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Life cycle assessment of metal products: A comparison between wire arc additive manufacturing and CNC milling

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ABSTRACT

The industrial progress made throughout these years has led to great results in terms of producing fast and with good quality. However, the impacts related to that production, whether these are environmental, economic, or social have been, at times, neglected. The manufacturing sector, as one of the most polluting sector, felt the urge to adapt to this industrial progress and find ways to produce with improved sustainability goals without compromising the quality of the final product and the production time. Industry easily understood the benefits of this greener approach, and, with this, new sustainable technologies started to emerge. Additive Manufacturing (AM) is one of those technologies that provide alternative sustainable paths to traditional manufacturing. In order to generalize the benefits of AM production in terms of sustainability, when compared to traditional processes, further investigations must be conducted. In this sense, the proposed work has the intention of finding the environmental impacts associated with a particular AM technique for the fabrication of metal parts, Wire Arc Additive Manufacturing (WAAM). A practical work based on the production of three different complexity metal parts considering an additive (WAAM) and a subtractive (Computer Numerical Control (CNC) Milling) manufacturing process is developed. To quantify the environmental impacts of both processes, the author resorts to the Life Cycle Assessment (LCA) methodology. The assessment is conducted in the SimaPro 9.2 software, accordingly to ISO 14044:2006 standard. The results allow a comparison between both types of manufacturing and enable the suggestion of measures to decrease the environmental footprint of WAAM. It was found that WAAM approach leads to a material saving ranging between 40% and 70% and an environmental impact reduction in the range of 12%–47%, compared to the subtractive approach for fabricating the 3 geometries considered in this study. The conclusions obtained are specific to this particular application and, once more, it is acknowledged that in order to reach a global understanding relative to this technology's environmental implications, extra research still needs to be made.

1. Introduction

Over the past years, with industrial progress, there has been intense exploitation of natural resources that has taken drastic proportions and started to cause considerable impacts on the environment, the economy, and society (Priarone et al., 2021). This has led to a restructuring of society's thinking where environmental awareness is prioritized and the urge to make several changes to achieve a sustainable way of living arises. Apart from the pressure made consumers to produce greener products (Shi and Faludi, 2020), stricter environmental legislation was created to constrain companies to comply with a more sustainable production process (Godina et al., 2020), (Naghshineh et al., 2020). As one of the most polluting sectors, the manufacturing sector needed to take action and adapt according to these major changes. One of the main

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challenges of this sector is finding out how to produce faster, using less raw material, and without compromising the quality of the final product (Ma et al., 2018).

Once industries started to adapt the production processes to a greener mentality (reduction of material waste, consumption of resources, energy, and emissions of CO_2 and other greenhouse gases), they realized that, in the long term, could also benefit monetarily from these changes. For example, concepts like the circular economy, where the preservation of natural resources (many of them being raw materials) is a priority, started to be implemented and can lead industries to more effective and efficient production, without disregarding the environmental impacts (Priarone et al., 2021), (Siva Rama Krishna e and Srikanth, 2021). In this sense, with the need of creating new sustainable technologies and improving the ones that already exist to obtain higher efficiency, the fourth industrial revolution, also known as Industry 4.0 arises (Burkhart and Aurich, 2015). As one of the key elements of Industry 4.0, Additive Manufacturing (AM) is seen as a revolutionary technology that incorporates sustainability into manufacturing systems and provides alternative paths to traditional manufacturing, as well as complementing it, for producing parts or products (Priarone et al., 2021), (Godina et al., 2020), (Burkhart and Aurich, 2015), (Gao et al., 2021).

AM consists of producing physical objects from 3D computer-aided design (CAD) files by building layers of material (Ma et al., 2018), (Gao et al., 2021), (Lúcio, 2017). The 3D printing production process has become increasingly popular due to its ability to optimize the production of a product or part through weight reduction, customization, and complex shapes printing, without the need for additional resources (Böckin e and Tillman, 2019), (Lúcio, 2017), (Pfähler et al., 2019). In addition, this technology also allows the reduction of several costs, for example, costs of production, logistics, inventories, development, and industrialization of a new product, and the reduction of time-to-market (Godina et al., 2020), (Pfähler et al., 2019). Not devaluing the advantages, it is worth noting that this technology also has some problems, mainly in terms of environmental impacts (high energy consumption) and production constraints (non-appropriate for mass production). These limitations need to be further exploited to fulfill the main goal of finding a solution that optimizes the production process, providing not only high-quality products but also reducing the costs and environmental impacts. As such, researchers have developed tools that facilitate analysis and subsequent evaluation of the environmental impacts, LCA being one of them (Kokare et al., 2023).

The present paper contributes to developments in this field since it resorts to the LCA methodology to characterize the environmental impacts associated with the production of metallic parts through both traditional (CNC Milling) and alternative (WAAM) manufacturing processes. The practical case is based on the production of three different complexity metal parts: a gear, a cylinder, and an S shape. The characterization of their environmental impacts was made through the SimaPro 9.2 software. Additionally, the aim is to compare both processes and draw conclusions relative to their sustainability potential for this particular application, as well as identify improvements to be implemented.

The paper is structured into six sections. Section 2, Literature review, presents the theoretical background that supports the developed work. It gives an introductory notion on WAAM and approaches the studies that already have been made regarding the application of the LCA methodology in this process. In Section 3 the LCA methodology is explained and further detailed, accordingly to ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines (ISO/TC 207, 2006). In Section 4 Case Studies, a characterization is made of the environmental impacts associated with the production of three different geometry metal parts through CNC Milling and WAAM technologies, considering the LCA methodology previously approached and its requirements and guidelines. Therefore, a specification of the goal and scope of the study is made, along with the assumptions and limitations, the identification of the functional unit and the system boundaries and, finally, a life cycle inventory is performed on each geometry. Section 5, Results analysed the results obtained, which enabled an understanding of the environmental impacts involved in the production of each geometry, for both considered technologies. Conclusions are drawn and based on them, suggestions to decrease the environmental impact associated with WAAM and CNC Milling are elaborated. Section 6, Conclusions, summarizes the paper's main contributions, points out the study's limitations, and presents future work recommendations

2. Literature review

2.1. Wire arc additive manufacturing

WAAM is a method that enables the creation of three-dimensional shapes through welding the materials, layer by layer, using wire feedstock and standard arc welding equipment (Bekker e and Verlinden, 2018), (Jafari et al., 2021). Fig. 1 describes the main steps that are required to produce a part by using this technique. The first step involves creating a three-dimensional representation of the part being produced using processes like computer-aided design (CAD). After that, this 3D representation should be saved in a standard format so that it can be used as an input for the slicing software. The software transforms the 3D model into 2D layers, thick enough to be precisely deposited, defines the appropriate parameters, and calculates an optimum path for depositing material. It should be noted that the parameters and the programming must be adapted depending on the specific material of the part being fabricated. Next, a computer numerical control (CNC) code with several program instructions is generated. That code will be sent as control information to the machine tool (robotic arm), specifying its motion, speed, and operations. After choosing the parameters and programming the machine, the product finally begins to be additively built layer by layer until the entire component is finished. In the majority of the cases, the part produced still has some quality requirements that need to be improved like low surface finish, and therefore, post-treatment processes are required (Singh e and Khanna, 2021).

As mentioned, to obtain a high-quality product with good mechanical features is imperative to acknowledge the inputs and outputs of the process, as well as establish the process parameters. WAAM's main inputs are the shielding gas, electricity, and welding wire. The outputs are crucial for determining how much room exists for improvement on an environmental, social, or economic level (Priarone et al., 2021), (Singh e and Khanna, 2021), (Li et al., 2022). For this technology, the outputs are the printed object, the welding spatter and the emissions to air. The specific parameters to be established are: the wire feed rate/speed, the travel/welding speed, the arc current, the voltage, the arc length, the shielding gas flow rate, the printing path strategy, the substrate temperature, the interlayer temperature, the heat input and the pre-heating process.

By being such a flexible technology, WAAM can have several applications and it is prioritized mainly in the aerospace, automotive, military, nuclear energy, marine, and mold and dies sectors (Jafari et al., 2021). Many alloys can be used as feedstock for this process; however, it is important to check the material suitability accordingly to the application in the cause. According to (Singh e and Khanna, 2021), titanium-based alloys, nickel-based superalloys, and bimetal materials are suitable for applications in the automotive, tools, molds, and marine. On the other hand, aluminium-based alloys are more appropriate for marine, corrosion resistance, high temperature, tools, and mold applications, and stainless steel-based alloys for aerospace, corrosion resistance, and high temperature.

WAAM has proven to be an advantageous process due to several characteristics, such as the following:

- With the growing environmental concerns and stricter legislations, customers started to praise companies that prioritize alternative

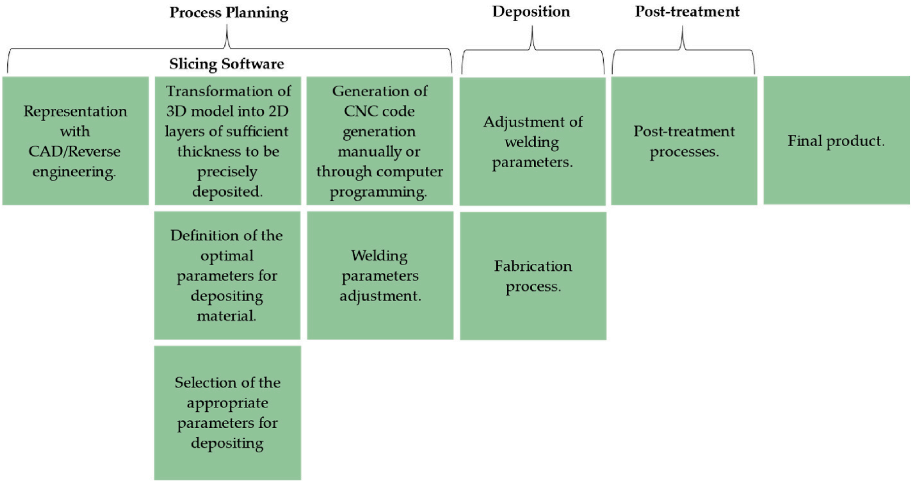

Fig. 1. WAAM steps to create a part. Adapted from (Singh e and Khanna, 2021).

manufacturing processes that lead to greener production (Mitchell, 2017).

- By allowing the creation of a product through the consequent deposition of materials in layers, this technology reduces the need for recurring additional processes to remove a substantial amount of material (Seow et al., 2020).
- This technology has the potential of producing several components, according to the customer's needs, in the same build and the ability to repair, remanufacture, and refurbish existing products with defects. With this in mind, it is notable that, not only the manufacturing costs will inevitability be lower, but also the product life cycle be extended (Priarone et al., 2021). Consequently, there will be a decrease in the stock constitution and a reduction of the supply chain complexity, since the production only occurs according to orders made.

Despite all the perks regarding the WAAM process, there are still some challenges that must be considered and tackled (Jafari et al., 2021).

- The high deposition rates lead to high levels of residual stress and consequently to distortions in the components. In this sense, more studies should be elaborated to analyze the influences of process conditions on thermal history, microstructure, and resultant mechanical and surface properties of parts.
- The high periodic heat inputs imply several characteristics such as grain growth, residual stress, delamination, warping, dimensional inaccuracy, humping, cracking, modification of the geometry of the layers and the microstructure of the material, etc., that translates into a low-quality part being produced. A better knowledge of the thermal conductivity of the material chosen as an input for the process and of the amount of heat that's applied during the process, as well as the base material's heat material might prevent some of these issues. If these issues cannot be prevented, then strategies for managing potential changes that could happen in the impacted heat zone during the cooling stage must be created.
- The porosity present in the process might conduct lower mechanical properties (fatigue, strength, durability, resistance) and therefore lower material performance, different size/shape distribution, and limited commercial applications. A possible solution for this problem would be the analysis and elaboration of studies relative to the porosity of each part produced, to achieve reduced and acceptable levels.
- The operator's lack of understanding of programming the 3D machines might lead to the production of parts with poor mechanical properties or even defects. Some measures can be applied to facilitate the printing process for the operator himself such as, for example, designing the part previously, considering factors such as part orientation, the slice and path chosen, the process parameters, and the geometric characteristics. Further studies should be elaborated to establish design rules that inform about the use of the WAAM process in general and demonstrate how to benefit from high-quality product design. Additionally, the workers must be trained in 3D programming, and open communication to understand their difficulties regarding the process should be privileged.
- Machine malfunctions might arise and those represent a possible threat to the quality of the production. To combat this, maintenance management plans must be developed.
- The environmental impacts associated with the production, in particular, the gas contamination. The development of a detailed analysis that allows the quantification of the environmental impacts involved in the process and the consequent study of alternatives to implement are some of the strategies that should be taken into account.
- The fact that the process itself limits the design of the final product, i.e., the part must be built according to certain parameters or techniques for its quality not to be compromised. To fix this problem is imperative to know the most critical characteristics of the part being produced and orient it accordingly.
- Product's functionality many is times compromised to make it cost-effective compared to existing traditional methods. The possibility can be explored of Integrating WAAM with other processes and machines to make the production more cost-effective and optimize it.

The present study focuses only on a specific WAAM process, the Gas Metal Arc Welding. However, WAAM has other two types of processes that must also be acknowledged. In the following items, a brief notion of each WAAM process is given based on (Jafari et al., 2021), (Singh e and Khanna, 2021), (Pattanayak and Sahoo, 2021).

- Gas Metal Arc Welding (GMAW)

Passage of an electric arc between the consumable electrode and the workpiece that originates the melting of the wire electrode and subsequently, along with the movement between the worktable and GMAW torch, the deposition takes place above the substrate surface. The final product without machining is obtained afterwards, due to the melting of the substrate and the wire caused by the heat developed during the process.

The process has as its main advantages, such as high material utilization, deposition rate and density, good surface quality of the final product, as well as low risk of contamination and porosity. As disadvantages, are considered the need to separate the wire feed system, the limited dimensions, the weld-fume and spatter produced. The executing unit is the CNC, which although accurate, it happens to be quite costly.

- Gas Tungsten Arc Welding (GTAW)

The process is similar to GMAW, the main difference is related to the electrode used. The process uses a non-consumable electrode and thus electrode material is not deposited on the weld bead. The principal advantages are the high deposition rate and the variable wire feed orientation. The executing unit is a robot being therefore more economical, flexible, and adaptable.

- Plasma Arc Welding (PAW)

An arc is formed between a tungsten electrode, that is positioned within the body of the torch, and the workpiece. This process allows for the separation of the plasma arc from the shielding gas envelope and, thanks to that, reveals to have a major advantage relatively to GTAW when comparing the welding distortions and heat-affected zones. However, it produces smaller welds at lower speeds. The executing unit is a robot being therefore more economical, flexible, and adaptable.

2.2. *LCA of AM processes*

The goal of this subsection is to provide a framework of all the developments relative to the application of the LCA methodology in WAAM. As inclusion criteria for this search, it was defined all the research articles that were written in English and contained keywords related to the present study. The search of information was made by using the Scopus indexing database and regarding different combinations of keywords, such as, “Life Cycle Assessment” AND “Wire Arc Additive Manufacturing”, “Life Cycle Assessment” AND “Additive Manufacturing”, “Environmental impacts” AND “Wire Arc Additive Manufacturing”, “Impact assessment” AND “Additive technologies”, “Impact assessment” and “Wire Arc Additive Manufacturing”. Considering these keywords total of approximately seven hundred articles were found from the aforementioned indexing databases. However, the majority of the articles were relative to the keywords “Life Cycle Assessment” AND “Additive Manufacturing” and did not directly approach the application of the LCA methodology on WAAM. Generally, it is seen that LCA method was used to study the environmental impacts mostly to AM processes like Selective Laser Melting (SLM), Electron Beam Melting (EBM), Fused Deposition Modelling (FDM) as previously indicated by Saade et al. (2020). LCA studies evaluating the environmental impacts of SLM in a variety of metal parts like automotive parts (Swetha et al., 2022), aircraft components (Huang et al., 2016), Inconel turbine blade (Torres-Carrillo et al., 2020), stainless steel hydraulic valves (Peng et al., 2020), stainless steel washers (Guarino et al., 2020), among others have been reported in the literature. LCA of EBM process has been carried out in manufacturing of Ti6Al4V parts (Ingarao e and Priarone, 2020), (Priarone et al., 2017), Ti6Al4V turbine (Paris et al., 2016), knee implant (Lyons et al., 2021) and femoral stem implant (Cappucci et al., 2020). Similarly, the environmental impacts of FDM process have also been studied in the manufacturing of products using raw materials like polylactic acid (PLA) (Cerdas et al., 2017), (Colombo Zefinetti et al., 2023), Acrylonitrile butadiene styrene (ABS) (Kwon et al., 2020), (Garcia et al., 2018), concrete (Alhumayani et al., 2020), (Mohammad et al., 2020), among others have also gained attention. WAAM has received comparatively lower attention than the above processes. Only three studies focussing on the LCA of WAAM were found (Bekker e and Verlinden, 2018), (Campatelli et al., 2020), (Priarone et al., 2020).

Bekker et al. (Bekker e and Verlinden, 2018) performed an LCA from cradle-to-gate perspective to characterize the environmental impacts of WAAM-produced stainless steel 308 l. They also approached the CNC Milling and Green Sand-Casting techniques to give context to the assessment and draw further conclusions about WAAM’s performance. Although the assessment contained sources of uncertainty and it was recognized that the results may vary according to the product being produced, it was concluded that, for this application, the environmental impact of WAAM equals the traditional manufacturing techniques. Stainless steel proved to be the main cause of environmental damage in each of the three techniques assessed. Therefore, the authors concluded that it would be important to start prioritizing techniques that allow mass reduction, being an example, WAAM. Although WAAM had lower impacts in stainless steel, they were still significant. Thus, it was acknowledged the importance of further research and developments in this field.

Gianni Campatelli et al. (2020) developed a case study, regarding the production of a steel blade, to point out the main differences in two different approaches of production: WAAM vs a pure milling process. A cradle-to-gate assessment was made given the subtractive and additive manufacturing processes and considering an end-of-life system boundary. The energy, material, and resource flows were quantified along the entire life cycle of the component and the results showed that the pure milling process involved a significantly higher amount of material, as well as higher energy demands. The authors concluded that the results obtained were expected since WAAM has a more efficient material usage than the pure milling process. Additionally, they also assumed three end-of-life scenarios, to emphasize the importance of recycling on environmental performance.

Priarone et al. (2020) performed a cradle-to-gate life cycle assessment of aluminium alloy parts, considering different size components and different deposition of material, to obtain a comparison between the performance of WAAM and subtractive manufacturing processes. For this comparison, a TOPSIS Multi-Criteria Decision Analysis method considering the manufacturing time, the product cost, the mechanical performance, and sustainability were developed. After its application, the authors concluded that WAAM has an advantage in the subtractive manufacturing processes when the criteria categories were equally important or when the sustainability of the process was prioritized. When time and cost were prioritized, subtractive manufacturing processes had an advantage. Additionally, it was observed that part geometry affects the outcomes of both additive and subtractive manufacturing processes. Although the results obtained are case specific, the authors defend that the methodology developed will serve as a support for process selection in other future studies.

2.3. *Motive for current study*

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

3. Methodology

LCA is a methodology that allows characterizing quantitatively and qualitatively the environmental impacts of a product system throughout its life cycle, from the extraction of raw materials (cradle) to the production phases, use, transportation, and end-of-life (grave) (Vieira et al., 2016), (Fernandes et al., 2019). It provides estimations of soil and water acidification, global warming, eutrophication, ozone layer depletion, and abiotic depletion of non-fossil and fossil resources (Almeida et al., 2021). This is mainly useful in activities such as product development and improvement, strategic planning, public policy making, marketing, and others. Although the cradle-to-grave interpretation is the one that is most often used, in some cases, it is more useful to conduct a partial LCA, for example, to analyze a portion of the life cycle upstream from the gate (the cradle-to-gate), downstream from the gate (the gate-to-grave) or to analyze the portion of life cycle between two gates (the gate-to-gate) (Lúcio, 2017).

The present study is developed considering this methodology and its requirements and guidelines established by ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines (ISO/TC 207, 2006). The LCA framework is displayed in Fig. 2. The first phase is relative to the goal and scope definition of the respective study and allows to understand the reason why the assessment is being performed, whether this is due to regulations, customer pressure, or even the possibility of standing out by "being a role model" for choosing greener productions. In this main phase the functional unit, system boundaries, methods, environmental impact categories used and the assumptions and limitations made are detailed and explained. The second phase of this methodology is called environmental inventory analysis and it has as a major concern the complete identification and analysis of all relevant inputs and outputs (raw materials, electricity, process consumables, waste, and emissions). The data present in this phase is either measured, calculated, or estimated through literature, experiments, or available databases. The third phase, the environmental impact assessment, enables the computation and categorization of the impacts involved in the functional unit's life cycle being, in this sense, a driver for the last phase of the methodology, the interpretation of the results. In this last phase, it is possible to observe with more detail the results obtained throughout the study and withdraw conclusions relative to the main environmental issues of the production in cause. An important detail that should also be noted is that LCA is a systematic process. Therefore, the information established in the early phases of the study can be rearranged throughout its course. Thereby, the changes to be made, as well as the consequences related to those changes must always be explained and detailed.

4. Case study

The WAAM process is used to produce a gear, cylinder and S-shaped geometries composed of ER70 steel (low alloyed steel). These geometries have different weights and varying geometrical complexities and hence, will consume variable quantities of inventories during their fabrication by additive and subtractive approaches. This will help effectively understand the influence of different inventories on the environmental impact of WAAM and CNC milling processes. The conclusions drawn from this study will help AM practitioners in understanding the different drivers of environmental sustainability and conditions under which the adoption of WAAM or CNC milling process is more sustainable environmentally. The parameters set for the WAAM process are presented in Table 1, based on a previous study by the authors involving WAAM of ER70 steel (Kokare et al., 2022). CNC Milling was considered a post-process operation in the WAAM production, however, due to the absence of the appropriate tools/machines (carbide cutting tools) it was not possible to execute it and data relative to its process parameters, as compressed air, lubricating oil, water, and electricity had to be calculated through the Ecoinvent 3 database. Additionally, data relative to the volume and mass of the final part also had to

Table 1
WAAM process parameters.

Process parameters	Geometry 1	Geometry 2	Geometry 3
Shielding gas flow rate (l/min)	16	16	16
Voltage(V)	18	18	18
Wire feed speed (m/min)	3	3	3
Travel speed (mm/min)	360	360	360
Interlayer cooling time (s)	180	180	180
Layer height (mm)	1.5	1.5	1.5
No. of layers	12	32	32

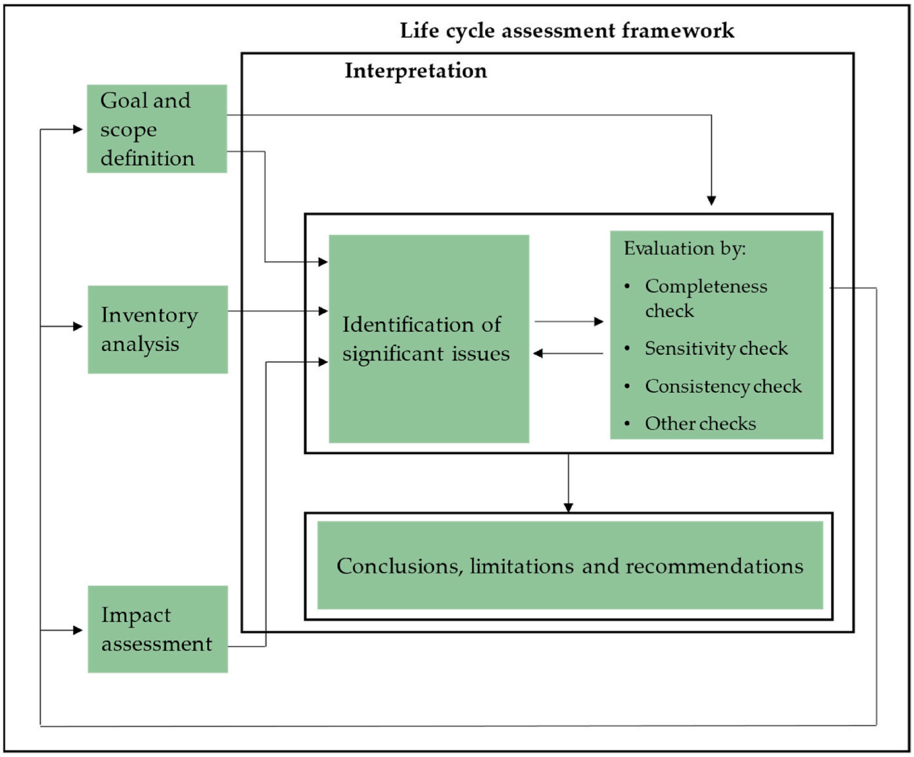

Fig. 2. Relationship between the four phases of the LCA. Adapted from (Jafari et al., 2021).

be estimated through the SolidWorks software. The environmental impacts of WAAM were then identified and characterized, according to the methodology described previously, and further compared with the impacts of the pure CNC Milling process. The LCA model used for both processes will be approached and explained in this section.

4.1. Life cycle assessment

The LCA methodology implemented in the case study follows the requirements and guidelines of the European standard, ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines (ISO/TC 207, 2006). The environmental data were either measured and calculated through specific processes, estimated through findings in literature sources, or provided directly from the Ecoinvent database 3.

4.1.1. Goal and scope definition

The present study has the intent of analyzing and quantifying the environmental impacts of an alternative manufacturing process, WAAM when producing three different metallic geometries: a gear, a cylinder, and an S shape. In the following sections, the gear shape part will be referred to as geometry 1, the cylinder shape part as geometry 2, and the S shape part as geometry 3. Beyond the characterization of the environmental impacts related to WAAM, to give the study, some context and further elaborate comparisons, the impacts related to a traditional manufacturing process, the CNC Milling were also characterized.

4.1.2. Functional unit and system boundaries

The functional unit can be a product, a service, or even a system that is analysed, categorized, and quantified, to be used as a reference unit. The present study considers three distinct functional units as follows: a unit each of a gear, cylinder, and S shaped geometries. Analysing these three distinct geometries will help in an effective understanding of how the environmental impact of each process is affected by the changes in product geometries and amounts of resources consumed. The following figure, Fig. 3, exemplifies the phases that are included in the assessment and demonstrates the system boundaries. Although CNC Milling is presented, due to the absence of the appropriate tools/machine (carbide cutting tools), it was not possible to perform it. Thus, data as volume and mass final parts had to be estimated through specific options (such as evaluate and stock manager) provided by the computer-aided design software, SolidWorks. The study comprehends all the product production phases, from the extraction of natural resources to the production of the final part. The use and disposal phases are not included, since this is a cradle-to-gate study. Transportation was also not considered. The mechanical testing and microstructural characterizations of WAAMed parts were also excluded from the scope of this study. In one of the previous works of the authors (Rodrigues et al., 2019), it has already been established that an as-built steel WAAM part shows excellent mechanical properties. Therefore, it can be assumed that WAAM and pure CNC milling approaches can guarantee similar level of performance of their products. The assessment was performed considering the ReCiPe 2016 (Hierarchical) method that the SimaPro 9.2 software has available. The comparison between both processes was made based on the manufacturing of 0.178 kg of ER90 steel (low alloyed steel) for geometry 1, 0.186 kg for geometry 2, and 0.109 kg for geometry 3. The values available in the Ecoinvent database are relative to 1 kg of steel. As this study is relative to specific values of kilograms of steel, the values present in the following subsections that were withdrawn from the database had to be converted. It was not conducted a sensitivity analysis or an uncertainty analysis.

4.1.3. Environmental inventory analysis

4.1.3.1. WAAM. To proceed to the inventory analysis of the process it is important to address which inputs are being considered, the stages involved, and the final outputs produced. The WAAM process requires as inputs: substrate, ER90 steel wire, energy consumption, and shielding gas, that in this case will be a mixture of 88% Ar and 12% CO_2. An important factor to consider is that the ER90 steel wire is a final product that results from the transformation of a steel billet. Firstly, to mold the steel billet into the desired shape (a rod), a hot rolling operation should take place. Afterward, the rod shape is exposed to the wire drawing process and the ER90 steel wire is finally obtained. To WAAM takes place, it is necessary to present the geometry that is to be achieved. Based on that, a G code is generated, and a printing path strategy is established. Accordingly, the steel wire is melted and deposited, layer by layer, into the substrate until the envisioned part is completed. All the values referent to these phases of the ER90 steel wire production were calculated considering the Ecoinvent 3 database. The processes of hot rolling and wire drawing always incur some type of material losses, wherefore, according to it, a loss of 5% and 4%, also based on the Ecoinvent 3 database, was assumed respectively.

A final part with no defects and good material properties is essentially due to the parameters established and the strategies used during the manufacturing process. Therefore, all the considerations made in the present study will be further specified. The mass of the deposited material was 0.302 kg for geometry 1, 0.218 kg for geometry 2, and 0.162 kg for geometry 3. The part is finished by using a CNC milling machine. The voltage of the process was set to be 18 V, the travel speed to be 360 mm/min, and the wire feed speed to be 3 m/min. The flow rate of the shielding gas, an 88% Ar and 12% CO_2 mixture, was monitored to be 16 l/min. It was necessary 230.4 l, 238.9 l, and 200 l of shielding gas to produce, respectively, geometry 1, 2, and 3. The energy consumption had to be monitored. The LabView software allowed to record of the voltage and current data of the part being produced and thereby making it possible to compute the power consumption of the electric arc regarding the WAAM machine. The power rating obtained was 1.75 kW. Successively, the energy consumed was calculated by simply multiplying the power rating and the process time, obtaining the value of 0.418 kWh for geometry 1, 0.436 kWh for geometry 2, and 0.365 kWh for geometry 3. The printing path was established using Prusa 3D slicer software. In some layers, the path followed the clockwise direction, and in other layers followed the counter-clockwise direction. This strategy of alternating directions avoids the accumulation of stress in the part being produced. To prevent deformation, it was set at an interlayer temperature of 100 °C. This resulted in an interlayer cooling time of 180 s. Geometry 1 was built with 12 layers and geometry 2 and 3 with 32 layers each, with layer height set to 1.5 mm based on the parameters suggested by CITOWAVE III 520 welding machine for carbon steel wire of 1 mm diameter. The outputs of the process were the final parts, the solid waste, and the pollutant emissions into the air. Due to the lack of specific

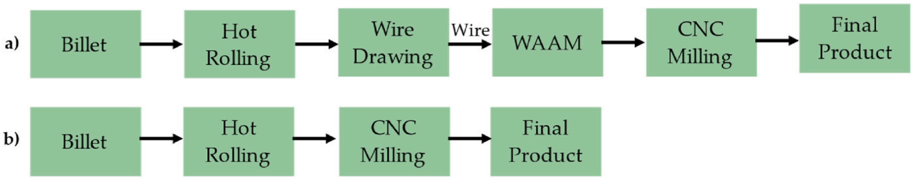

Fig. 3. System boundaries for a) WAAM b) Pure CNC milling.

equipment, the emissions related to the production were not measured. The finish machining times, and the material removed during finish machining were obtained based on the CNC milling simulations in SolidWorks CAM software. The substrate plate for WAAM was also not considered so that, afterward, a fair comparison with CNC milling can be made. As mentioned previously, the mass of the initial and final parts was estimated in the SolidWorks software. The obtained value for the final product of geometry 1 was 0.178 kg of geometry 2 was 0.186 kg and of geometry 3 was 0.109 kg. Given the information above and (1), it is possible to compare the mass of the final part produced with the mass of the raw material used. Thus, theoretical buy-to-fly (BTF) ratio of 1.7 for geometry 1, 1.17 for geometry 2, and 1.49 for geometry 3 were obtained.

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

The CNC Milling process value is relative to the quantity of removed material. Therefore, to calculate it, the amount of material deposited was subtracted from the final product. The calculated value was 0.124 kg for geometry 1, 0.032 for geometry 2, and 0.053 for geometry 3. For further detail, the final parts produced, as well as the CAD model view and the WAAM part preview are represented in Fig. 4. To summarize all the information specified, the inventory of the WAAM process, for all the geometries produced, is depicted in Table 2.

4.1.3.2. CNC milling. The CNC milling process requires the following as inputs: the ER90 steel bar, a CNC machine, and the cutting tools and CNC milling machine tool. Before initiating the machining itself, it is necessary to transform the raw material, i.e the steel billet, into a bar. For that and similarly to the WAAM, it is considered, a hot rolling operation in this stage. Subsequently, the CNC Milling process initiates and the bar is milled until the predefined/desired dimensions are achieved. The values regarding the ER90 steel wire production phases were calculated considering the Ecoinvent 3 database. Also considering Ecoinvent 3 database, a material loss of 5% was assumed for the hot rolling process. As referred to earlier, it was not possible to execute the CNC milling process due to the absence of the appropriate tools/machines. However, the CNC milling process was simulated in SolidWorks CAM software to obtain accurate machining times, volumes of raw material required, and raw material removed. The data relative to compressed air, lubricating oil, water, and electricity were calculated considering the Ecoinvent 3 database, and the data relative to the mass of the final part was estimated in the SolidWorks software.

For geometry 1, the initial billet was assumed to be 70 mm in diameter and 17 mm in height, for geometry 2 was assumed to be 51 mm in diameter and 51 mm in height and for geometry 3 was assumed to be 62 mm in diameter, 112 mm in length, and 21 mm in height. The estimated mass, for the initial billet, was 0.509 kg for geometry 1, 0.605 kg for geometry 2, and 0.528 kg for geometry 3. As for the final product, the estimated mass, for geometry 1 was 0.178 kg, for geometry 2 was 0.186 kg and for geometry 3 was 0.109 kg. The quantity of removed material was calculated by subtracting the initial mass of the billet from the mass of the final product. For this calculation, the 5% material losses, must be considered in the initial billet mass. The values obtained for geometry 1, 2 and 3 were respectively 0.312 kg, 0.419 kg and 0.446 kg. Estimated the mass of both the initial billet and final product, (1) was once more used to calculate the theoretical BTF ratio. A value of 2.86 was obtained for geometry 1, 3.25 for geometry 2, and 4.86 for geometry 3.

All the information mentioned, for all the geometries, is outlined in the inventory of the CNC Milling process and are represented in Table 3.

4.2. Material savings by WAAM

After understanding the results obtained in the inventory of each case study, some observations regarding the BTF ratio and the quantity of removed material can be made. In the first place, it is important to acknowledge that the BTF ratio is inversely proportional to the productivity measure, meaning the bigger the BTF ratio, the lower the

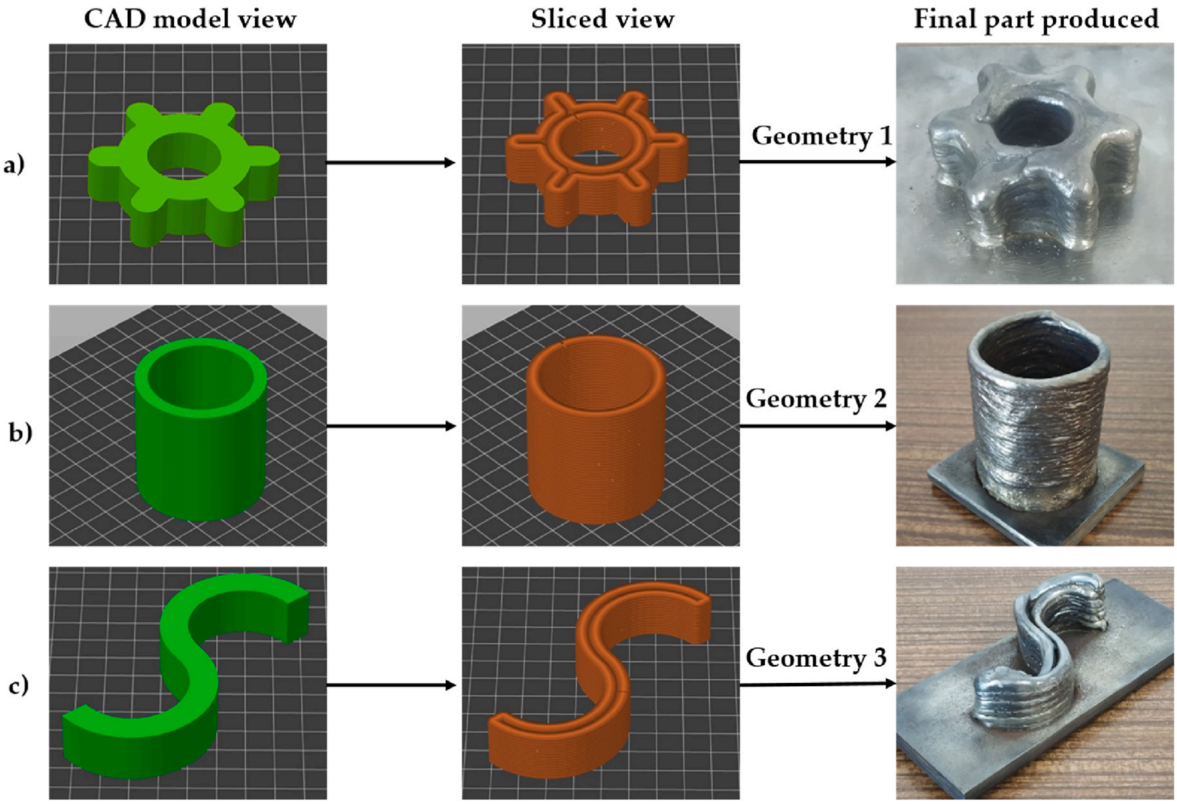

Fig. 4. CAD representation vs Final part of a) geometry 1 b) geometry 2 c) geometry 3.

Table 2
LCI of WAAM for all geometries produced.

	Material/Process	Geometry 1	Geometry 2	Geometry 3	Units	Type of data	Reference
WAAM + CNC Milling	Steel billet	0.329	0.238	0.177	kg	Calculated	Ecoinvent 3 database
	Shielding gas	230.4	238.9	200	l or dm3	Measured	Measured data
	Hot Rolling	0.329	0.238	0.177	kg	Calculated	Ecoinvent 3 database
	Wire Drawing	0.314	0.227	0.168	kg	Calculated	Ecoinvent 3 database
	WAAM Deposition	0.302	0.218	0.162	kg	Measured	Measured data
	Electricity (WAAM)	0.418	0.436	0.365	kWh	Calculated	Calculated data
	Electricity (Milling)	0.517	0.133	0.222	kWh	Calculated	Ecoinvent 3 database
	CNC Milling	0.124	0.032	0.053	kg	Calculated	Calculated data
	Final Product	0.178	0.186	0.109	kg	Estimated	CAD representation in SolidWorks

Table 3
LCI of CNC Milling for all geometries produced.

	Material/Process	Geometry 1	Geometry 2	Geometry 3	Units	Type of data	Reference
CNC Milling	Steel billet	0.534	0.635	0.555	kg	Calculated	Ecoinvent 3 database
	Hot Rolling	0.534	0.6345	0.555	kg	Calculated	
	Compressed Air	0.399	0.536	0.571	m3	Calculated	
	Lubricating Oil	0.001	0.002	0.002	kg	Calculated	
	Water	0.005	0.007	0.007	m3	Calculated	
	Electricity	1.3	1.746	1.858	kWh	Calculated	
	CNC Milling	0.312	0.419	0.446	kg	Calculated	Calculated data
	Final Product	0.178	0.186	0.109	kg	Estimated	CAD model in SolidWorks

material efficiency of the production is and vice-versa. Equation (2) exemplifies that relation. Thus, it was expected that WAAM would have lower values of BTF ratio then the CNC milling process.

$$Buy\ to\ fly\ (BTF)\ ratio = \frac{1}{material\ efficiency} = \frac{Input\ mass}{Output\ mass} \tag{2}$$

In addition, it was observed that the BTF ratio was related to the amount of material removed. Lower BTF ratios result in lower values of removed material that consequently translate into higher productivity. Figs. 5 and 6 were elaborated in order to demonstrate this relation. In Fig. 5, relative to the WAAM production of each geometry, can be observed that geometry 1 had the highest value of material removal and geometry 2 the lowest. On the other hand, in Fig. 6, relative to the CNC Milling production of each geometry, geometry 3 had the highest value of material removal and geometry 1 the lowest. Thus, it can be inferred that, for the CNC Milling process, better results are obtained the more "filled" the geometries being produced are. For the WAAM process it's the opposite, better results are obtained the less "filled" the geometries being produced are. In this sense, by having a higher material efficiency (or lower BTF ratios), WAAM can contribute to reduce certain environmental impacts such as material waste. In this study WAAM reported a material efficiency between 59% and 85% while CNC milling showed it between 21% and 35%. Better material efficiency than subtractive processes has been reported for different AM processes in the existing scientific literature. For instance, Campatelli et al. (2020) demonstrated that pure subtractive CNC milling consumes around 2.5 times more material than WAAM in manufacturing a steel airfoil. Lyons et al. (2021) reported a material efficiency of 65% of EBM process as compared to 15% for CNC milling, in manufacturing a Ti6Al4V knee implant. Similarly, Paris et al. (2016) observed better environmental performance by EBM compared to CNC milling, as CNC milling had significantly lower material utilization (14%) in manufacturing a Ti6Al4V turbine. Additionally, Huang et al. (2016) showed that thousands of tonnes of aluminium, titanium and nickel alloys could be saved per year by 2050, if AM processes like SLM, EBM, DMLS are used to manufacture some aircraft components instead of conventional processes.

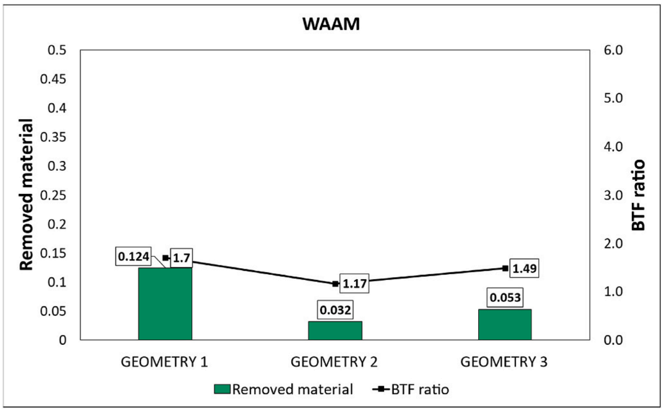

Fig. 5. Removed material vs BTF ratio for WAAM production.

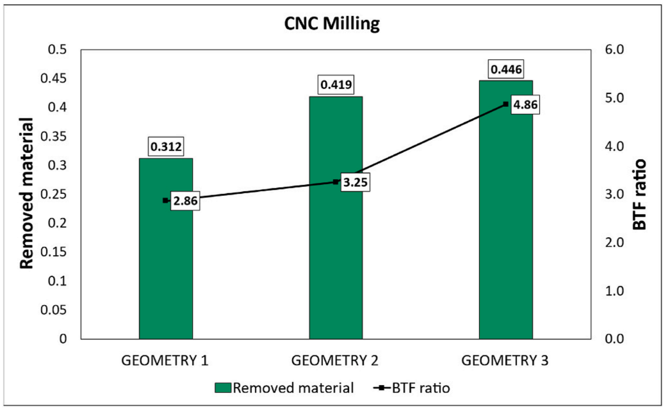

Fig. 6. Removed material vs BTF ratio for CNC Milling production.

5. Results

5.1. *Environmental impact assessment*

To carry out an environmental impact assessment it is necessary to choose an impact assessment method. For the case studies considered, the assessment was carried out accordingly to the ReCiPe 2016 (Hierarchist) method. ReCiPe method can either calculate the impacts for one specific environmental problem (midpoint indicators) or aggregate the impacts in levels (endpoint indicators). In this analysis, both were explored. Table 4 represents the characterization results obtained for the 18 midpoint indicators considered.

To simplify the interpretation of the results, these midpoint indicators were converted to endpoints through an aggregation process and 3 endpoint indicators were considered: Human Health, Ecosystems, and Resources. In Figs. 7 and 8 are displayed the impacts that each production caused on those 3 endpoint indicators, for each geometry. The highest impacts, for both processes, are relative to the human health indicator. Analysing it in greater detail in Table 5, it is possible to understand that the inventory input that contributes the most to the human health impacts is the production of the steel billet. In the majority of the geometries produced and considering both technologies, this input represented more than 50% of the total human health impacts. The results obtained are mainly due to the fact that the steel billet is produced through continuous casting and this process generates a considerable amount of hazardous gases. In this section further suggestions are made to approach this issue but, beyond that, it could be considered for future research on human safety in the continuous casting process.

The following analysis is made considering the total impact, meaning the aggregation of these 3 endpoint indicators. Uncertainty was not assumed in the aggregation processes. The total environmental impact (expressed in milli-points (mPt)) that both processes have in the production of the different geometries, is elaborated in Fig. 9. In this figure, it is seen that WAAM is more ecological alternative than CNC milling in fabrication of all 3 functional units. For manufacturing the functional units considered, WAAM approach causes an environmental impact ranging between 74.31 and 110 mPt while that of CNC milling lies in the range of 125.7–153.24 mPt. As a result of the geometries and processes used, the results obtained were expected. CNC Milling is a subtractive process therefore, the higher the need to remove material in the geometry production, the higher the total environmental impact will be. WAAM is an additive process, the higher the need to deposit material to produce the desired geometry, the higher the total environmental impact will be. The detailed contribution of each inventory input to the overall environmental impacts of both the processes are discussed in the following subsections.

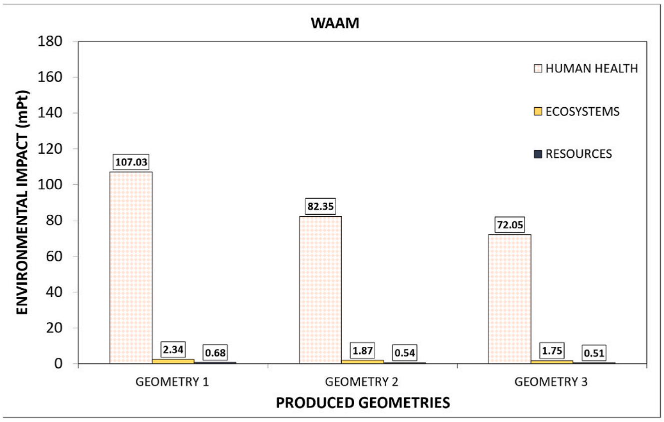

Fig. 7. Environmental analysis of WAAM, midpoint indicators.

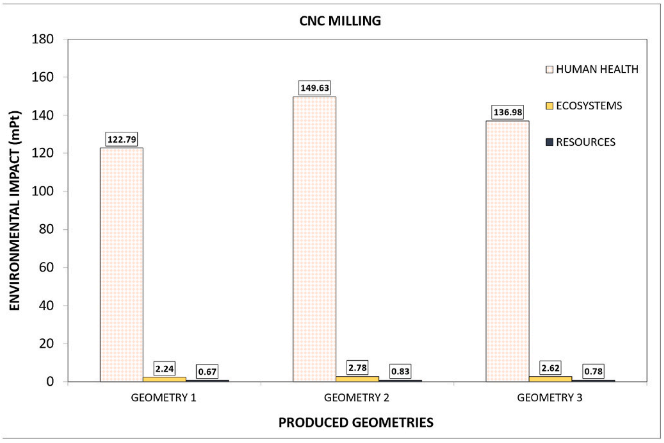

Fig. 8. Environmental analysis of CNC Milling, midpoint indicators.

5.2. *Interpretation of LCA results*

5.2.1. *WAAM*

The different contributions of the inventory inputs for the WAAM process are displayed in Fig. 10, to be easily analysed. The production of the steel billet has proven to be the highest environmental impact for each geometry produced, being responsible for 53% of the total environmental impact of geometry 1, 50% of geometry 2, and 42% of geometry 3. The consumptions of shielding gas and electricity also have significant contributions. The shielding gas contributed 21% for geometry 1, 28% for geometry 2, and 26% for geometry 3. The electricity had

Table 4
ReCiPe Midpoint Impact Assessment characterization results.

Impact category	Unit	Geometry 1		Geometry 2		Geometry 3	
		WAAM	CNC Milling	WAAM	CNC Milling	WAAM	CNC Milling
Global warming	kg CO2 eq	1.81E+00	1.78E+00	1.44E+00	2.20E+00	1.34E+00	2.07E+00
Stratospheric ozone depletion	kg CFC11 eq	6.25E-07	5.51E-07	5.01E-07	6.96E-07	4.82E-07	6.78E-07
Ionizing radiation	kBq Co-60 eq	4.21E-01	3.43E-01	3.33E-01	4.52E-01	3.08E-01	4.69E-01
Ozone formation, Human health	kg NOx eq	3.79E-03	4.00E-03	3.01E-03	4.91E-03	2.86E-03	4.57E-03
Fine particulate matter formation	kg PM2.5 eq	2.79E-03	2.95E-03	2.21E-03	3.63E-03	2.08E-03	3.40E-03
Ozone formation, Terrestrial ecosystems	kg NOx eq	3.95E-03	4.23E-03	3.13E-03	5.19E-03	2.96E-03	4.82E-03
Terrestrial acidification	kg SO2 eq	6.03E-03	5.48E-03	4.90E-03	6.84E-03	4.89E-03	6.53E-03
Freshwater eutrophication	kg P eq	1.20E-03	1.16E-03	9.42E-04	1.46E-03	8.61E-04	1.42E-03
Marine eutrophication	kg N eq	9.17E-05	8.28E-05	7.22E-05	1.04E-04	6.50E-05	1.02E-04
Terrestrial ecotoxicity	kg 1,4-DCB	5.45E+00	7.60E+00	4.09E+00	9.13E+00	3.28E+00	8.14E+00
Freshwater ecotoxicity	kg 1,4-DCB	1.21E-01	1.64E-01	8.52E-02	2.04E-01	7.54E-02	1.93E-01
Marine ecotoxicity	kg 1,4-DCB	1.62E-01	2.19E-01	1.15E-01	2.71E-01	1.01E-01	2.56E-01
Human carcinogenic toxicity	kg 1,4-DCB	7.34E-01	1.00E+00	5.38E-01	1.20E+00	4.16E-01	1.06E+00
Human non-carcinogenic toxicity	kg 1,4-DCB	2.05E+00	2.19E+00	1.58E+00	2.74E+00	1.43E+00	2.61E+00
Land use	m2a crop eq	4.65E-02	4.80E-02	3.61E-02	5.92E-02	3.27E-02	5.56E-02
Mineral resource scarcity	kg Cu eq	4.71E-02	7.51E-02	3.42E-02	8.95E-02	2.57E-02	7.85E-02
Fossil resource scarcity	kg oil eq	4.43E-01	4.30E-01	3.55E-01	5.34E-01	3.39E-01	5.07E-01
Water consumption	m3	4.26E-02	2.21E-02	3.69E-02	2.81E-02	3.19E-02	2.76E-02

Table 5
Human Health impacts analysis.

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

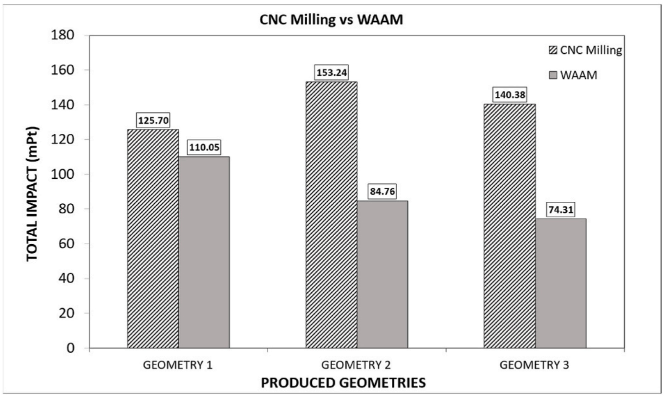

Fig. 9. Overall environmental impacts CNC Milling and WAAM for each geometry.

a contribution of 8% for geometry 1, 11% for geometry 2, and 18% for geometry 3. The remaining contributions are related to the processes of hot rolling, wire drawing, and CNC Milling. Compared with the others, their percentages are relatively low. The hot rolling process generated a 3% impact on the production geometries of all geometries. The wire drawing generated 6% for geometry 1 and 2, and 5% for geometry 3. The CNC Milling generated 9% for geometry 1, 3% for geometry 2, and 6% for geometry 3. It is further noted that, for each geometry produced, the hot rolling process is considered the lowest environmental impact. In short, the geometry 1 production presented higher impacts for the different inventory inputs and the geometry 3 production presented lower impacts.

5.2.2. CNC milling

Similar to WAAM, the different contributions of the inventory inputs for the CNC Milling process are displayed in Fig. 11. The production of the steel billet has also proven to be the highest environmental impact contributor for each geometry produced. It accounted for 75% of the total environmental impact for geometry 1, 74% for geometry 2, and 70% for geometry 3. The CNC Milling process also has a significant contribution, generating a 20% impact for geometry 1 production, 22% for geometry 2, and 26% for geometry 3. The remaining contribution is related to the hot rolling process, whose impacts are relatively low, for geometry 1 (5%), geometry 2 (5%), and geometry 3 (4%) productions. To summarize, the geometry 2 production presented higher impacts for the different inventory inputs and geometry 1 production presented lower impacts.

5.3. Discussion

In this particular application and considering all the geometries produced, WAAM has proven to be the best option ecologically. Compared to CNC milling, WAAM showed a raw material saving of 38%, 62% and 68% in the fabrication of geometry 1, geometry 2 and geometry 3, respectively. The environmental impact assessment results show that WAAM is found to be the most environmentally friendly option causing an ecological impact reduction of 12%, 45%, and 47% in the fabrication of geometry 1, geometry 2 and geometry 3, correspondingly. From the breakdown of the environmental impacts of both the manufacturing approaches discussed earlier, it is observed that the raw material consumed is the primary driver of the environmental impact for both processes. Therefore, it can be said that WAAM is more environmentally friendly in manufacturing of the analysed geometries due to its better material efficiencies than CNC milling approach.

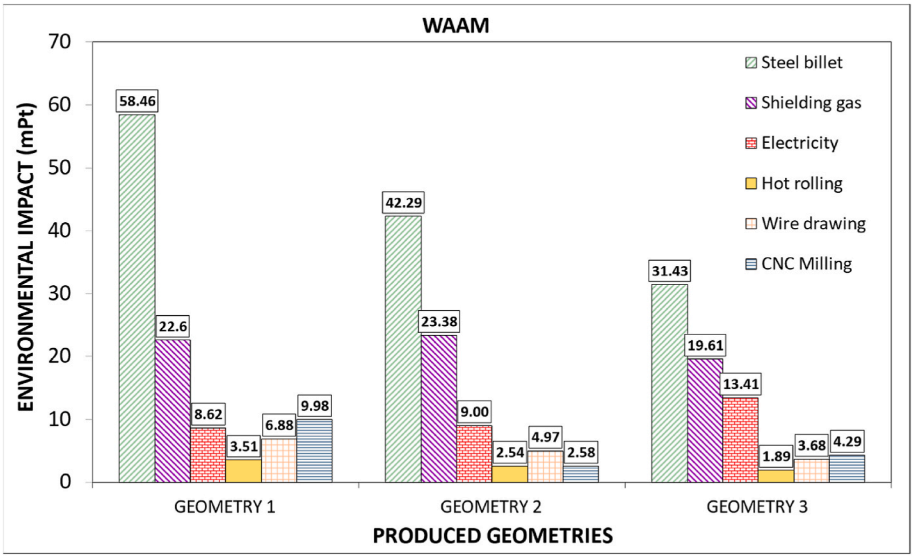

Fig. 10. WAAM environmental analysis for each geometry produced.

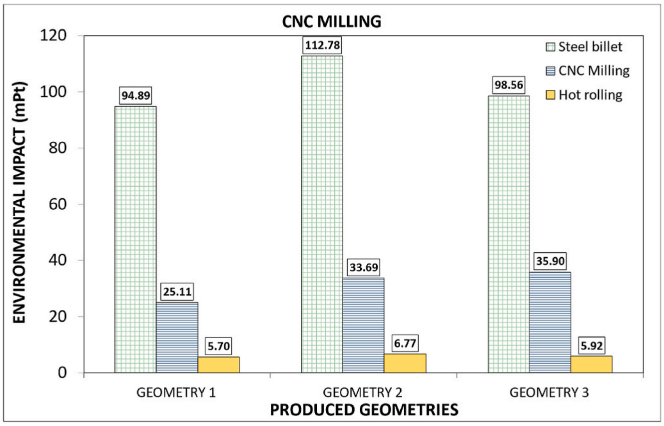

Fig. 11. CNC milling environmental analysis for each shape produced.

When analysing separately both processes, it is possible to get an understanding of which inventory inputs have higher and lower contributions to the total environmental impact. In both processes and for all the geometries considered, primary material production, the steel billet production was the stage that contributed with the highest environmental impact, and the hot rolling process was the stage that contributed with the lowest environmental impact. This agrees with the previous studies focussed on LCA of WAAM. Bekker and Verlinden (Bekker e and Verlinden, 2018) found that the production of steel billet contributes to nearly 78% of the total environmental impact of the stainless steel WAAM part, while the hot rolling phase accounts for merely 1% of the total impact. A similar trend is observed in WAAM of steel carried out by Priarone et al. (2020), where the feedstock material is responsible for more than two-thirds of the cumulative energy demand (CED) of WAAM approach. The production of steel billet is made by continuous casting. This process is connected with certain environmental issues such as material waste and hazardous emissions, making, therefore, the results obtained foreseeable. The hot rolling process itself has a few environmental implications. But besides that, it is also clear that, to the case studies developed and the technologies used, this process only represents a small stage, whose sole purpose is to mold the steel billet into the desired shape for the input. In this sense, its contribution will be little to the total environmental impact.

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

5.3.1. *Suggestions to reduce environmental impact*

As previously mentioned, the steel billet production was the stage that contributed more to the total impacts of all the produced geometries. Therefore, this subsection will focus on this subject and further suggest measures for decreasing the impacts related. The steel billet is produced through the continuous casting process. This type of production not only generates pollutant emissions but also produces a significant amount of waste that can be translated into gaseous waste, for the most part, and to liquid emissions and solid waste (sand waste, investment casting waste, cleaning room waste, and slag waste) (TheMetalCasting.com, 2022).

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

- Create appropriate treatments to reduce the toxicity of the waste produced allowing it, therefore, to be recycled.
- Use appropriate machines to prevent gas and liquid emissions, for example, gas-removing systems (Mazur et al., 2003).
- Create new processes that combine proper waste management with good performance and efficiency (Gentil et al., 2011).
- Adopt techniques to recycle the solid waste resulting from the foundry.
- Steel can easily be recycled without changing the inherent material properties. This means that scrap can be produced as a high-quality metal (Reliance Foundry Co. Ltd, 2020). Fig. 12 exemplifies this procedure. However, the process of secondary steelmaking still needs some environmental improvements, since it requires high energy consumption and harmful emissions are released.

Although the production of steel billet has proven to be the most environmentally damaging stage, the consumption of shielding gas and the consumption of electricity for the WAAM process and the CNC Milling stage for the CNC Milling process, also showed significant impacts when compared with the other inventory inputs. As for WAAM, a possible solution for the consumption of shielding gas would be to implement new technologies that allow an optimization of the required gas flow for the process. For energy consumption, an option could be the use of renewable energy but that would require further investigation to be implemented. As for CNC and relative to the CNC Milling stage, the main factor that contributes to its significant impact, is the solid material waste caused. Thus, the solutions to be applied are related to waste management processes and recycling techniques (Fig. 12).

6. Conclusion

The present study intended to characterize and compare the environmental impacts of WAAM and CNC Milling processes, as well as identify possible improvements, through the application of the LCA methodology in the production of three different geometries. This study characterizes the environmental performance of WAAM, considering the effect of the finish machining required to achieve final dimensions and surface finish, and the geometrical complexity of parts for steel. The finish machining times and the material removed during finish machining were obtained based on the simulations performed in SolidWorks Cam software. The geometrical complexity of parts was characterized using the BTF ratio which varied between 1.17 and 1.7 for WAAM while for CNC milling it varied between 2.86 and 4.86. Additionally, some measures to reduce the environmental impact associated with the raw material production were also suggested. The production of those three different geometries occurred under the same circumstances and having into account the same process parameters. The assessment was conducted in the SimaPro 9.2 software, according to the standard

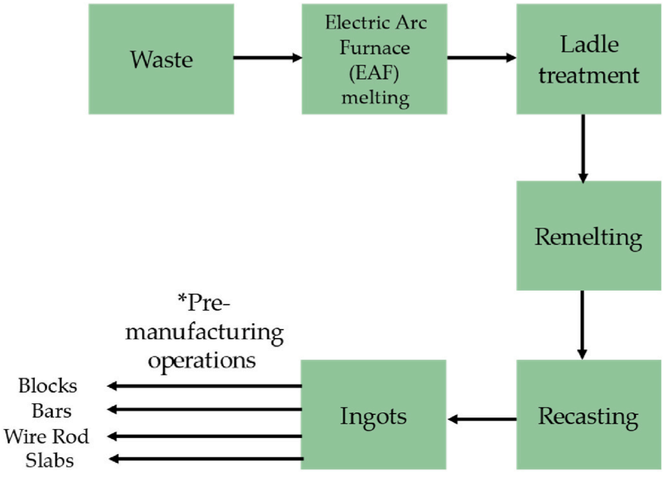

Fig. 12. Secondary steel making. Elaborated based on (Priarone et al., 2021).

ISO 14044:2006: Environmental management - Life cycle assessment - Requirements and guidelines (ISO/TC 207, 2006). The main conclusions drawn are stated in the following points.

- The BTF ratio has a relation to the amount of material removed in the production process. Lower BTF ratios translate into lower values of material removed and consequently into low material waste. Overall, WAAM proved to have a lesser need to remove material and therefore, to have an advantage relative to the CNC Milling process.
- WAAM was the best ecological option due to its better material utilization for all the geometries produced, proving to have a 12% environmental impact reduction in geometry 1 production, 45% in geometry 2, and 47% in geometry 3 relatively to CNC Milling.
- Considering the total environmental impact, the highest contributions, for both processes, were related to the production of the steel billet. For WAAM, this inventory input was responsible for 53%, 50%, and 42% of the total environmental impact of respectively geometry 1, geometry 2, and geometry 3. For CNC Milling, it accounted for 75% of the total environmental impact for geometry 1, 74% for geometry 2, and 70% for geometry 3.
- Considering the total environmental impact, the lowest contributions, for both processes, were related to the hot rolling process. This stage generated a 3% impact on the production of all geometries through WAAM. As for CNC Milling, an approximately 5% impact was verified for all geometries.
- From a product geometry perspective, more complex geometries that have higher BTF and hence, have higher environmental impact (as in case of geometry 1 fabricated by WAAM). However, more complex geometries can have lower environmental impact if their overall material consumption is lower than less complex geometries (as in case of geometry 2 and 3).
- The production of the steel billet represented, for the majority of the geometries produced and considering both technologies, more than 50% of the total human health impacts.
- The solutions proposed regarding steel billet production were mainly relative to waste management, recycling options, and complementary equipment.

This study presented a contribution to the body of knowledge relative to the application of the LCA methodology in WAAM. The results obtained for this particular study compared the environmental impacts of WAAM with only CNC milling and corroborated the hypothesis that this process is less environmentally damaging. To further generalize the WAAM's environmental performance, more comparison evaluations should be conducted, considering other processes (traditional or alternative) besides CNC Milling, as well as, other materials, process settings, and geometries (Bekker e and Verlinden, 2018), (Campatelli et al., 2020), (Ford e and Despeisse, 2016), (Bekker et al., 2016). Future works should consider the use and disposal phases in the assessment and must also approach an economical (Life cycle costing: LCC) and social life cycle assessment (Social Life Cycle Assessment: SLCA).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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References

Alhumayani, H., Gomaa, M., Soebarto, V., Jabi, e W., 2020. Environmental assessment of large-scale 3D printing in construction: a comparative study between cob and concrete. J. Clean. Prod. 270 https://doi.org/10.1016/j.jclepro.2020.122463.

Almeida, J., Magro, C., Mateus, E.P., Ribeiro, e A.B., 2021. Life cycle assessment of electrodialytic technologies to recover raw materials from mine tailings. , n.o 7, Art. n.o 7, jan Sustainability 13. https://doi.org/10.3390/su13073915.

Bekker e, A.C.M., Verlinden, J.C., 2018. Life cycle assessment of wire + arc additive manufacturing compared to green sand casting and CNC milling in stainless steel. J. Clean. Prod. 177, 438–447. https://doi.org/10.1016/j.jclepro.2017.12.148 mar.

Bekker, A.C.M., Verlinden, J.C., Galimberti, e G., 2016. «Challenges in Assessing the Sustainability of Wire + Arc Additive Manufacturing for Large Structures».

Böckin e, D., Tillman, A.-M., 2019. Environmental assessment of additive manufacturing in the automotive industry. jul J. Clean. Prod. 226, 977–987. https://doi.org/10.1016/j.jclepro.2019.04.086.

Burkhart, M., Aurich, J.C., 2015. Framework to predict the environmental impact of additive manufacturing in the life cycle of a commercial vehicle. Procedia CIRP 29, 408–413. https://doi.org/10.1016/j.procir.2015.02.194 jan.

Campatelli, G., Montevecchi, F., Venturini, G., Ingarao, G., Priarone, e P.C., 2020. Integrated WAAM-subtractive versus pure subtractive manufacturing approaches: an energy efficiency comparison, 1 Int. J. of Precis. Eng. and Manuf. Green Tech. 7, 1–11. https://doi.org/10.1007/s40684-019-00071-y. jan.

Cappucci, G.M., Pini, M., Neri, P., Marassi, M., Bassoli, E., Ferrari, e A.M., 2020. Environmental sustainability of orthopedic devices produced with powder bed fusion. J. Ind. Ecol. 24 (3), 681–694. https://doi.org/10.1111/jiec.12968. , n.o.

Cerdas, F., Juraschek, M., Thiede, S., Herrmann, e C., 2017. Life cycle assessment of 3D printed products in a distributed manufacturing system. J. Ind. Ecol. 21, S80–S93. https://doi.org/10.1111/jiec.12618.

Colombo Zefinetti, F., Spreafico, C., Regazzoni, D., Landi, e D., 2023. In: Gerbino, S., Lanzotti, A., Martorelli, M., Mirálbes Buil, R., Rizzi, C., Roucoules, e L. (Eds.), «Eco-Assessment of Design for Additive Manufacturing Solutions Defined at Different Levels of Detail», Em Advances On Mechanics, Design Engineering And Manufacturing IV. Springer International Publishing, Cham, pp. 1079–1089. https://doi.org/10.1007/978-3-031-15928-2_94.

Fernandes, J., Peixoto, M., Mateus, R., Gervásio, e H., 2019. Life cycle analysis of environmental impacts of earthen materials in the Portuguese context: rammed earth and compressed earth blocks. J. Clean. Prod. 241, 118286 https://doi.org/10.1016/j.jclepro.2019.118286 dez.

Ford e, S., Despeisse, M., 2016. Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. nov J. Clean. Prod. 137, 1573–1587. https://doi.org/10.1016/j.jclepro.2016.04.150.

Gao, C., Wolff, S., Wang, e S., 2021. Eco-friendly additive manufacturing of metals: energy efficiency and life cycle analysis. jul J. Manuf. Syst. 60, 459–472. https://doi.org/10.1016/j.jmsy.2021.06.011.

Garcia, F.L., Moris, V.A.S., Nunes, A.O., Silva, e D.A. L., 2018. Environmental performance of additive manufacturing process – an overview. Rapid Prototyp. J. 24 (7), 1166–1177. https://doi.org/10.1108/RPJ-05-2017-0108.

Gentil, E.C., Gallo, D., Christensen, e T.H., 2011. Environmental evaluation of municipal waste prevention. , n.o 12 Waste Manag. 31, 2371–2379. https://doi.org/10.1016/j.wasman.2011.07.030. dez.

Godina, R., Ribeiro, I., Matos, F., Ferreira, B.T., Carvalho, H., Peças, e P., 2020. «Impact assessment of additive manufacturing on sustainable business models in industry 4.0 context». , n.o 17, Art. n.o 17, jan Sustainability 12. https://doi.org/10.3390/su12177066.

Guarino, S., Ponticelli, G.S., Venettacci, e S., 2020. Environmental assessment of Selective Laser Melting compared with Laser Cutting of 316L stainless steel: a case study for flat washers' production. CIRP J. Manuf. Sci. Technol. 31, 525–538. https://doi.org/10.1016/j.cirpj.2020.08.004.

Huang, R., et al., 2016. Energy and emissions saving potential of additive manufacturing: the case of lightweight aircraft components. J. Clean. Prod. 135, 1559–1570. https://doi.org/10.1016/j.jclepro.2015.04.109.

Ingarao e, G., Priarone, P.C., 2020. A comparative assessment of energy demand and life cycle costs for additive- and subtractive-based manufacturing approaches. J. Manuf. Process. 56, 1219–1229. https://doi.org/10.1016/j.jmapro.2020.06.009.

jul ISO/TC 207/SC 5 Life Cycle Assessment, «Environmental Management — Life Cycle Assessment — Requirements and Guidelines», 2006. ISO International Organization for Standardization.

Jafari, D., Vaneker, T.H.J., Gibson, e I., 2021. Wire and arc additive manufacturing: opportunities and challenges to control the quality and accuracy of manufactured parts. Mater. Des. 202, 109471 https://doi.org/10.1016/j.matdes.2021.109471 abr.

Kokare, S., Oliveira, J.P., Santos, T.G., Godina, e R., 2022. «Environmental and Economic Assessment of a Steel Wall Fabricated by Wire-Based Directed Energy Deposition», Additive Manufacturing, 103316. https://doi.org/10.1016/j.addma.2022.103316.

Kokare, S., Godina, R., Oliveira, e J.P., 2023. «Life Cycle Inventory of Additive Manufacturing Processes: A Review». em Quality Innovation and Sustainability, Cham, pp. 77–86. https://doi.org/10.1007/978-3-031-12914-8_7.

Kwon, J.Y., Kim, N., Ma, e J., 2020. Environmental sustainability evaluation of additive manufacturing using the NIST test artifact. J. Mech. Sci. Technol. 34 (3), 1265–1274. https://doi.org/10.1007/s12206-020-0225-1.

Li, Y., Su, C., Zhu, e J., 2022. Comprehensive review of wire arc additive manufacturing: hardware system, physical process, monitoring, property characterization, application and future prospects. Results Eng. 13, 100330 https://doi.org/10.1016/j.rineng.2021.100330 mar.

Lúcio, J., 2017. «Social Life Cycle Assessment for Additive Manufacturing: A Review», Mestre em Engenharia e Gestão Industrial. Universidade Nova de Lisboa.

Lyons, R., Newell, A., Ghadimi, P., Papakostas, e N., 2021. Environmental impacts of conventional and additive manufacturing for the production of Ti-6Al-4V knee implant: a life cycle approach. , n.o 3–4 Int. J. Adv. Manuf. Technol. 112, 787–801. https://doi.org/10.1007/s00170-020-06367-7. jan.

Ma, J., Harstvedt, J.D., Dunaway, D., Bian, L., Jaradat, e R., 2018. An exploratory investigation of Additively Manufactured Product life cycle sustainability assessment. J. Clean. Prod. 192, 55–70. https://doi.org/10.1016/j.jclepro.2018.04.249 ago.

Mazur, M., Bogacki, M., Oleniacz, R., Łopata, e A., 2003. Assessment of ecological effects of the implementation of continuous casting of steel. Stahl Eisen 123, 109–113 jun.

Mitchell, G.R., 2017. Climate change and manufacturing. Procedia Manuf. 12, 298–306. https://doi.org/10.1016/j.promfg.2017.08.033.

Mohammad, M., Masad, E., Al-Ghamdi, e S.G., 2020. 3d concrete printing sustainability: a comparative life cycle assessment of four construction method scenarios. Buildings 10, 1–20. https://doi.org/10.3390/buildings10120245. º 12.

Naghshineh, B., Lourenço, F., Godina, R., Jacinto, C., Carvalho, e H., 2020. A social life cycle assessment framework for additive manufacturing products. Appl. Sci. 10 https://doi.org/10.3390/app10134459. , Art. n.º 13, jan.

Paris, H., Mokhtarian, H., Coatanéa, E., Museau, M., Ituarte, e I.F., 2016. Comparative environmental impacts of additive and subtractive manufacturing technologies. CIRP Ann. - Manuf. Technol. 65 (1), 29–32. https://doi.org/10.1016/j.cirp.2016.04.036. , n.o.

Pattanayak, S., Sahoo, S.K., 2021. Gas metal arc welding based additive manufacturing—a review. CIRP J. Manuf. Sci. Technol. 33, 398–442. https://doi.org/10.1016/j.cirpj.2021.04.010 mai.

Peng, T., Wang, Y., Zhu, Y., Yang, Y., Yang, Y., Tang, e R., 2020. Life cycle assessment of selective-laser-melting-produced hydraulic valve body with integrated design and manufacturing optimization: a cradle-to-gate study. Addit. Manuf. 36 https://doi.org/10.1016/j.addma.2020.101530.

Pfähler, K., Morar, D., Kemper, e H.-G., 2019. Exploring application fields of additive manufacturing along the product life cycle. Procedia CIRP 81, 151–156. https://doi.org/10.1016/j.procir.2019.03.027 jan.

Priarone, P.C., Ingarao, G., di Lorenzo, R., Settineri, e L., 2017. Influence of material-related aspects of additive and subtractive Ti-6Al-4V manufacturing on energy demand and carbon dioxide emissions. J. Ind. Ecol. 21, S191. https://doi.org/10.1111/jiec.12523. –S202.

Priarone, P.C., Pagone, E., Martina, F., Catalano, A.R., Settineri, e L., 2020. Multi-criteria environmental and economic impact assessment of wire arc additive manufacturing. CIRP Annals 69, 37–40. https://doi.org/10.1016/j.cirp.2020.04.010 jan.

Priarone, P.C., Campatelli, G., Catalano, A.R., Baffa, e F., 2021. Life-cycle energy and carbon saving potential of Wire Arc Additive Manufacturing for the repair of mold inserts. CIRP J. Manuf. Sci. Technol. 35, 943–958. https://doi.org/10.1016/j.cirpj.2021.10.007 nov.

Reliance Foundry Co Ltd, 2020. «How is Steel Made? An introduction to the production and properties of steel alloys», 2 de julho de. https://www.reliance-foundry.com/blog/how-is-steel-made (acedido 14 de setembro de 2022).

Rodrigues, T.A., Duarte, V., Avila, J.A., Santos, T.G., Miranda, R.M., Oliveira, e J.P., 2019. Wire and arc additive manufacturing of HSLA steel: effect of thermal cycles on microstructure and mechanical properties. Addit. Manuf. 27, 440–450. https://doi.org/10.1016/j.addma.2019.03.029 mai.

Saade, M.R.M., Yahia, A., Amor, e B., 2020. How has LCA been applied to 3D printing? A systematic literature review and recommendations for future studies. J. Clean. Prod. 244 https://doi.org/10.1016/j.jclepro.2019.118803.

Seow, C.E., et al., 2020. Effect of crack-like defects on the fracture behaviour of wire + arc additively manufactured nickel-base alloy 718. Addit. Manuf. 36, 101578 https://doi.org/10.1016/j.addma.2020.101578 dez.

Shi, Y., Faludi, J., 2020. Using life cycle assessment to determine if high utilization is the dominant force for sustainable polymer additive manufacturing. Addit. Manuf. 35, 101307 https://doi.org/10.1016/j.addma.2020.101307 out.

Singh e, S.R., Khanna, P., 2021. Wire arc additive manufacturing (WAAM): a new process to shape engineering materials. Mater. Today Proc. 44, 118–128. https://doi.org/10.1016/j.matpr.2020.08.030 jan.

Siva Rama Krishna e, L., Srikanth, P.J., 2021. Evaluation of environmental impact of additive and subtractive manufacturing processes for sustainable manufacturing. Mater. Today Proc. 45, 3054–3060. https://doi.org/10.1016/j.matpr.2020.12.060 jan.

Swetha, R., Siva Rama Krishna, L., Hari Sai Kiran, B., Ravinder Reddy, P., Venkatesh, e S., 2022. Comparative study on life cycle assessment of components produced by additive and conventional manufacturing process. Mater. Today Proc. 62, 4332–4340. https://doi.org/10.1016/j.matpr.2022.04.840.

TheMetalCasting.com, «Environmental Issues». https://www.themetalcasting.com/enviornmental-issues.html (acedido 14 de setembro de 2022).

Torres-Carrillo, S., Siller, H.R., Vila, C., López, C., Rodríguez, e C.A., 2020. Environmental analysis of selective laser melting in the manufacturing of aeronautical turbine blades. J. Clean. Prod. 246 https://doi.org/10.1016/j.jclepro.2019.119068.

Vieira, D.R., Calmon, J.L., Coelho, e F.Z., 2016. Life cycle assessment (LCA) applied to the manufacturing of common and ecological concrete: a review. Construct. Build. Mater. 124, 656–666. https://doi.org/10.1016/j.conbuildmat.2016.07.125 out.