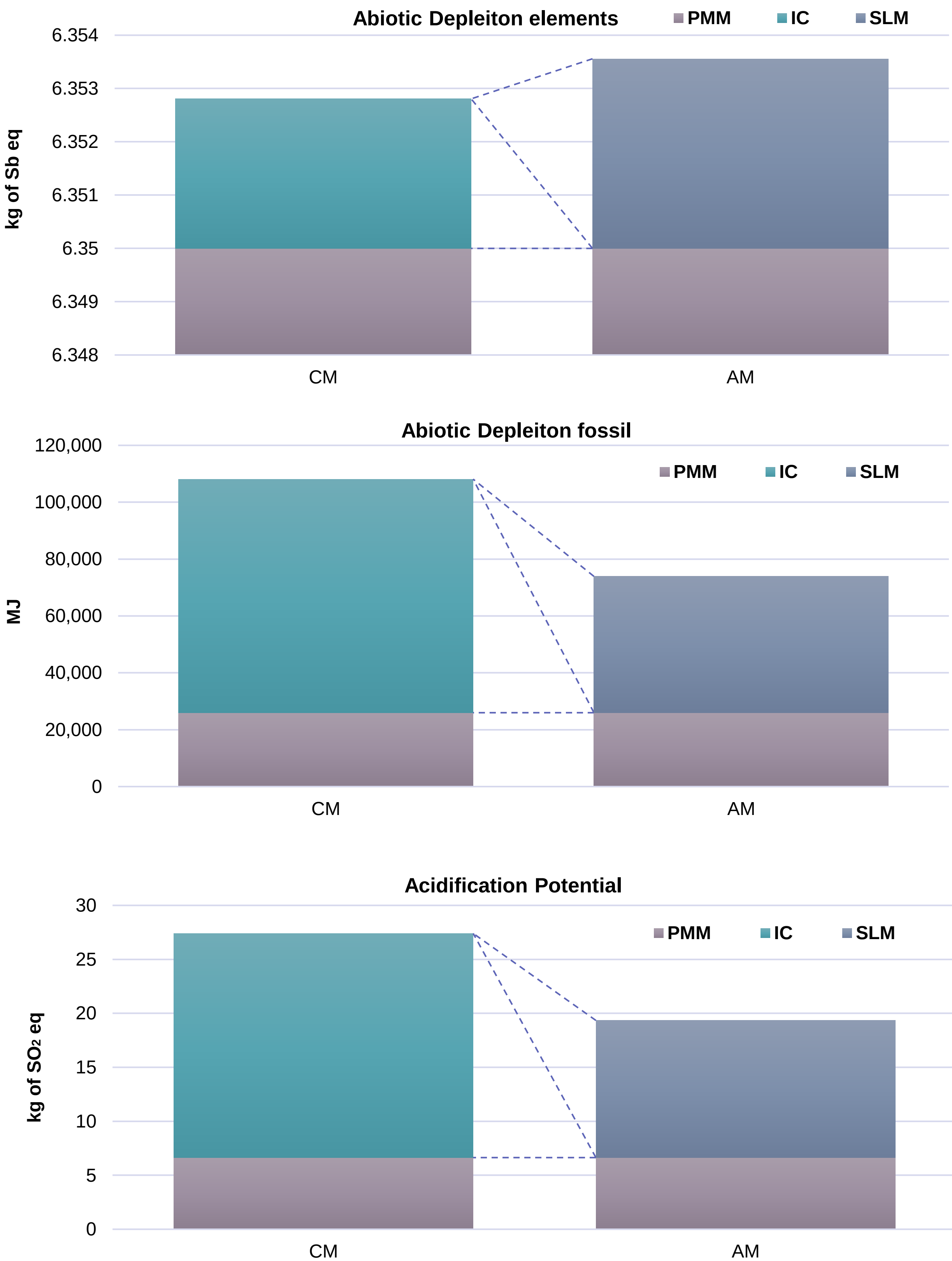
In this case, the obtained results provide information about the potential toxicity of air, water and soil of each stage analyzed in the process of investment casting, precision machining and selective laser melting. If we want to analyze the manufacturing process of these parts from a global perspective, we need to consider the combination of individual manufacturing technologies. In the comparative chart (Fig. 25), the results show the differences between the environmental sustainability analysis of Conventional Manufacturing and Additive Manufacturing of each environmental impact. The environmental loads are calculated by applying the data of energy, material, and fluid along the processes. The environmental impacts can vary depending on the indicator impacts methodology selected because every methodology has a different point category and different emission factor.

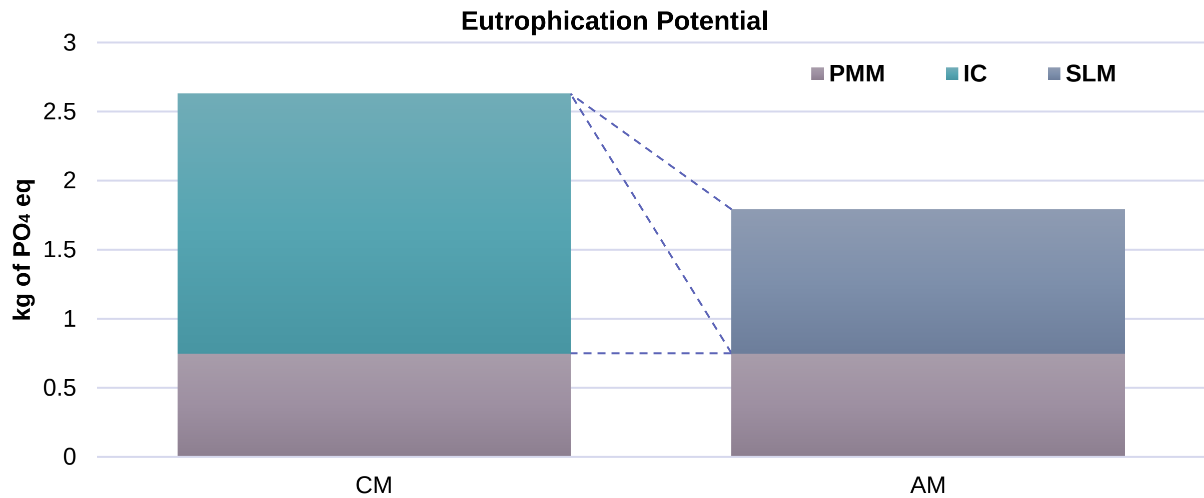
The normalization factor is not considering in the environmental impacts results, this assessment is not mandatory, but optional in the ISO Standard, the normalization represent a specific factor of an area or a country to have a more precise information of the indicator impacts, but México hasn't data of environmental loads yet.

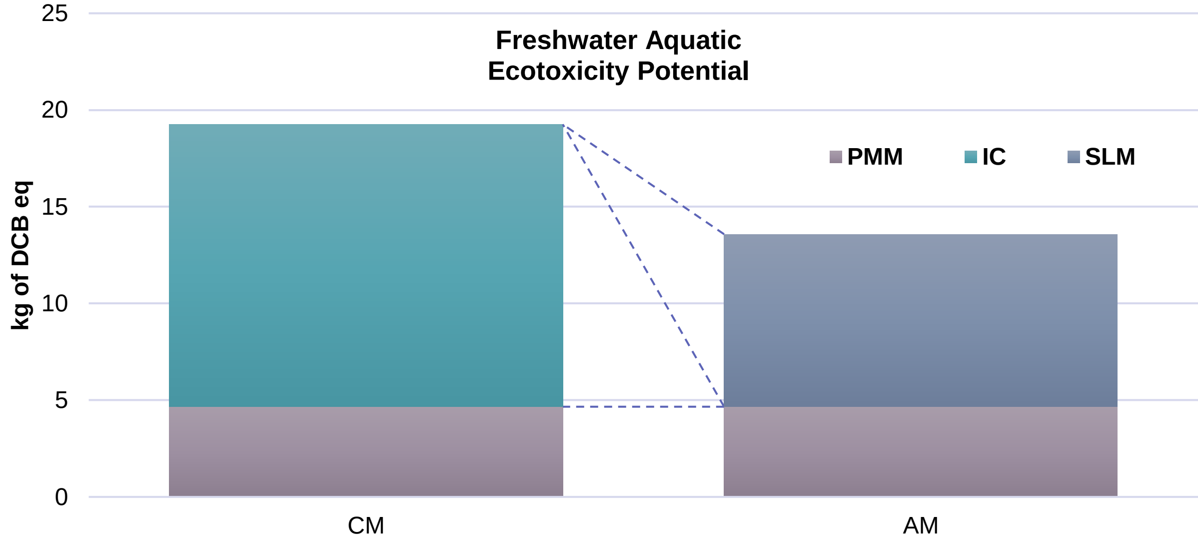
Table 20 Results of environmental impacts analysis.

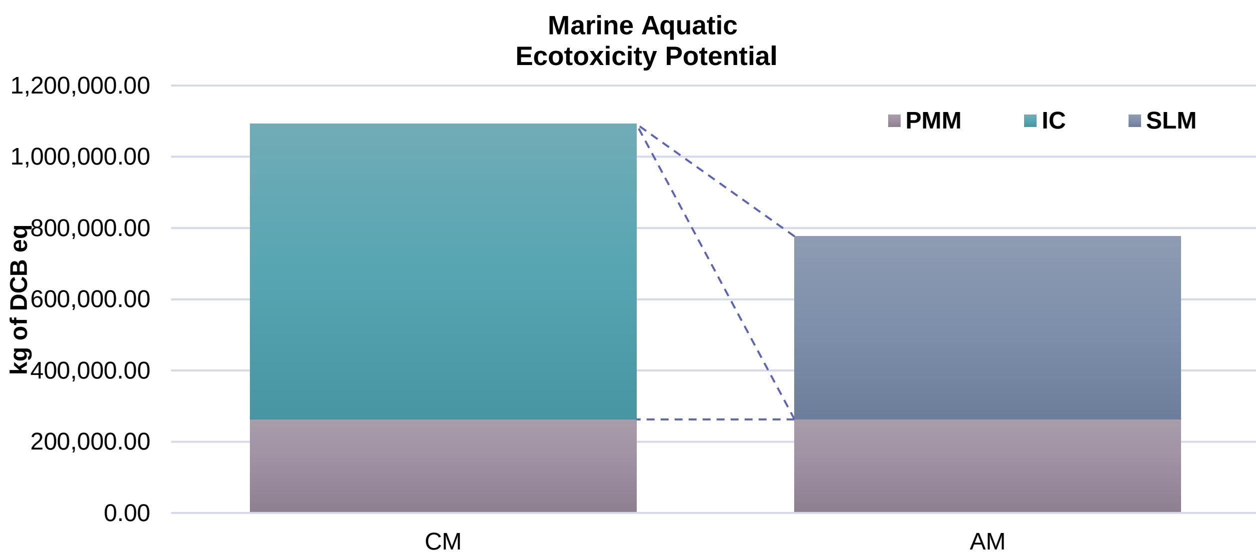
	Indicator	Results in Kg equivalents	Methodology
IC	Abiotic Depleiton elements	2.81E-03	CML 2001
	Abiotic Depleiton fossil	82,138.67	CML 2001
	Acidification Potential	20.766	CML 2001
	Eutrophication Potential	1.879	CML 2001
	Freshwater Aquatic Ecotoxicity Potential	14.595	CML 2001
	Global Warming Potential	7,263.30	CML 2001
	Marine Aquatic Ecotoxicity Potential	829,603.71	CML 2001
	Ozone Layer Depleiton Potential	3.23E-07	CML 2001
	Photochemical Ozone Creation Potential	1.326	CML 2001
	Terrestic Ecotoxicity Potential	5.139	CML 2001
	Human Toxicity Potential	331.818	CML 2001
	Human Toxicity, cancer effects	5.78E-06	USEtox
	Human Toxicity, non-cancer effects	2.34E-05	USEtox
SLM	Abiotic Depleiton elements	3.56E-03	CML 2001
	Abiotic Depleiton fossil	47,956.78	CML 2001
	Acidification Potential	12.706	CML 2001
	Eutrophication Potential	1.042	CML 2001
	Freshwater Aquatic Ecotoxicity Potential	8.917	CML 2001
	Global Warming Potential	4,501.49	CML 2001
	Marine Aquatic Ecotoxicity Potential	513,927.71	CML 2001
	Ozone Layer Depleiton Potential	1.95E-07	CML 2001
	Photochemical Ozone Creation Potential	0.812	CML 2001
	Terrestic Ecotoxicity Potential	3.157	CML 2001
	Human Toxicity Potential	204.109	CML 2001
	Human Toxicity, cancer effects	3.52E-06	USEtox
	Human Toxicity, non-cancer effects	1.16E-05	USEtox
PMM	Abiotic Depleiton elements	6.35	CML 2001
	Abiotic Depleiton fossil	25,976	CML 2001
	Acidification Potential	6.638	CML 2001
	Eutrophication Potential	0.75	CML 2001
	Freshwater Aquatic Ecotoxicity Potential	4.663	CML 2001
	Global Warming Potential	2,509.28	CML 2001
	Marine Aquatic Ecotoxicity Potential	262,610.65	CML 2001
	Ozone Layer Depleiton Potential	1.00E-07	CML 2001
	Photochemical Ozone Creation Potential	0.431	CML 2001
	Terrestic Ecotoxicity Potential	1.642	CML 2001
	Human Toxicity Potential	100.836	CML 2001
	Human Toxicity, cancer effects	1.93E-06	USEtox
	Human Toxicity, non-cancer effects	7.80E-06	USEtox

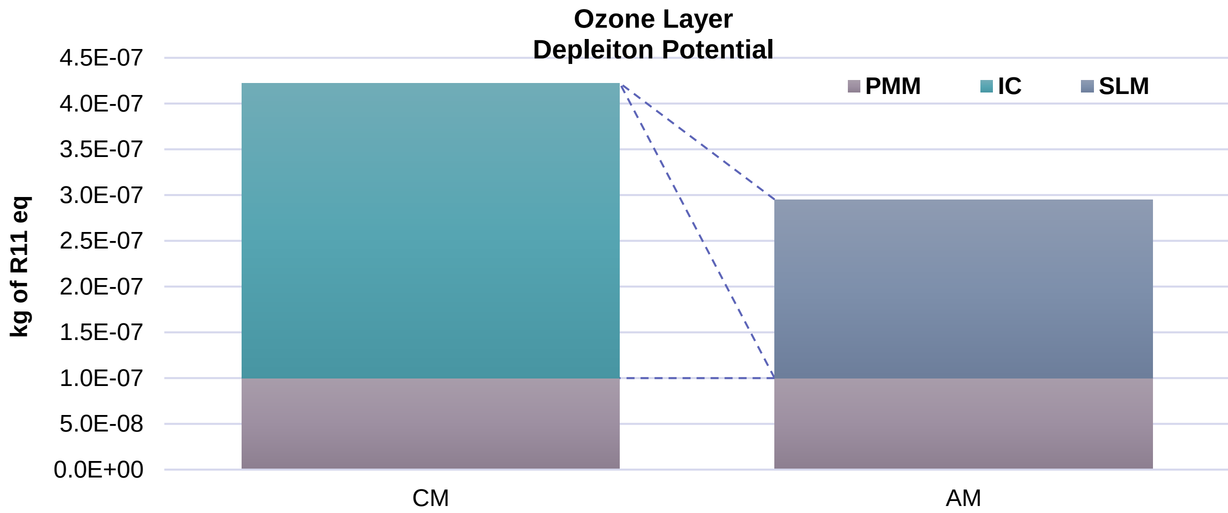
Fig. 25. Comparative charts of Environmental Impacts.

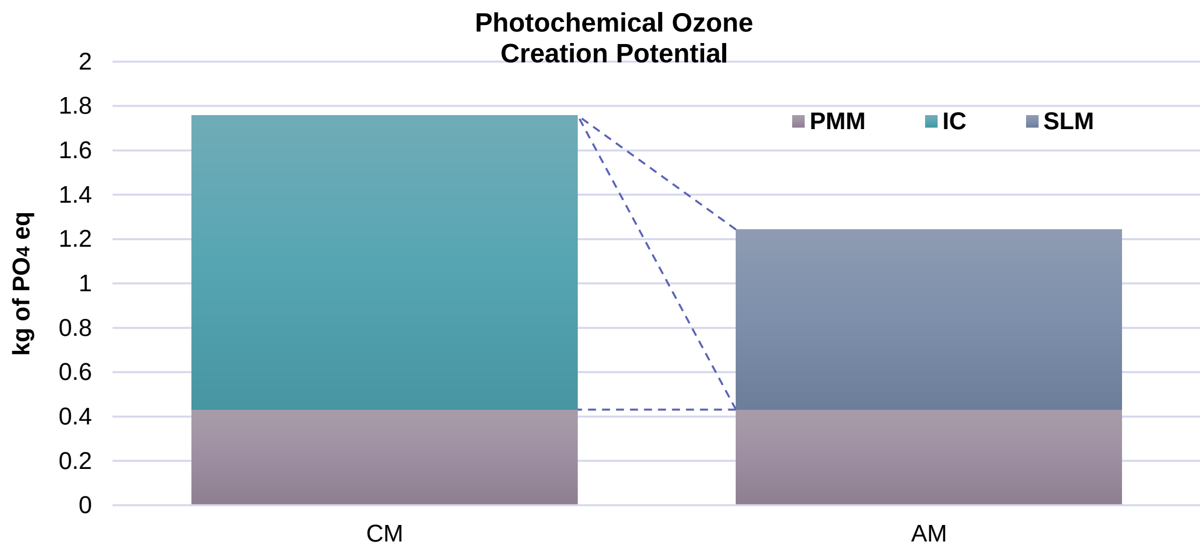


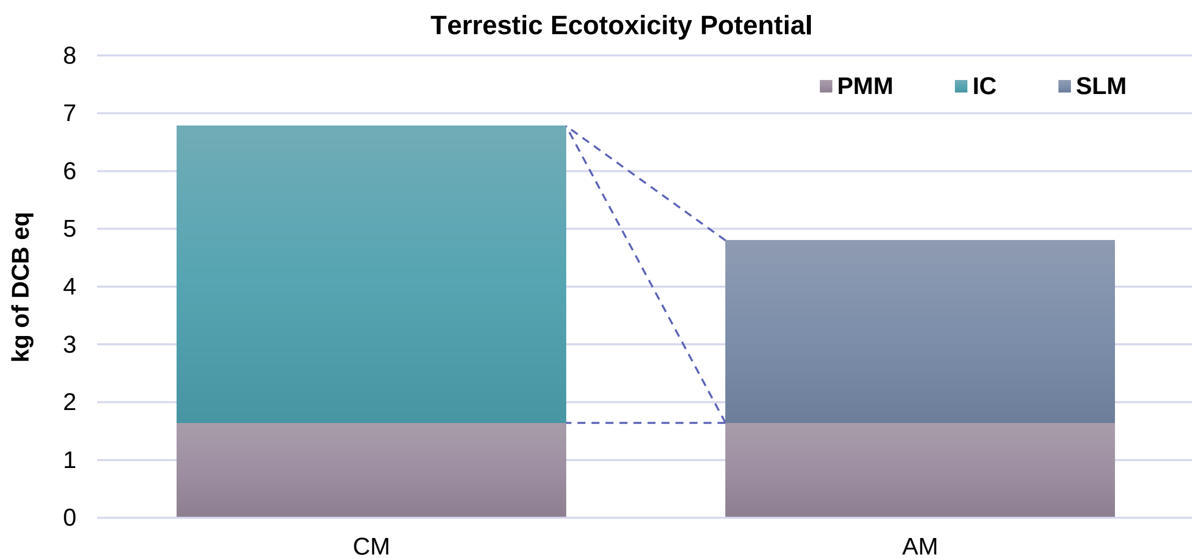

Eutrophication Potential
kg of PO4 eq
3
2.5
2
1.5
1
0.5
0
PMM
IC
SLM
CM
AM

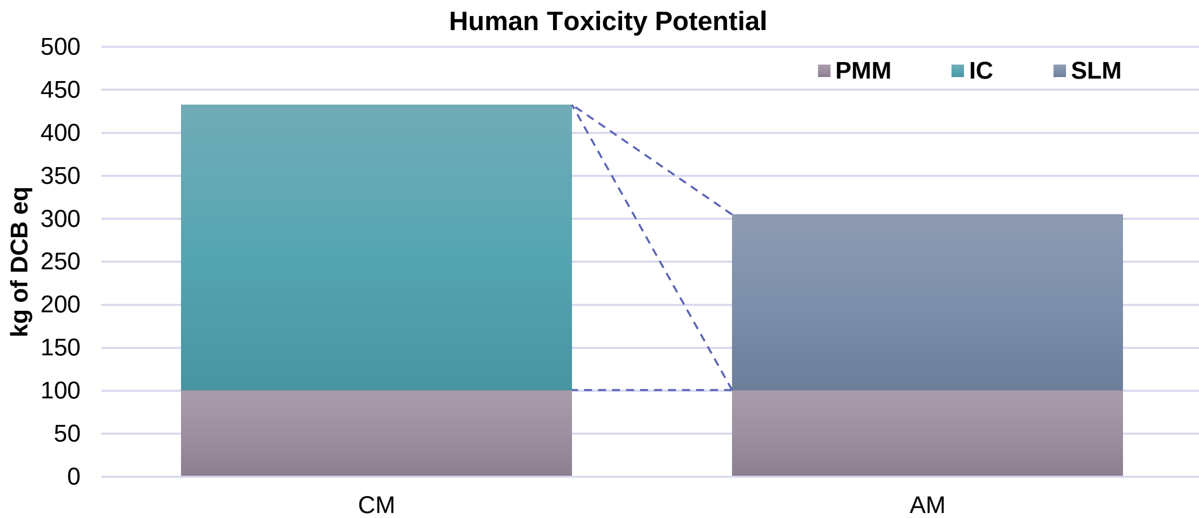

Freshwater Aquatic
Ecotoxicity Potential
kg of DCB eq
25
20
15
10
5
0
PMM
IC
SLM
CM
AM

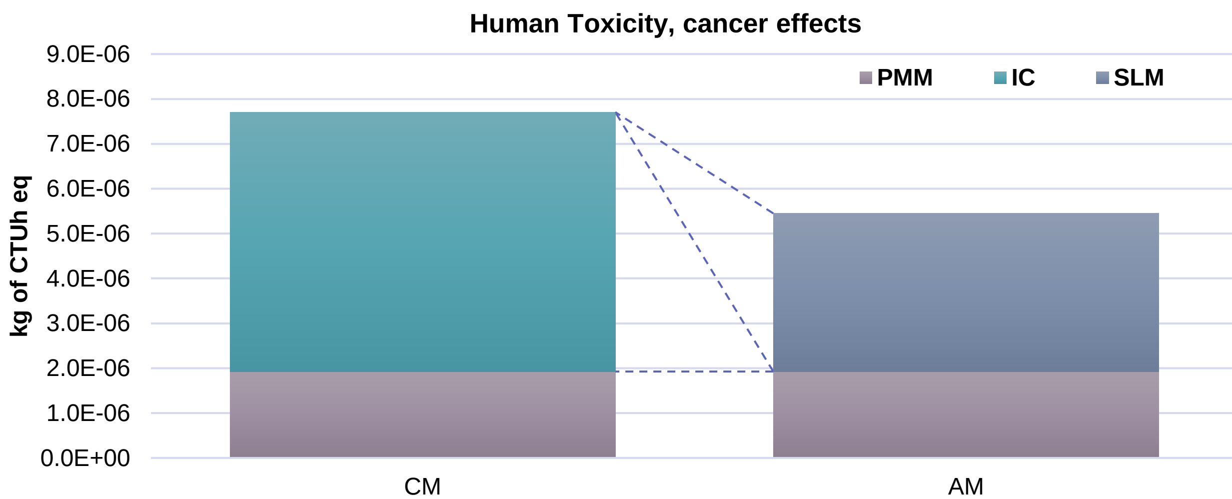

Marine Aquatic
Ecotoxicity Potential
kg of DCB eq
1,200,000.00
1,000,000.00
800,000.00
600,000.00
400,000.00
200,000.00
0.00
PMM
IC
SLM
CM
AM

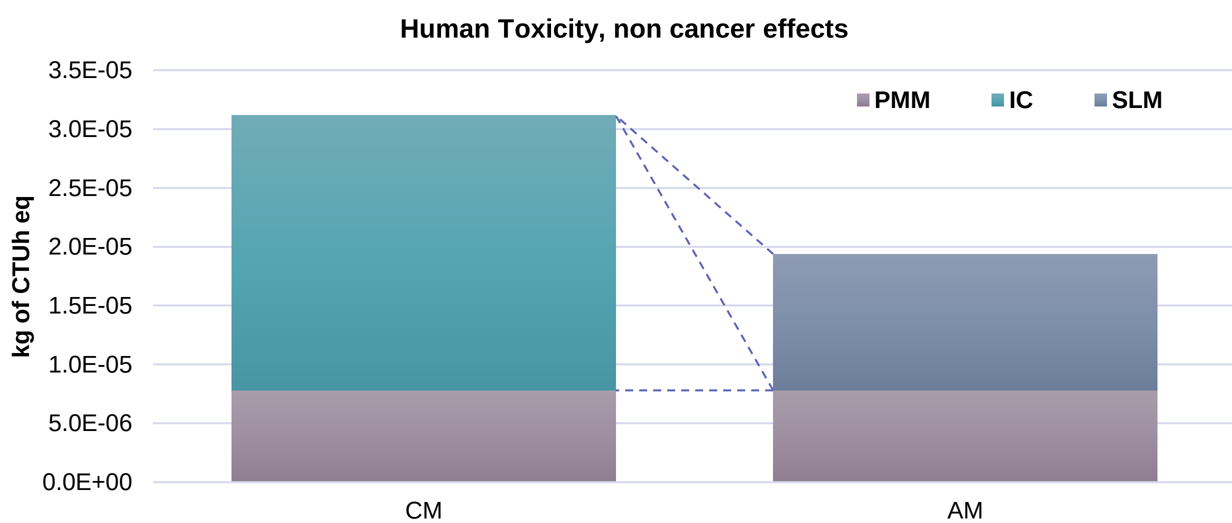

Ozone Layer
Depleiton Potential
kg of R11 eq
4.5E-07
4.0E-07
3.5E-07
3.0E-07
2.5E-07
2.0E-07
1.5E-07
1.0E-07
5.0E-08
0.0E+00
PMM
IC
SLM
CM
AM


Photochemical Ozone
Creation Potential
kg of PO4 eq
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
PMM
IC
SLM
CM
AM


Terrestic Ecotoxicity Potential
kg of DCB eq
8
7
6
5
4
3
2
1
0
PMM
IC
SLM
CM
AM


Human Toxicity Potential
kg of DCB eq
500
450
400
350
300
250
200
150
100
50
0
PMM
IC
SLM
CM
AM


Human Toxicity, cancer effects
kg of CTUh eq
9.0E-06
8.0E-06
7.0E-06
6.0E-06
5.0E-06
4.0E-06
3.0E-06
2.0E-06
1.0E-06
0.0E+00
PMM
IC
SLM
CM
AM


Human Toxicity, non cancer effects
kg of CTUh eq
3.5E-05
3.0E-05
2.5E-05
2.0E-05
1.5E-05
1.0E-05
5.0E-06
0.0E+00
PMM
IC
SLM
CM
AM

3.1.2. Carbon footprint

Carbon footprint was calculated by applying the data of how much energy and work-hours are consumed for heavy machinery in the manufacturing processes. If we go deeper into the Global Warming Potential emissions, we can see from the data that the material input and the pouring operations are the main contributors to the gas emission (Table 21). In the process of Precision Machining Manufacturing, energy is directly consumed by heavy machinery, in which each stage in operation along the turbine blade manufacturing will be monitored.

Table 21
Energy consumption of Investment Casting Process.

Investment Casting Stage	Amount	Energy (kWh)	Kg CO_2-eq
Raw Material[1] (Wilson et al., 2014)	67.12 kg	5 202.07	2 308.34
Pattern making tree	600 parts	443.93	197
Shell-making	30 Pattern trees	4 842.9	2 149
Pouring & Dewaxing	6.67 hr.	4 401.34	1 953
Molten metal[2] (Margolis et al., 1999)	48.06 kg	17.46	7.7
Cleaning & Finishing	48.06 kg	8.69	3.85
Total		**14 916.4**	**6 618.9**

In literature review is called: [1]Metal in bar stock; [2]Refining and Pouring.

Thus, after knowing the energy consumption of each machine, it is essential to specify the data information of energy and fluids consumption. The energy consumption of Precision Machining Manufacturing is illustrated in Table 22, and the energy consumption for Selective Laser Melting process is in Table 23.

The energy consumption can vary depending on the energy source, in this case, the emissions factor where calculated according to “Electricity Production Mix” data. This source includes general information of its production over the world.

Table 22
Energy consumption of Precision Machining Manufacturing process.

Precision Machining	Amount	Energy (kWh)	Kg CO_2-eq.
Grinding	48.06 kg	4 817.76	2 140.49
Nitric Clean	43.26 kg (2 hr.)	145.78	302.98
FPI Process	43.26 kg	59.31	14.27
Shot peen	43.26 kg	22.19	9.85
Nitric Clean Second	43.26 kg (0.8 hr.)	116.63	36.06
Marking & Packaging	43.26 kg	6.75	5.64
Total		**5 168.41**	**2 509.28**

Table 23
Energy consumption of Selective Laser Melting Manufacturing process.

Selective Laser Melting	Amount	Energy (kWh)	Kg CO_2-eq.
Powder Material	70.51kg	45.83	473.91
SLM Process	70.51kg	9 076.53	4 027.58
Total		**9 122.36**	**4 501.49**

The methodology implemented here is CML 2001 with the last data actualization in January 2016, which provides the results of Global Warming Potential over 100 years in kg CO_2 equivalent emissions (GWP 100). The concept of GWP 100 refers to the equivalence in all the emissions released in the process that cause hazardous effects in a period of 100 years. The comparative results of the carbon footprint from the cradle-to-gate analysis with a batch of 600 parts between CM and AM are illustrated in Fig. 26**.**

According to the results, the directly and indirectly energy consumed in the process of manufacturing is the greatest part of the total life cycle of a turbine blade. Conventional Manufacturing has a total of 9772.58 kg CO_2 and Additive Manufacturing a total of 7010.77 kg CO_2. Again, in the assessment of both alternatives, we can see that Additive Manufacturing achieves less Global Warning Emissions with a reduction of 22%.

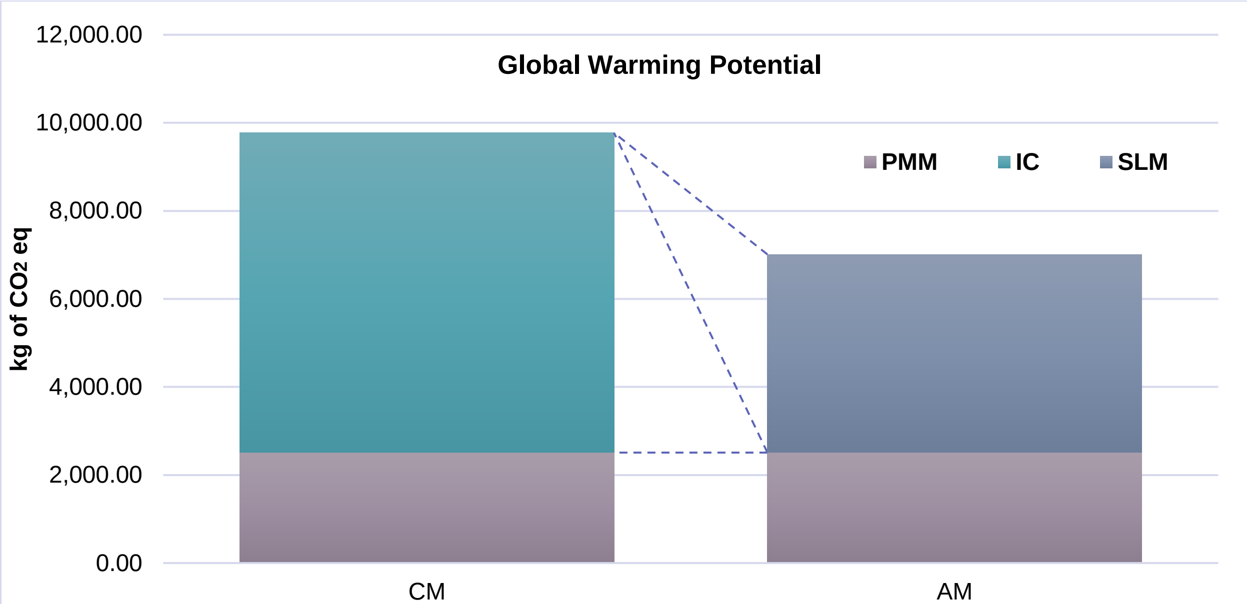


Fig. 26 Comparison of carbon footprint, based in CML 2001-Jan 2016, GWP 100.

3.1.3. Environmental Comparison Measurement

To understand the comparison results between CM and AM is providing the benefits from an environmental point of view. The following equation contributes to the make-decision of which technology used. The interpretation of results is expressed as: below a value 1 it is a more significant benefit in the used of AM; above a value 1, it is more effective to continue using CM. If the results are equal to 1, then both technologies are similar in terms of environmental impact.

$$R = \frac{EI_{AM}}{EI_{CM}} \quad (26)$$

Where R is the ratio of the indicators, EI_{AM} is the environmental impact of additive manufacturing and EI_{CM} is the environmental impact of conventional manufacturing.

After the application of the equation upside, the results are shown in Table 24, where none of the indicators have more benefits in CM, but the environmental impacts of Abiotic depletion elements and Human Toxicity with non-cancer effects have a similar impact between AM and CM.

The toxicity potential of Global Warming, Acidification, Eutrophication, Ozone Depletion, Human health, Terrestrial and Marine ecotoxicity have benefits in the implementation of Additive Manufacturing.

Table 24
Ratio results of the environmental indicators.

Indicator	Ratio Results
Abiotic Depleiton elements	$R = \frac{6.3535}{6.3528} = 1.00011$
Abiotic Depleiton fossil	$R = \frac{73932}{108114} = 0.684$
Acidification Potential	$R = \frac{19.34}{27.40} = 0.705$
Eutrophication Potential	$R = \frac{1.79}{2.62} = 0.681$
Freshwater Aquatic Ecotoxicity Potential	$R = \frac{13.58}{19.25} = 0.705$
Global Warming Potential	$R = \frac{7010.77}{9772.58} = 0.717$
Marine Aquatic Ecotoxicity Potential	$R = \frac{776538}{1092214} = 0.710$
Ozone Layer Depleiton Potential	$R = \frac{0.00000029}{0.00000042} = 0.69$
Photochemical Ozone Creation Potential	$R = \frac{1.243}{1.757} = 0.707$
Terrestic Ecotoxicity Potential	$R = \frac{4.79}{6.78} = 0.706$
Human Toxicity Potential	$R = \frac{304.94}{432.65} = 0.704$
Human Toxicity, cancer effects	$R = \frac{0.0000054}{0.0000077} = 0.701$
Human Toxicity, non-cancer effects	$R = \frac{0.000019}{0.000031} = 0.612$

Chapter 4: Conclusions

The present study provides an environmental analysis of Selective Laser Melting (SLM) and compares it with Conventional Manufacturing that applies Investment Casting Techniques for Turbine Blades Manufacturing. The resultant analysis shows that it is possible to reduce global warming and energy consumption with the proposed Additive Manufacturing based process plan. The analysis shows that the reduction of the carbon footprint and environmental impact in the use of Additive Manufacturing is of approximately 22% in comparison to Conventional Manufacturing. The observation of the results also shows that the energy consumption to manufacture a batch of 600 turbine blade parts conventionally is distinctly higher than with Additive Manufacturing. Therefore, this last has a quantified potential to reduce the environmental impacts and to reduce the carbon footprint.

Design for Manufacturing and Manufacturing Process Planning decisions can optimize many factors for the whole product lifecycle. The collection of data of this work can be a piece of crucial information for manufacturing companies in order to have a greater understanding of the relationship between emergent technologies and the environmental impacts. The present study has implications in decision-making because from our point of view data and information will help to companies with similar manufacturing process plans derived from similar parts regarding geometry and material. Design engineers will also have further information apart from the functional and mechanical performances advantages of powder bed fusion technologies.

We could add that the findings also support other studies that recommend the adoption of Additive Manufacturing in order not only to improve design features but also to reduce the environmental impact in the aerospace parts manufacturing. The implementation of AM technologies to produce aerospace components can improve the process not only in sustainability issues but also in technological ones. This emerging technology that is available now will replace some stages of production processes, thus ensuring optimization and high productivity to reduce the companies supply chain cost and delivery times.

4.1. Future Work

Results of the carbon footprint concerning the production time of units produced are shown in Fig. 27. We can observe in the figure below that in this case of study the additive manufacturing doesn't save production time in comparison with conventional manufacturing. Calculating the forecast over 2800 unit produced (regarding global warming potential), the AM have less harmful toxicity, but not in the case of production time-saving. The production time estimated for AM is 99 weeks and 21 weeks for CM.

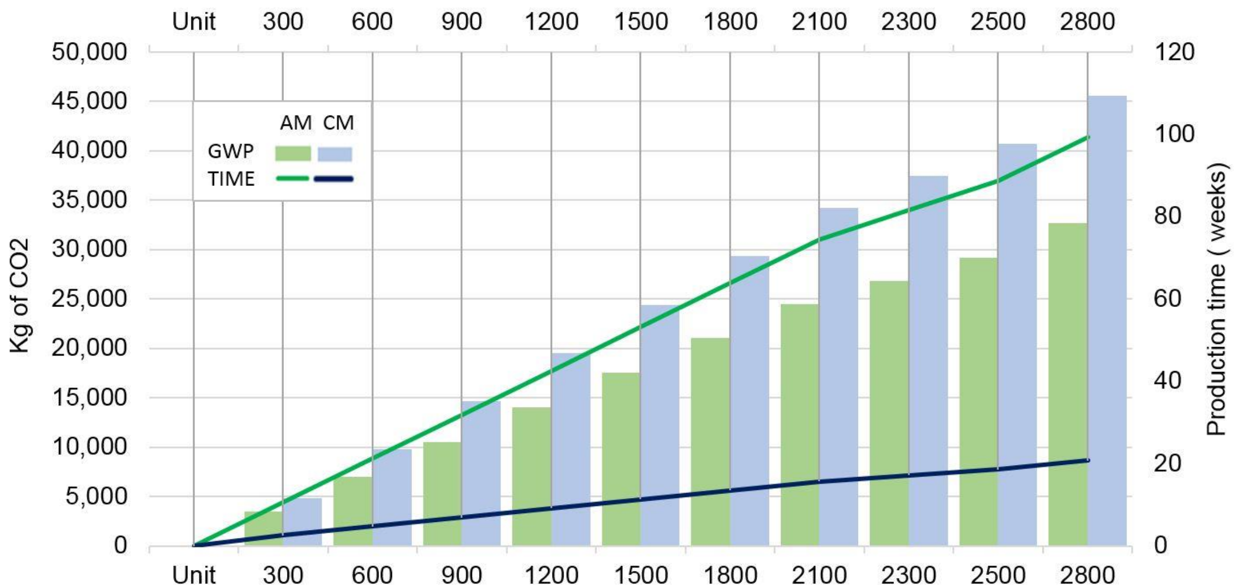


Fig. 27. Results of the carbon footprint concerning the production time of units produced.

In further studies, more work is needed to analyze the sustainability and sensitivity results regarding a modification of process parameters. For example, within the selected additive manufacturing machine we can adjust parameters like laser power, exposure time, point distance and building speed. A design of experiments will allow optimizing the environmental metrics beyond the initial results. The part geometry and surface quality requirements are also key issues when selecting the process because the energy consumption is affected by processing time.

In Fig. 28 it is shown the improvement of surface quality in 3D blade prototypes, their mechanicals test confirm that aren't competitive in terms of porosity, density, stress test and tensile test. During the SLM process, pores and cracks may form in the sample; they may result from internal stresses owing to temperature gradients in different parts, inappropriate processing parameters and use of poor quality metallic powders. To reduce the porosity and increase the density a Hot Isostatic Pressing (HIP) is proposed. The HIP treatment seems to be necessary when highly demanding components in terms of mechanical or fatigue behavior are produced. The environmental impacts of AM will increase if it is added the toxicity potential of HIP process.

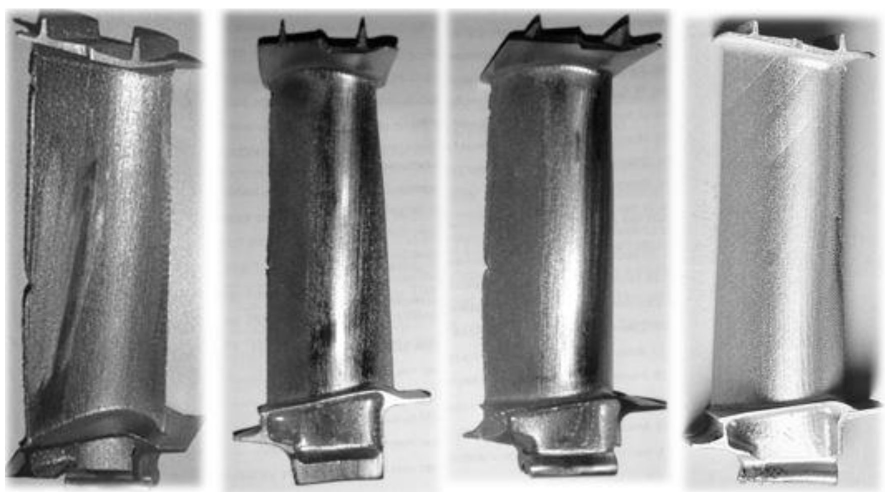


Fig. 28. Prototypes of 3D blades.

Summarizing the case of study, the Additive Manufacturing is competitive in terms of:

Sustainability

- Less energy consumption and harmful toxicity.
- Environmental productivity regarding carbon footprint.

Manufacturing

- The selection of the correct parameters can improve the reduction of weight, but not in case of time-savings.
- It is needed more studies to equal the mechanical properties of the 3D turbine blade and the conventional casting.

Appendix A: List of Abbreviations

Table 25
The abbreviations are in order of the alphabet.

	Nomenclature
Abiotic Depleiton elements	ADP elements
Abiotic Depletion fossil	ADP fossil
Acidification moles	AP moles
Acidification Potential	AP
Additive Manufacturing	AM
Carbon Dioxide	CO_2
Eutrophication Potential	EP
Fluorchloromethane	R11
Freshwater Aquatic Ecotoxicity Potential	FAETP
Global Warming Potential	GWP
Greenhouse gas	GHG
Human Toxicity Potential	HTP
Human Toxicity, cancer effects	HT cancer effects
Human Toxicity, non-cancer effects	HT non-cancer effects
International Organization for Standardization	ISO
Kilo volt-ampere reactive hour	KVARH
Kilo volt-ampere-hour	KVAH
Kilowatt-hour	KWH
Life Cycle Assessment	LCA
Life Cycle Impact Assessment	LCIA
Life Cycle Inventory Analysis	LCI
Marine Aquatic Ecotoxicity Potential	MAETP
Methane	CH_4
Ozone Layer Depletion Potential	ODP
Photochemical Ozone Creation Potential	POCP
Power factor	PF
Selective Laser Melting	SLM
Sulfur Dioxide	SO_2
Terrestic Ecotoxicity Potential	TETP

Appendix B: Materials for Metal Additive Manufacturing in Aerospace Industry

Table 26
General materials characteristics that can be used for metal AM in Aerospace Industry.

Material	Characteristics
Aluminum AlSi10Mg	AlSi10Mg is a typical casting alloy with good casting properties and is typically used for cast parts with thin walls and complex geometry. It offers good strength, hardness, and dynamic properties and is therefore also used for parts subject to high loads. Parts in EOS Aluminum AlSi10Mg are ideal for applications which require a combination of good thermal properties and low weight, e.g., motorsports and aerospace interior.
Nickel Alloy IN625	It is expected to have good corrosion resistance. Especially sea-water applications require high pitting and crevice corrosion resistance, stress-corrosion resistance against chloride-ions, high tensile and corrosion-fatigue strength. However, corrosion resistance has not been verified yet, and therefore it is recommended to conduct relevant corrosion tests and studies prior to use in the specific corrosive environment.
Nickel Alloy IN718	Because of its strength, INCONEL alloy 718 is more resistant than most materials to deformation during hot forming. This kind of precipitation hardening nickel-chromium alloy is characterized by having good tensile, fatigue, creep, and rupture strength at temperatures up to 700 °C (1290 °F), heat-resistant, outstanding corrosion resistance
Stainless Steel 316L	Parts built from Stainless Steel 316L can be machined, shot peened and polished in as-built or stress relieved (AMS2759) states if required. Solution annealing is not necessary because the mechanical properties of the as-built state are showing desired values (ASTM A403). Parts are not ideal in the temperature range 427-816°C.
Titanium Ti64	This light alloy is characterized by having excellent mechanical properties and corrosion resistance combined with low specific weight and biocompatibility. Lightweight with high specific strength (strength per density), Corrosion resistance, commonly used in biomedical applications, Laser-sintered parts fulfill requirements of ASTM F1472 (for Ti6Al4V) and ASTM F136 (for Ti6Al4V ELI) regarding the maximum concentration of impurities, very good adhesion (cell growth tested with good results).

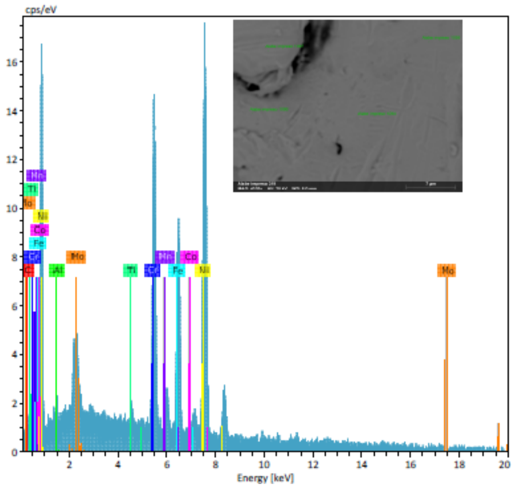
Table 27
Mechanical properties of the metal powders that can be used in AM.

Material	Tensile strength		Yield strength	
	As built	*Heat treated*	*As built*	*Heat treated*
Aluminum AlSi10Mg	460 ± 20 Mpa	345 ± 100 MPa	270 ± 10MPa	230 ± 15MPa
Nickel Alloy IN625	990 ± 50 Mpa	1040 ± 100 Mpa	725 ± 50 Mpa	720 ± 100 MPa
Nickel Alloy IN718	871 ± 43 Mpa	1170 ± 50 MPa	N. I.	970 ± 50 MPa
Stainless Steel 316L	590 MPa	N. I.	500 Mpa	N. I.
Titanium Ti64	1290 ± 50 MPa	Min. 930 MPa	1140 ± 50 MPa	min. 930 MPa
Material	**Modulus of elasticity**		**Elongation at break**	
	As built	*Heat treated*	*As built*	*Heat treated*
Aluminum AlSi10Mg	75 ± 10GPa	75 ± 10GPa	(9 ± 2) %	(12 ± 2) %
Nickel Alloy IN625	170 ± 20 Gpa	170 ± 20 Gpa	(35 ± 5) %	min. 30%, typ. (35 ± 5) %
Nickel Alloy IN718	167 ± 40 Gpa	167 ± 40 Gpa	N. I.	16 ± 3 %
Stainless Steel 316L	N. I.	N. I.	46.7%	N. I.
Titanium Ti64	110 ± 15 Gpa	110 ± 15 Gpa	(7 ± 3) %	Min. 10%

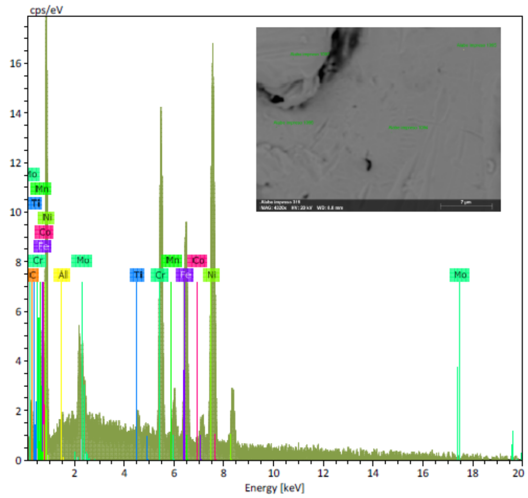
Table 28
Physical properties of the types of metal powder that may be used in AM.

Material	Part accuracy	Min. Wall thickness	Surface roughness
Aluminum AlSi10Mg	± 100µm	0.3 – 0.4 mm	Ra 6 - 10 µm, Rz 30 - 40 µm
Nickel Alloy IN625	Small parts: ± 40 - 60µm Large parts: ± 0.2%	0.3 - 0.4 mm	Ra 4 – 6.5 µm Rz 20 - 50 µm
Nickel Alloy IN718	Small parts: ±40–60µm Large parts: ± 2%	0.3 - 0.4 mm	Ra 4 – 6.5 µm Rz 20 - 50 µm
Stainless Steel 316L	± 20-50µm	0.3 - 0.4 mm	Ra 13 ±5 µm Rz 80 ±20 µm
Titanium Ti64	± 50µm	0.3 – 0.4 mm	Ra 9 - 12 µm Rz 40 - 80 µm
Material	**Volume rate**	**Density**	**Hardness**
Aluminum AlSi10Mg	7.4 mm³/s (26.6 cm³/h)	2.67 g/cm³	approx. 119 ± 5HBW
Nickel Alloy IN625	2 mm³/s (7.2 cm³/h)	8.4 g/cm³	approx. 30HRC
Nickel Alloy IN718	2 mm³/s (7.2 cm³/h)	8.15 g/cm³	approx. 30HRC
Stainless Steel 316L	2 mm³/s (7.2 cm³/h)	7.9 g/cm³	approx. 89HRB
Titanium Ti64	3.75 mm³/s (13.5 cm³/h)	4.41 g/cm³	320 ± 12 HV5

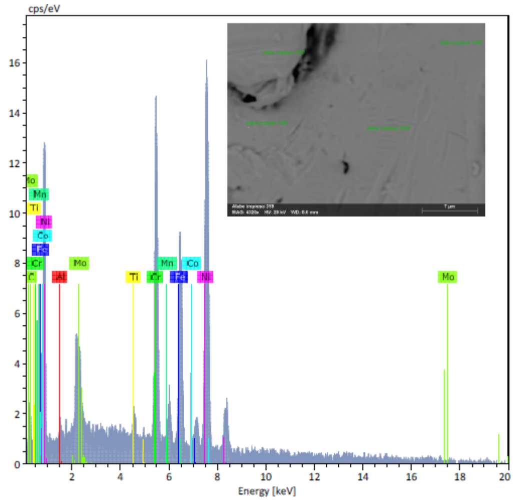
Appendix C: Results of analysis SEM



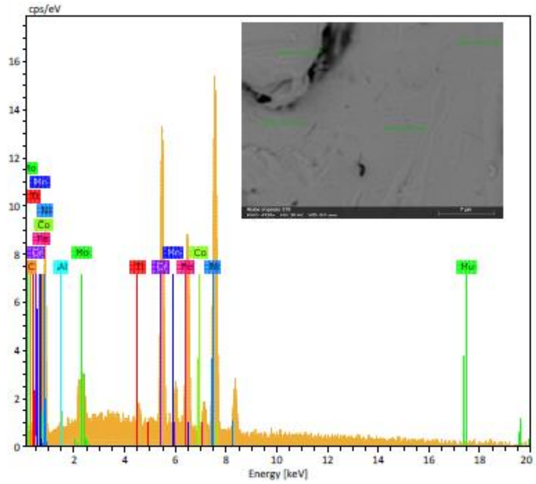
(a)



(b)



(c)



(d)

Fig. 29. Results of analysis SEM in four different points of a 3D turbine blade.

Element	At. No.	Line s.	Netto	Mass [%]	Mass Norm. [%]
Nickel	28	K-Serie	4586	20.49	44.88
Chromium	24	K-Serie	3482	8.33	18.25
Iron	26	K-Serie	2514	8.09	17.71
Molybdenum	42	L-Serie	1255	3.60	7.88
Carbon	6	K-Serie	132	2.26	4.95
Cobalt	27	K-Serie	450	1.82	3.98
Titanium	22	K-Serie	224	0.57	1.24
Aluminium	13	K-Serie	165	0.51	1.11
Manganese	25	K-Serie	0	0.00	0.00
			Sum	45.66	100.00

(a)

Element	At. No.	Line s.	Netto	Mass [%]	Mass Norm. [%]
Nickel	28	K-Serie	4532	21.09	44.09
Chromium	24	K-Serie	3424	9.09	19.01
Iron	26	K-Serie	2360	8.17	17.08
Carbon	6	K-Serie	221	3.87	8.10
Molybdenum	42	L-Serie	1202	3.27	6.84
Cobalt	27	K-Serie	466	1.99	4.17
Titanium	22	K-Serie	98	0.22	0.47
Aluminium	13	K-Serie	42	0.12	0.24
Manganese	25	K-Serie	0	0.00	0.00
			Sum	47.83	100.00

(b)

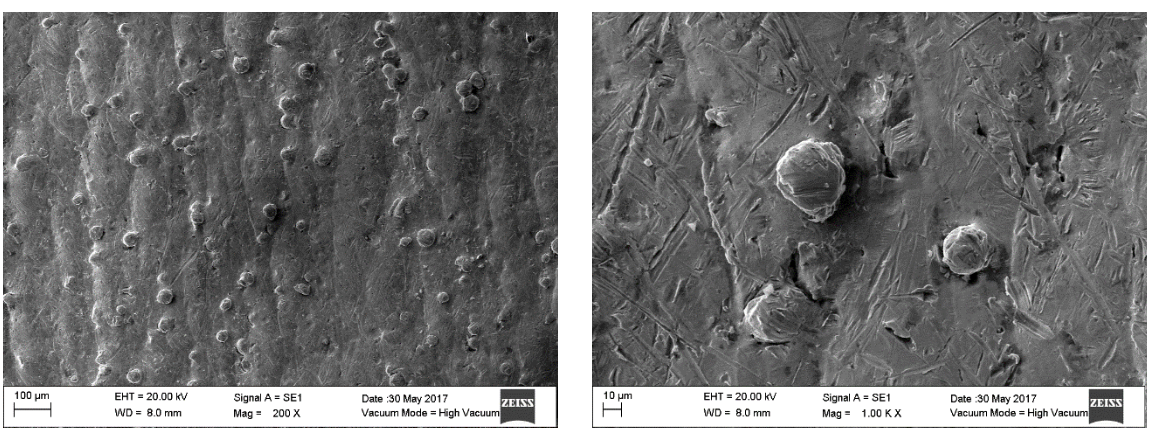
Element	At. No.	Line s.	Netto	Mass [%]	Mass Norm. [%]
Nickel	28	K-Serie	4819	23.36	45.51
Chromium	24	K-Serie	3675	8.14	15.86
Iron	26	K-Serie	2444	7.79	15.18
Carbon	6	K-Serie	273	4.66	9.08
Molybdenum	42	L-Serie	1294	3.99	7.78
Cobalt	27	K-Serie	545	2.29	4.45
Titanium	22	K-Serie	292	0.70	1.36
Aluminium	13	K-Serie	101	0.40	0.78
Manganese	25	K-Serie	0	0.00	0.00
			Sum	51.33	100.00

(c)

Element	At. No.	Line s.	Netto	Mass [%]	Mass Norm. [%]
Nickel	28	K-Serie	5397	24.53	45.17
Chromium	24	K-Serie	4301	10.78	19.85
Iron	26	K-Serie	3028	10.09	18.58
Molybdenum	42	L-Serie	1014	3.76	6.93
Cobalt	27	K-Serie	599	2.49	4.58
Carbon	6	K-Serie	91	1.60	2.95
Manganese	25	K-Serie	249	0.71	1.30
Aluminium	13	K-Serie	52	0.26	0.49
Titanium	22	K-Serie	36	0.09	0.16
			Sum	54.31	100.00

(d)

Fig. 30. Analysis SEM of chemical composition in four different points of a 3D turbine blade.



(a) **(b)**

Fig. 31. Images of a 3D turbine blade at different scale obtained with an SEM Microscope (a) 100µm, Mag= 200 X (b) 10µm, Mag= 1.00 K X

Appendix D: Process flow diagram

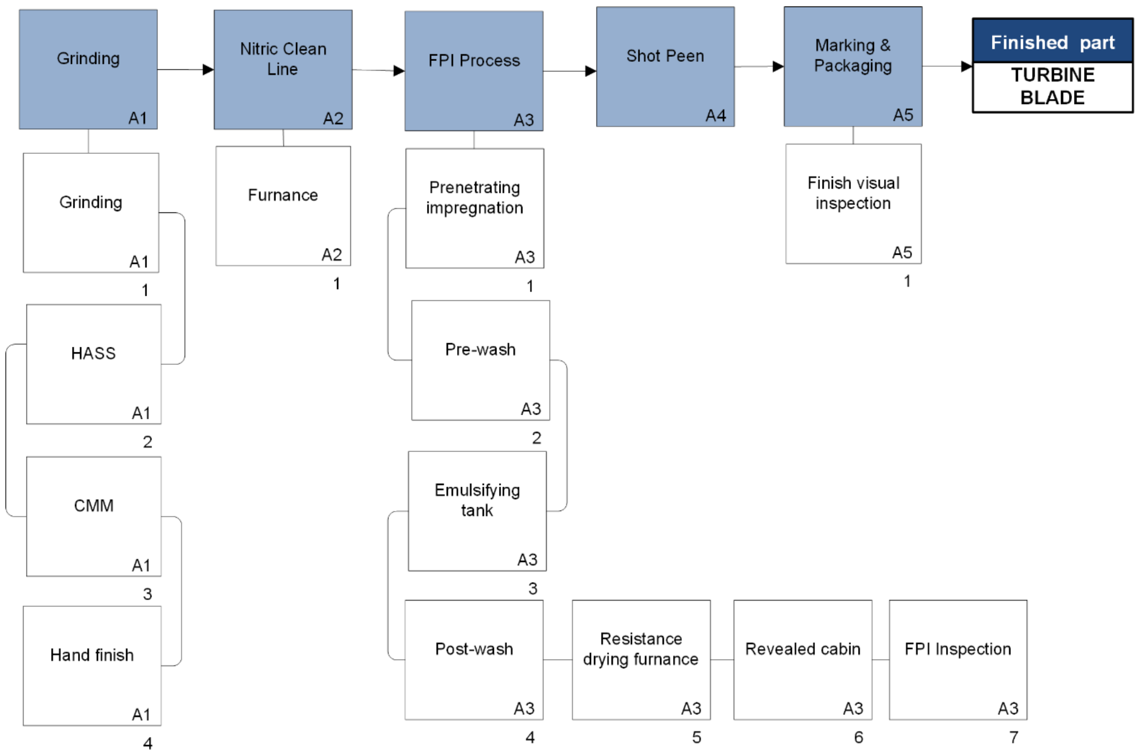


Fig. 32. Precision Machining Process and its operations.

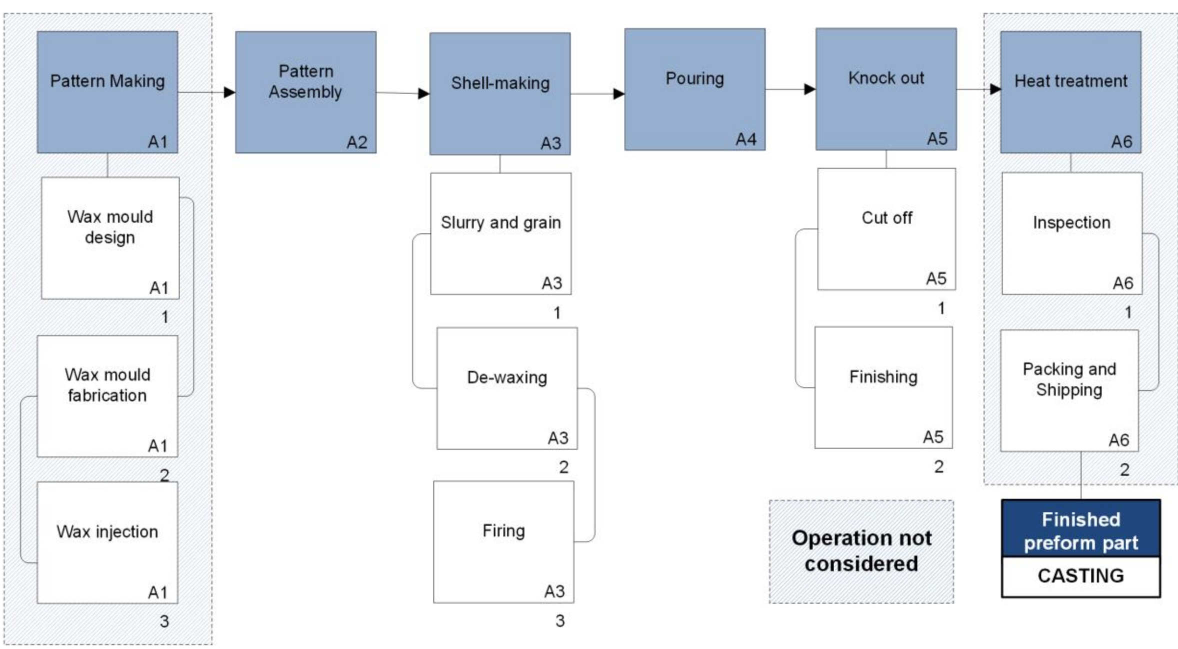


Fig. 33. Investment Casting Process and its operations.

Appendix E: Energy Consumption

Table 29
Energy consumption of Investment Casting Process.

Stages	Machine	Notes	A	V	PF	3√	kVA	kWh	kWh	kWh 600pz
Raw Metal	Fabrication of raw metal	Metal in bar stock form (Margolis et al.)					*Wilson et al.*			**5 202.07**
Patterns making tree	Wax model design	No Considered	N.C	N.C	N.C	N.C	N.C	N.C	N.C	**443.93**
	Wax mold fabrication		16	0.22	0.90	1.73	5.48	4.93	4.93	
	Wax injection		16	0.22	0.90	1.73	5.48	4.93	4.93	
	Pattern assembly		16	0.22	0.90	1.73	5.48	4.93	4.93	
Shell-making	Refractory slurry and grain	8 times	32	0.48	0.90	1.73	23.92	21.52	43.05	**4 842.89**
	Dry	3 hours	16	0.22	0.90	1.73	5.48	4.93	118.38	
Pouring	Dewaxing	Control cabinet load	103	0.46	0.90	1.73	73.77	66.39	336.48	**3 230.97**
		Heater power supply load	158	0.46	0.90	1.73	113.16	101.85		
		Maximum combined full load	261	0.46	0.90	1.73	186.93	168.24		
	Firing	Cleaning - 2 hours				*Honeywell - Furnance #5*			632.81	
	Pouring	Melted metal	522	0.48	0.90	1.73	390.12	351.11	351.11	**1 170.37**
		Molten metal (Margolis et al.)								**17.46**
Cleaning & Finishing	Knock out / shakeout	Lose 0,80 kg of ceramic	7	0.22	0.90	0	1.39	1.25	1.25	**8.69**
	Cleaning rotatory system	3 min x 1 tree	7	0.22	0.90	0	1.39	1.25	1.25	
	Cut off	Cut tool	7	0.40	0.90	0	2.52	2.27	2.27	
	Grinding	Scrap	7	0.40	0.90	1.73	4.36	3.92	3.92	
									TOTAL	**14 916.4**

Table 30
Energy consumption of Precision Machining Process.

Area	Machine	Notes	A	V	PF	3√	kVA	kWh	kWh	kWh 600Pz
Grinding and HF	Blohm 8-1 Grind Root Form	Grinder Machine	16	0.48	0.90	1.73	11.97	10.77	19.876	**1 490.70**
		Coolant system	7	0.48	0.73	1.73	4.25	3.10		
		Vertical auxiliary grinding	N.I	N.I	N.I	N.I	N.I	6.00		
	Blohm 8-2 Tip/slot	Grinder Machine	16	0.48	0.90	1.73	11.97	10.77	19.876	**1 490.70**
		Coolant system	7	0.48	0.73	1.73	4.25	3.10		
		Auxiliary grinding spindle	N.I	N.I	N.I	N.I	N.I	6.00		
	Blohm 8-3 Z Form	Grinder Machine	16	0.48	0.90	1.73	11.97	10.77	19.876	**1 490.70**
		Coolant system	7	0.48	0.73	1.73	4.25	3.10		
		Auxiliary grinding spindle	N.I	N.I	N.I	N.I	N.I	6.00		
	HASS	Machine	3	0.12	0.90	1.73	0.66	0.60	0.597	**8.53**
	CMM	Power supply of 2 outlets	16	0.11	0.90	1.73	2.74	2.47	5.269	**263.46**
		CMM Machine	5.8	0.11	0.90	1.73	1.00	0.90		
		Heat generated	6.5	0.11	0.90	1.73	1.11	1.00		
		Peripherals Workstation	5.8	0.11	0.90	1.73	1.00	0.90		
	Hand Finish	Burr	7	0.10	0.90	1.73	1.09	0.98	0.982	**73.66**
Nitric Clean Line	Furnance		7	0.46	0.55	1.73	3.07	1.69	36.45	**13.50**
	Pumping system		4.5	0.48	0.50	1.73	1.87	1.87		**14.96**
	Scrubber VIRON		6	0.48	0.77	1.73	3.84	5.92		**47.32**
	Feeding boards	Power	6.5	0.22	0.55	1.73	1.36	7.49		**59.94**
	Tank (per 10)	10.00	0.5	0.48	0.55	1.73	0.23	1.26		**10.06**
FPI Process	Penetrating impregnation		0.3	0.48	0.90	1.73	0.22	0.20	14.83	**0.81**
	Prewash		0.3	0.12	0.90	1.73	0.05	0.05		**0.19**
	Emulsifying tank		0.3	0.44	0.90	1.73	0.21	0.19		**0.74**
	Postwash		3.5	0.22	0.90	1.73	1.20	1.08		**4.32**
	Resistance drying furnace		20	0.46	0.90	1.73	14.34	12.91		**51.63**

	Revealed cabin		0.3	0.48	0.90	1.73	0.22	0.20		**0.81**
	FPI Inspection		0.3	0.48	0.90	1.73	0.22	0.20		**0.81**
Final Operation	Shot Peen	Machine	18.5	0.48	0.44	1.73	6.77	2.98	4.44	**22.19**
		Wire Control	2	0.16	0.90	1.73	0.50	0.45		
		Touch panel	1	0.24	0.90	1.73	0.37	0.34		
		Touch panel 2	2	0.24	0.90	1.73	0.75	0.67		
	Part Marking	Laser Marking System	3	0.13	0.90	1.41	0.25	0.23	0.23	**6.75**
	Finish Visual Inspection		0	0	0.90	1.73	0	0	0	**0**
	Nitric Clean Second Line	4.00	0.3	0.48	0.90	1.73	0.22	0.20	14.58	**116.63**
	Packaging		0	0	0.90	1.73	0	0	0	**0**
								TOTAL	**136.99**	**5 168.41**

Table 31
Energy consumption of Selective Laser Melting Process

Machine	A	V	PF	3√	kVA	kWh	kWh	kWh 600pz
Feeding boards	32	0.40	0.40	1.73	8.87	3.547	28.141	**8 442.43**
Chiller	16	0.40	0.40	1.73	4.43	1.774	1.552	**465.58**
Powder Sieving Station	16	0.40	0.09	0	0.58	0.052	0.030	**9.07**
Nitrogen-Generator	10	0.23	0.40	0	0.92	0.368	0.515	**154.56**
EdNiCon Workbench	10	0.23	0.09	0	0.21	0.019	0.016	**4.89**
Atomization of powder								**35.45**
							Total	**9 111.97**

Appendix F: Process diagram using GaBi Software.

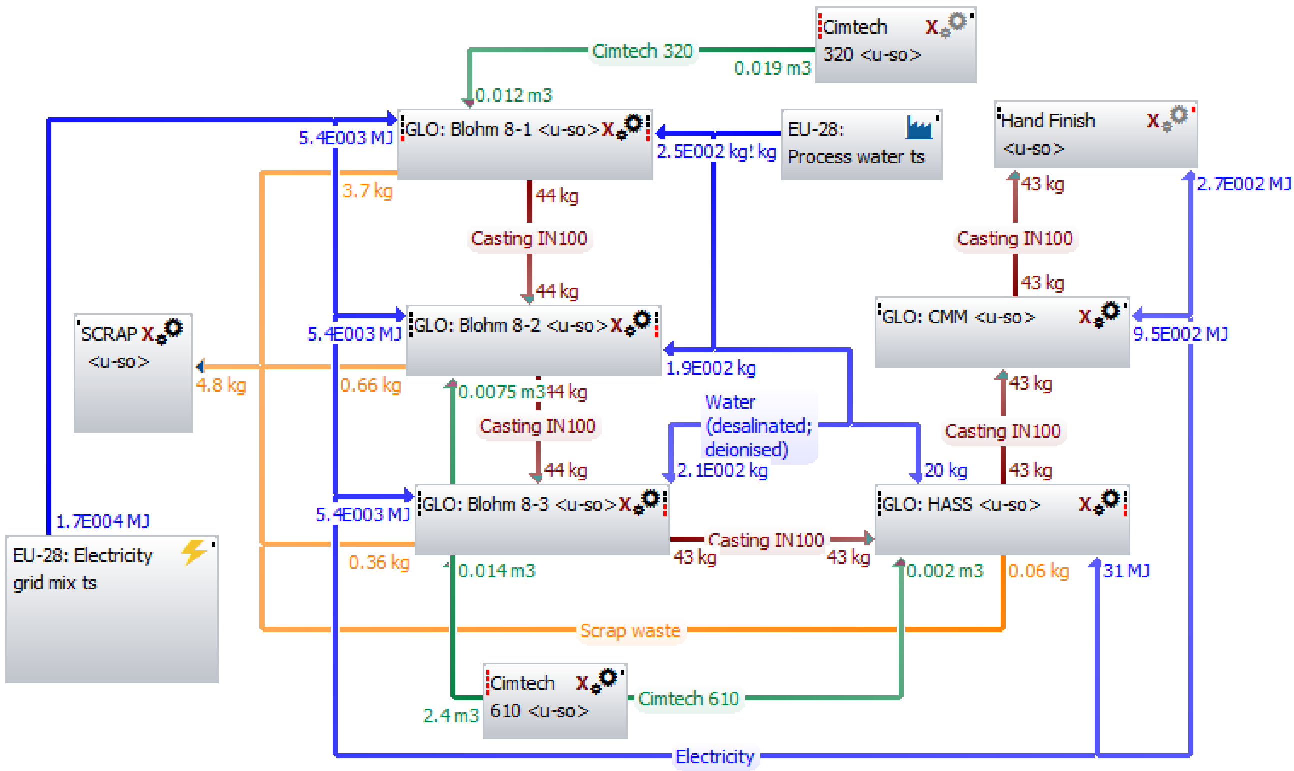


Fig. 34. Process flow diagram of Grinding and Hand Finish Area.

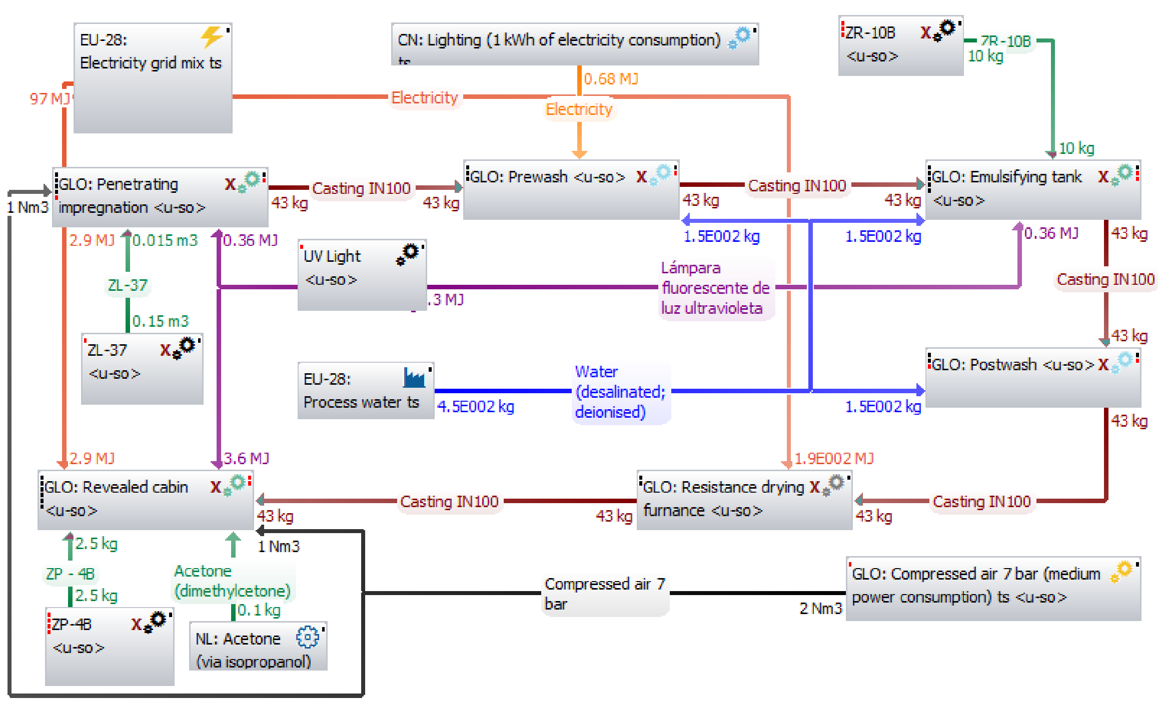


Fig. 35. Process flow diagram of Fluorescents Process Inspection.

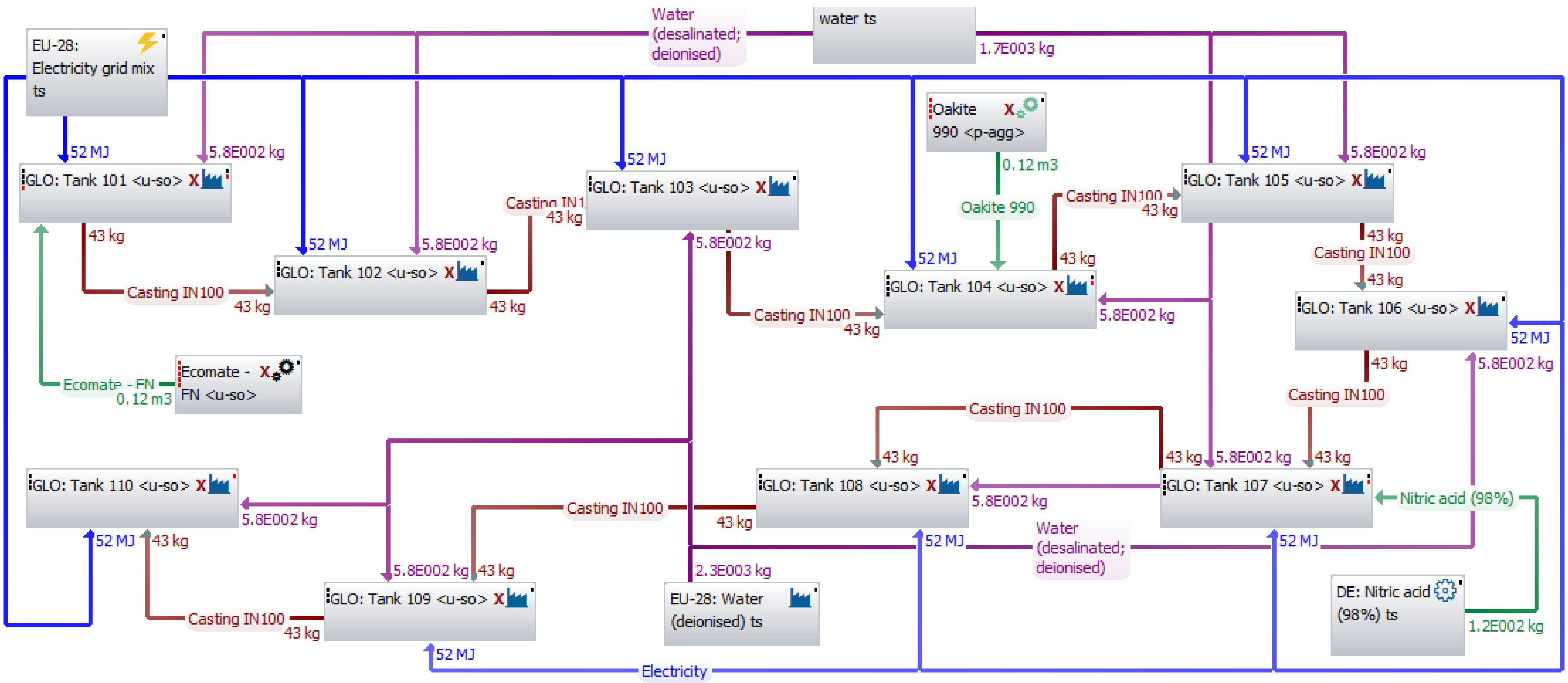


Fig. 36. Process flow diagram of Nitric Clean Inspection.

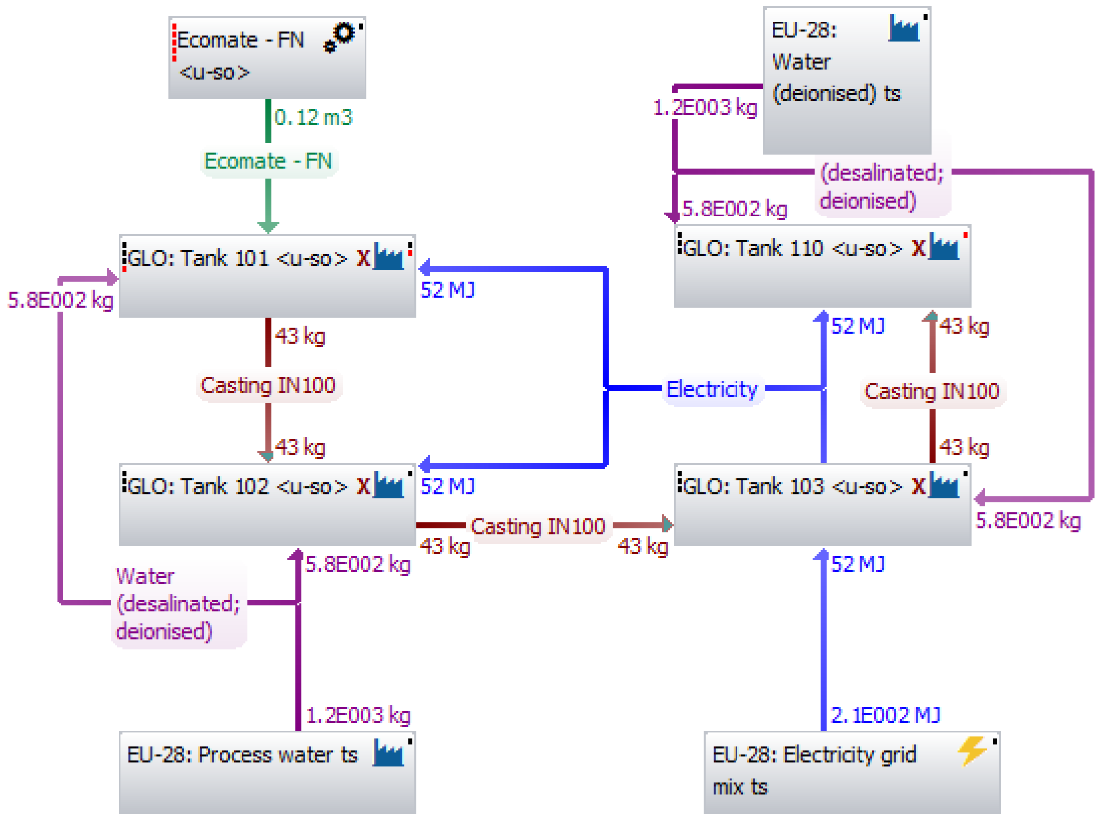


Fig. 37. Process flow diagram of Nitric Clean-Second Line Inspection.

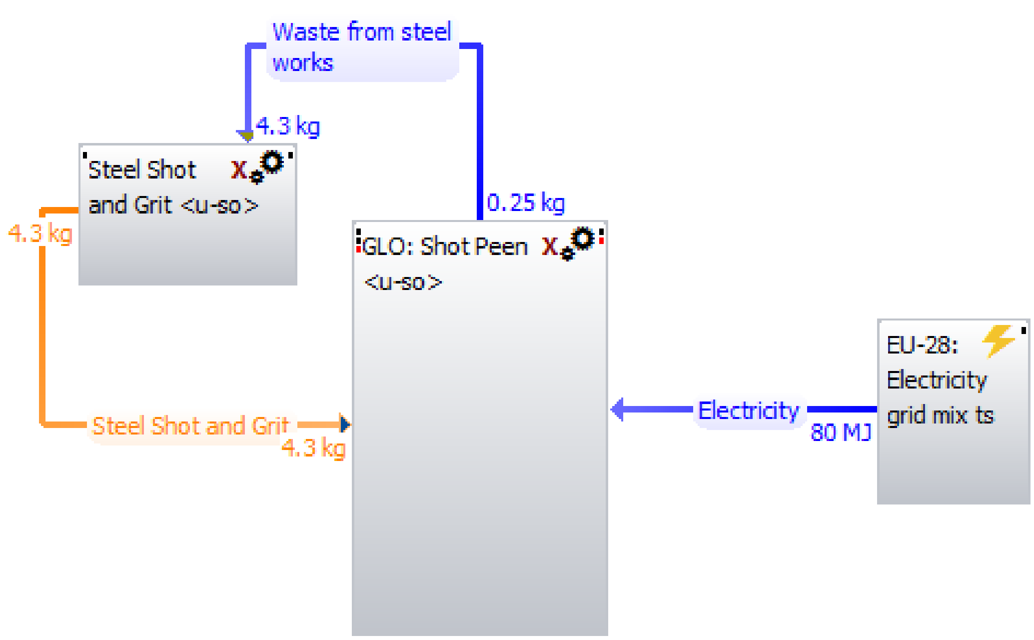


Fig. 38. Process flow diagram of Shot Peen Process.

Appendix G: Environmental Impacts

Table 32
Factors for Process Emissions - Greenhouse Gases Listed in the Kyoto Protocol

Emission	Chemical formula	Conversion Factor (GWP_{100})
Carbon Dioxide	CO2	1
Methane	CH4	21
Nitrous Oxide	N2O	310
HFC-23	CHF3	11700
HFC-32	CH2F2	650
HFC-41	CH3F	150
HFC-125	CHF2CF3	2800
HFC-134	CHF2CHF2	1000
HFC-134a	CH2FCF3	1300
HFC-143	CH3CF3	300
HFC-143a	CH3CHF2	3800
HFC-152a	CF3CHFCF3	140
HFC-227ea	CF3CH2CF3	2900
HFC-236fa	CHF2CH2CF3	6300
HFC-245fa	CH3CF2CH2CF3	560
HFC-43-I0mee	CF3CHFCHFCF2CF3	1300
Perfluoromethane (PFC-14)	CF4	6500
Perfluoroethane (PFC-116)	C2F6	9200
Perfluoropropane (PFC-218)	C3F8	7000
Perfluorocyclobutane (PFC-318)	c-C4F8	8700
Perfluorobutane (PFC-3-1-10)	C4F10	7000
Perfluoropentane (PFC-4-1-12)	C5F12	7500
Perfluorohexane (PFC-5-1-14)	C6F14	7400
Sulfur hexafluoride	SF6	23900

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