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Article

# Assessment Methodology for Calculating Environmental Indicators in the Production of Metal Parts based on the Wire and Arc Manufacturing Method (WAAM)

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**Abstract:** Life Cycle Assessment (LCA) is a technique developed to measure possible environmental impacts during the manufacture and use of a given product or service. Additive Manufacturing (AM) has proven to be suitable in several industries, especially wire and arc additive manufacturing (WAAM), offering many advantages such as delivery time and reduction in terms of material waste, energy consumption and equivalent CO<sub>2</sub> emissions (CO<sub>2</sub>e). This study aimed to develop a methodology to evaluate environmental indicators during the life cycle assessment, from gate-to-gate, in the production of two low-alloy carbon steel metal parts (flanges) using ER-90 wire and allowed identifying the main stages that most influence environmental indicators. The total energy consumption in the production of flanges 1 and 2 were, respectively, 10,239.0 MJ, 12,754.0 MJ and the total carbon footprint, respectively, 714.1 kgCO<sub>2</sub>e kg<sup>-1</sup> and 749.3 kgCO<sub>2</sub>e kg<sup>-1</sup>.

**Keywords:** environmental indicators; wire and arc additive manufacturing; life cycle assessment; atmospheric emission; carbon footprint; energy demand; sustainable development

## 1. Introduction

Life cycle assessment (LCA) is a management tool created to compute inputs and outputs of a production system, with the aim of evaluating the environmental performance of products during the various stages of their life cycle. LCA is used to identify which of these life cycle paths are most impactful on the environment and evaluates the cost of changes and the corresponding impact of changes in a computational simulation environment [1-5]. LCA is an internationally recognized methodology for modeling production systems. The main objectives of LCA are to improve the environmental performance of production processes and assist in the creation of sustainable products. In public policies, LCA contributes to the formation of sustainability criteria and requirements, in addition to providing a scientific basis for the implementation of environmental standards and regulations [6-8].

However, the life cycle inventory is dependent on a robust database of information about inputs and production waste, their mass and energy flows, and their environmental impacts. A life cycle assessment is generated in four steps. The first stage is qualitative and involves determining the objectives of the LCA, its scope with the limits of the system analyzed in the life cycle, its environmental analysis dimensions and its functional unit. The second stage is quantitative, and the life cycle inventory (LCI) is constructed. In the third stage, the life cycle impact assessment (LCIA) is carried out relating the LCI with the environmental impact considerations and in the fourth stage, the interpretative process relates the LCI and LCIA data and proposes recommendations for

improving the process in the determined scope of analysis. At this stage, sustainability indicators can be proposed for critical points of environmental vulnerability [9].

In this sense, LCA has been applied in industry 4.0, where machines are connected to each other to make decisions without human involvement, making industries more productive and efficient, in addition to reducing waste [10-18]. Additive manufacturing (AM) has proven essential to support this productive change in industry 4.0. It consists of a manufacturing method capable of creating large-scale objects through a three-dimensional digital model [19-20]. Its application has been proven to reduce the use of materials and optimize the final product, in addition to presenting a high deposition rate and lower equipment costs [21-25].

Among the various AM processes, the Wire Arc Additive Manufacturing (WAAM) stands out in the manufacture of metallic parts, aiming to save production time and cost by reducing raw material waste and generated energy, as well as making the production process more sustainable [26, 27]. WAAM is a well-structured and complex process, derived from electric arc welding processes, in which a torch is used with continuous wire feed for deposition of base material [28, 29]. Its effectiveness can be observed by carrying out a Life-Cycle Assessment (LCA), a method used for analyzing the environmental impact of a product, process, service or other economic activity, throughout its life cycle [30-36], being an important tool to help decision-making aligned with sustainable practices. It is, therefore, a comprehensive tool for quantifying and interpreting the environmental impacts of a product or service from cradle to grave, that is, from raw material extraction process to its final disposal [37, 38].

Many LCA works allow the comparison between product and process alternatives, evaluating factors such as changes in the use of raw materials and production processes, in order to minimize their effects. For this purpose, it becomes necessary to evaluate the stages of the life cycle and their effects. Subsequently, it is possible to carry out comparative analyses of life cycles of competing systems with the same function, to identify which one has lower impact in the environment by generating less pollution and requiring less resources, among other relevant indicators for decision-making [39-40].

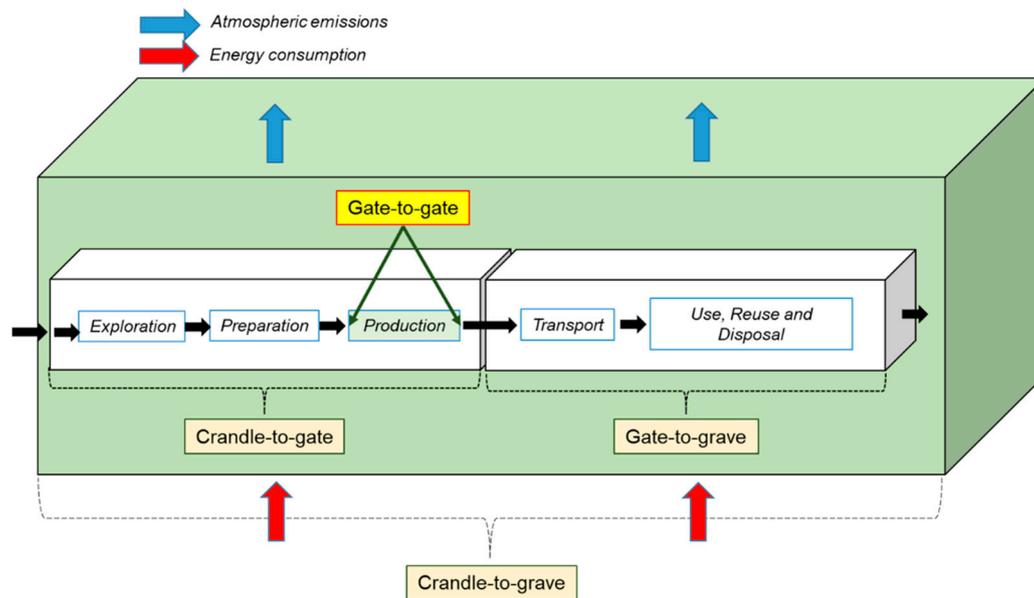
LCA involves the collection, organization and evaluation of all inputs and outputs of a production system, allowing the analysis of the potential environmental impact throughout its life cycle. This comprehensive approach involves assessing all attributes and aspects related to natural environment, human health and resources, enabling the understanding and management of environmental impacts more efficiently. It also stands out for focusing on the perspective of products life cycle, which grants it a broad scope. This characteristic is fundamental to avoid the undesirable transfer from one phase of the life cycle to another, from one region to another [41, 42]. Life-Cycle Assessment methodology can be useful to acquire a comprehensive knowledge of the environmental impacts generated by industrial products throughout their life cycle. The information needed for these evaluation methods can be measured or calculated, with consumption factors expressing the amount of materials and energy consumed by an activity per amount of final product, and emission factors expressing the amount of pollutant emitted by an activity per amount of final product generated or energy consumed [43- 52].

However, despite many LCA applications, the methodology has limitations that should be taken into account in the studies as well as in the evaluation of their results. In Brazil, in particular, the greatest limitations in LCA studies are national database unavailability, method uncertainty in relation to results for decision making, difficulties collecting primary data, complexity in life cycle inventory (LCI) phase, difficulty comparing quantitative results of studies with the same object and high cost and time spent to execute an LCA.

In this environmental context, this work aims to develop a methodology to evaluate environmental impacts, focused on greenhouse gas (GHG) emissions and energy demands during the production of two flange pieces using the wire and arc additive manufacturing method (WAAM), considering only the manufacturing stages of the products, restricting itself to the stages of exclusive participation of the production industry.

## 2. Materials and Methods

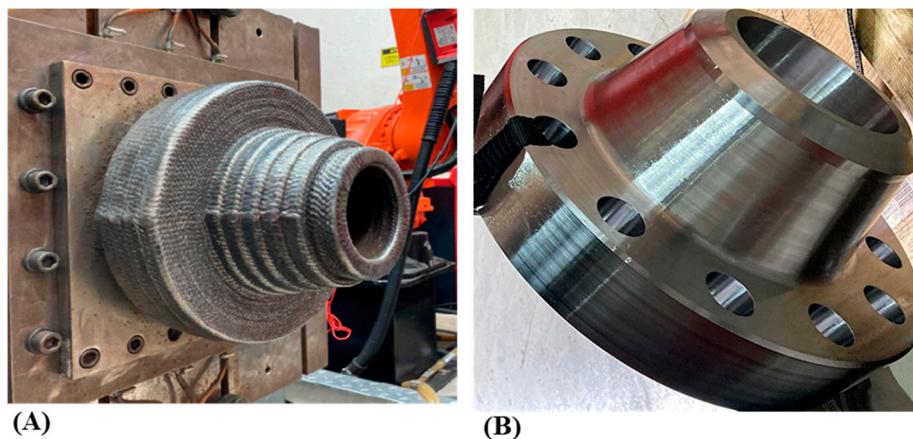
Life Cycle Assessment (LCA) was prepared in accordance with the ABNT NBR ISO 14040:2009 and ABNT NBR ISO 14044:2009 standards [53, 54], with three defined stages: objective and scope; inventory analysis; and impact assessment. This work adopted, as functional unit, the production of two pieces of flanges considering the limit of gate-to-gate systems, whose main function is to seal the connection between two pipes, preventing any fluid from escaping at these junctions, as shown in Figure 1. In addition, the phases assessed for the work analysis comprehend the material production until its manufacture in the factory. The study was restricted to the stage in which the company operates directly, within its production processes, having the transport stages removed from the analysis.



**Figure 1.** Stages that make up the life cycle of a given product with energy consumption and atmospheric emissions.

### 2.1. Data Quality

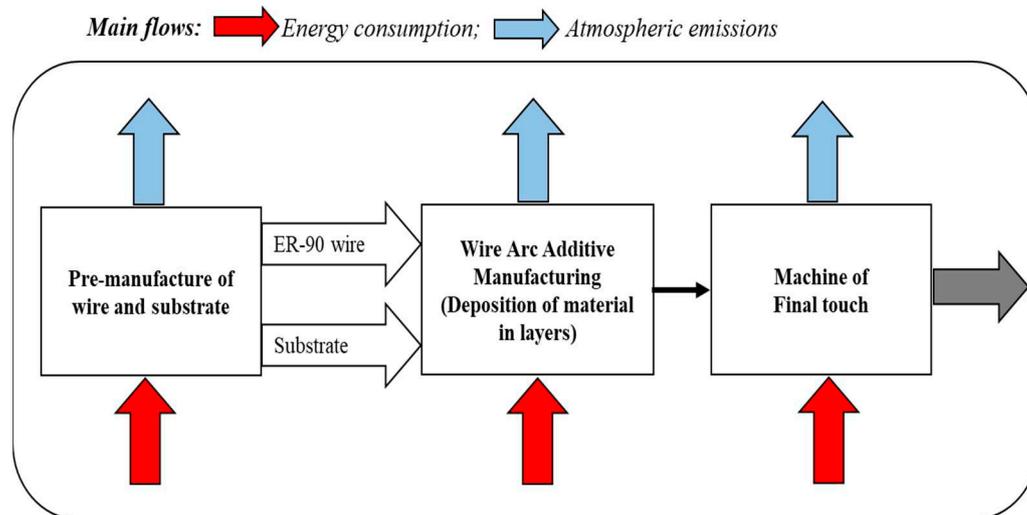
For the study to be successful, data quality and reliability are essential items. Thus, it used data from primary sources for information on WAAM system inputs and outputs measured by National Laboratory of Welding Technology (LNTSold) and the Air Pollution Control Laboratory of the Federal University of Rio de Janeiro, Brazil. Figure 2 shows the construction of the flange parts carried out in laboratory to obtain experimental data. Secondary and other data were obtained from bibliographic research and database, which will be described in the methodology.



**Figure 2.** Production of flanges in the laboratory (LNTSold). (A) Flange ring deposition and (B) Flange after machining.

### 2.1.1. Product and equipment edge system

WAAM edge system is shown in Figure 3, using low-alloy carbon steel (ER-90) for the parts production. Input flows work as electricity for running machines, while out-puts are the gases emitted in the process at each stage.



**Figure 3.** Frontier of the Wire and Arc Additive Manufacturing (WAAM).

## 2.2. Life Cycle Inventory Analysis (LCI)

### 2.2.1. WAAM material production and pre-manufacturing

Data referring to the process shown in Figure 3 were found in literature per kg of the built part using the forging method [55] and, to obtain the results, they were multiplied by the mass used in the process to obtain a flange. Value of the raw material mass used in the calculation of results was based on the size of the flange produced by WAAM, obtaining a value of  $m = 340.5\text{kg}$ .

The first stage of Figure 3 took into account the material fabrication, its hot rolling into large plates and wire drawing. At this manufacturing stage, it was possible, with the use of literature [56], to obtain data on energy spent in the respective processes and emission of greenhouse gases (GHG) directly or indirectly into the atmosphere in  $\text{CO}_2$  equivalent ( $\text{CO}_2\text{e}$ ), and the results were  $54.8\text{ MJ kg}^{-1}$  and  $4.35\text{ KgCO}_2\text{e Kg}^{-1}$ , respectively.

Using information from Worldsteel Association (WSA) and Aço do Brasil institute, it was possible to obtain data on greenhouse gas (GHG) emissions in  $\text{CO}_2\text{e}$ , waste generation and embodied energy related to crude steel production. It was also possible to remove emission data using the OpenLca software, and agribalyse database that contains some Ecoinvent data. The methodologies used were IMPACT 2002+, ReCiPe 2016 Midpoint (H) and IPCC 2013 GWP 100a. The values are shown in Table 1.

**Table 1.** Environmental indicators of steel manufacturing.

| Sustainability Indicator  | Reference  | Process and Material   | Average (2018 – 2020) |
|---|--|------------------------|-----------------------|
| GHG emissions<br>( $\text{kg CO}_2\text{e kg}^{-1}$<br>crude steel) | Brazil Steel Institute:<br>World Steel Association | Crude steel production | 1.8                   |
|   | Brazil Steel Institute: IPCC<br>methodology (2021) | Crude steel production | 1.7                   |
|   | OpenLca: IMPACT 2002+                              | Hot rolling of steel   | 1.846                 |
|   |  | Steel drawing          | 0.455                 |
|   |  | Hot rolling of steel   | 1.959                 |

|  |                                     |                        |       |
|--|-------------------------------------|------------------------|-------|
|  | OpenLca: ReCiPe<br>2016Midpoint (H) | Steel drawing          | 0.495 |
|  | OpenLca: IPCC 2013 GWP<br>100a      | Hot rolling of steel   | 1.926 |
|  |                                     | Steel drawing          | 0.486 |
| Embodied energy<br>(MJ kg <sup>-1</sup> crude steel) | WorldSteel Association              | Crude steel production | 20.4  |

The system has 120 layers, each with 1 bead, to make the central cylinder. And the waiting time for each layer to dry is 2 minutes. In the construction of the flanges thickness. Waiting for these cords, in this situation, lasts 2 minutes and the wait between layers lasts an average of 4.5 minutes. The calculation of stand-by times in the WAAM for flanges are shown in Table 2.

Table 2. Calculation of waiting times in WAAM for flange 1 and flange 2.

| Layer gap in flange<br>thickening<br>(Flange 1)(Flange 2)                         | Cords per<br>layer | Waiting time per cord<br>(min) | Total waiting time between<br>cords (min)<br>(Flange 1)(Flange 2) |
|---|--------------------|--------------------------------|---|
| 1-51-6  | 9                  | 2                              | 80 96   |
| 6-77-8  | 8                  |                                | 28 28   |
| 8-99-10   | 7                  |                                | 24 22   |
| 10-11 11-12   | 6                  |                                | 20 20   |
| 12-13 13-14   | 5                  |                                | 16 16   |
| 14-41 15-41   | 4                  |                                | 168 162   |
| <b>Total time spent waiting between cords (min):</b>                              |                    |                                | <b>336 346</b>  |
| Waiting time between layers (min):  |                    |                                | 4.54.5  |
| Number of layers:   |                    |                                | 41 41   |
| <b>Total time spent waiting between layers (min):</b>                             |                    |                                | <b>180 180</b>  |
| Number of layers in the central cylinder deposition<br>(each layer has 1 cord):   |                    |                                | 120 120   |
| Waiting time between layers (min):  |                    |                                | 2 2   |
| <b>Total time spent waiting between layers in the central cylinder<br/>(min):</b> |                    |                                | <b>238 238</b>  |
| <b>Total time spent during WAAM initialization and adjustment<br/>(min)</b>       |                    |                                | <b>30 30</b>  |
| <b>Total time spent with WAAM in stand-by (T<sub>masb</sub>)</b>                  |                    |                                | <b>784 794</b>  |

The time spent in deposition ( $T_{mad}$ ) was calculated through the consumption of shielding gas. The consumption flow in the production of each flange and the amount of volume used for deposition are known.

### 2.3. Life Cycle Impact Assessment (LCIA)

#### 2.3.1. Calculation of energy demand in WAAM process

In the second stage of the production process, shown in Figure 3, the electrical energy required during the process was evaluated. For this calculation, the energy consumed by the machine in 2 operating moments was considered: during stand-by and during material deposition. Energy demand is calculated according to Equation (1):

$$E_{WAAM2} = (P_{masb} \times T_{masb}) + (P_{mad} \times T_{mad}) + (E_{gas} \times C_g \times T_{mad})(1)$$

Where,

$E_{WAAM2}$ : electrical energy demand of the WAAM unit process in step 2 (MJ)

$P_{masb}$ : WAAM system power demand in stand-by mode (kW)

$T_{masb}$ : time of initialization, configuration and wait between layers and strands (h)

$P_{mad}$ : WAAM system power demand in deposition mode (kW)

$T_{mad}$ : deposition time (h)

$E_{gas}$ : shielding gas embodied energy (MJ/L)

$C_g$ : shielding gas consumption rate (L/h).

The data for carrying out the calculations of the electrical energy demand of the MAAA unitary process in stage 2 are presented in Table 3.

**Table 3.** Data required to calculate energy demand in step 2.

| Parameter         | Flange 1 | Flange 2 |
|-------------------|----------|----------|
| $P_{masb}$ (kW)   | 0.0426   | 0.0426   |
| $T_{masb}$ (h)    | 13.07    | 13.23    |
| $P_{mad}$ (kW)    | 3.5      | 3.5      |
| $T_{mad}$ (h)     | 61.1     | 60.0     |
| $E_{gas}$ (L/min) | 0.0285   | 0.0285   |
| $C_g$ (L/min)     | 15.0     | 15.0     |

In step 3 of Figure 3, for finishing machining, 2 machines are used, one to machine the internal diameter and the external part and other to make the holes in the flange. For this stage, the operating and stand-by time of the machines was disregarded and the operating times were estimated according to manufacturing information. The required electrical energy was calculated according to Equation (2):

$$E_{MAAA3} = (P_{mq1} \times T_{mq1}) + (P_{mq2} \times T_{mq2}) \quad (2)$$

Where,

$E_{WAAAM3}$ : electrical energy demand of the WAAM unit process in step 3 (MJ)

$P_{mq1}$ : machining machine power demand (inside diameter) (kW)

$T_{mq1}$ : machine time (h)

$P_{mq2}$ : power demand of the machining machine (parts hole) (MJ)

$T_{mq2}$ : final finishing machine time in cutting (h)

During the machining of the part, the material is extracted and removed, the holes in the flange are made, obtaining the part in its final format, ready for use. Machining data are presented in Table 4.

**Table 4.** Data regarding the machining of the flange manufactured by MAAA.

| Parameter  | Flange 1 | Flange 2 |
|--|----------|----------|
| Electrical power demand: Machining machine 1 (inside diameter machining) ( $P_{mq1}$ ) | 23.18 kW | 23.18 kW |
| Total time on Machine 1 ( $T_{mq1}$ )  | 4 hours  | 30 hours |
| Electrical power demand: Machining machine 2 (parts drilling machining) ( $P_{mq2}$ )  | 17.31 kW | 17.31 kW |
| Total time on Machine 2 ( $T_{mq2}$ )  | 10 hours | 20 hours |

### 2.3.2. Calculation of CO<sub>2</sub>e emissions in WAAM process

To transform this measured energy into CO<sub>2</sub> emissions in the environment, it is necessary to calculate the Carbon Emission Factor (CEF), an estimate of CO<sub>2</sub> amount associated with a given electrical energy generation. This study is carried out by the Brazilian Ministry of Science, Technology, Innovations and Communications, which prepares constant inventories on CO<sub>2</sub> Emission Factor in electricity generation in Brazilian National Interconnected System and makes them available on its online portal [57]. Through the CEF it is possible to value the environmental impact using electricity in machinery, and the average in the last 5 years, from 2018 to 2022, was calculated as 0.0759 kgCO<sub>2</sub> kWh<sup>-1</sup>.

To calculate CO<sub>2</sub> emission in the WAAM production process it was necessary to use electrical energy demands in WAAM found and applied in Equation (3):

$$CO_{2\ WAAM} = (E_{WAAM2} + E_{WAAM3}) \times CEF + Cf_{gas} \quad (3)$$

Where,

$CO_{2\ WAAM}$ : CO<sub>2</sub> emission in WAAM (kgCO<sub>2e</sub>)

$E_{WAAM2}$ : energy demand of WAAM unit process in step 2 (kWh)

$E_{WAAM3}$ : energy demand of WAAM unit process in step 3 (kWh)

$CEF$ : Carbon Emission Factor of local electricity grid (kgCO<sub>2e</sub> kWh<sup>-1</sup>)

$Cf_{gas}$ : Carbon footprint related to shielding gas (kgCO<sub>2e</sub>)

In order to calculate the greenhouse gases (GHG) emission in CO<sub>2e</sub> in this work, it was necessary to convert the gas volume (Argon + 8% CO<sub>2</sub>) to kg. Using the European Life Cycle database and the Intergovernmental Panel on Climate Change [58, 59], we could obtain the GHG emission factors involved in the production of gases, in kgCO<sub>2e</sub> Kg<sup>-1</sup>, for argon and CO<sub>2</sub>, 0.88425 and 0.811, respectively. The total CO<sub>2e</sub> emission present in shielding gas is shown in Table 5.

**Table 5.** Equivalent CO<sub>2</sub> Emission (CO<sub>2e</sub>).

| Gases present in the shielding gas            | Total volume ( L) |          | Total mass (kg) |          | GHG emissions (kg CO <sub>2e</sub> ) |          |
|---|-------------------|----------|-----------------|----------|--------------------------------------|----------|
|   | Flange 1          | Flange 2 | Flange 1        | Flange 2 | Flange 1                             | Flange 2 |
| Ar  | 253.0248.4        |          | 79.077.1        |          | 69.5                                 | 68.2     |
| CO <sub>2</sub> (8%)                          | 22.0              | 21.6     | 7.5             | 7.4      | 13.6                                 | 13.4     |
| Total present in shielding gas ( $Cf_{gas}$ ) |                   |          |                 |          | 90.6                                 | 89.0     |

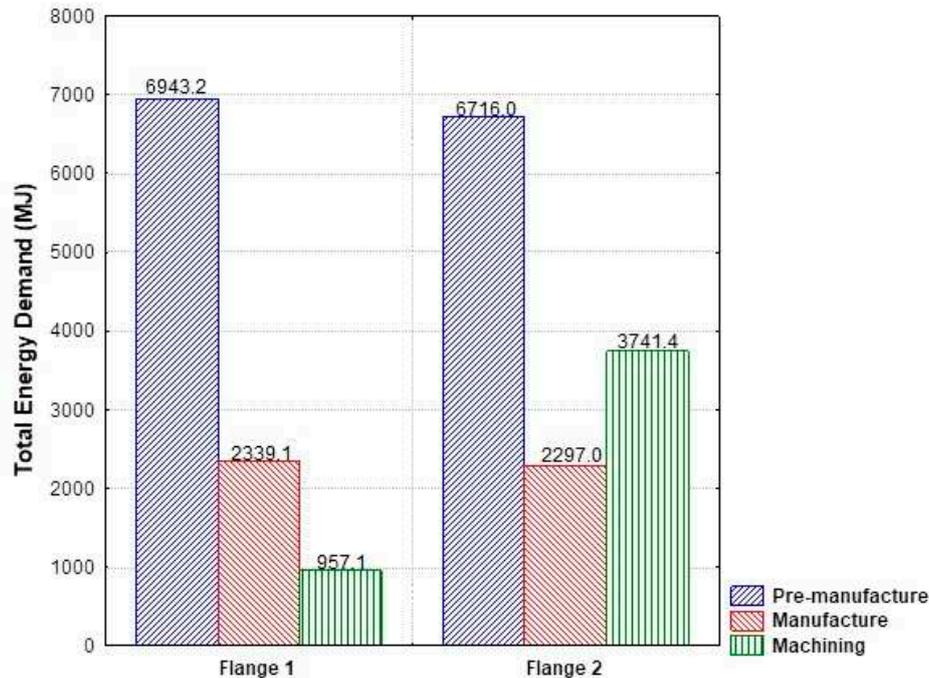
It is important to highlight that in Table 5, the emission of CO<sub>2</sub> itself present in the gas mixture is added, which represents 8% of the total volume. For flange 1 and 2 they were 7.5 kg and 7.4 kg, respectively. These values were obtained from the data in Table 6.

**Table 6.** Parameters for calculating the masses of shielding gases.

| Parameter             | Flange 1  | Flange 2  |
|-----------------------|-----------|-----------|
| <b>Argon</b>          |           |           |
| Pressure (bar)        | 190       | 190       |
| Volume (L)            | 253       | 248.4     |
| Temperature (K)       | 294       | 294       |
| MM (g/mol)            | 39.948    | 39.948    |
| R (L bar/mol K)       | 0.0831451 | 0.0831451 |
| n (mol)               | 1966.5    | 1930.7    |
| Mass (Kg)             | 79.0      | 77.1      |
| <b>CO<sub>2</sub></b> |           |           |
| Pressure (bar)        | 190       | 190       |
| Volume (L)            | 22        | 21.6      |
| Temperature (K)       | 294       | 294       |
| MM (g/mol)            | 44.009    | 44.009    |
| R (L bar/mol K)       | 0.0831451 | 0.0831451 |
| n (mol)               | 171.0     | 167.9     |
| Mass (Kg)             | 7.5       | 7.4       |

### 3. Results and Discussion

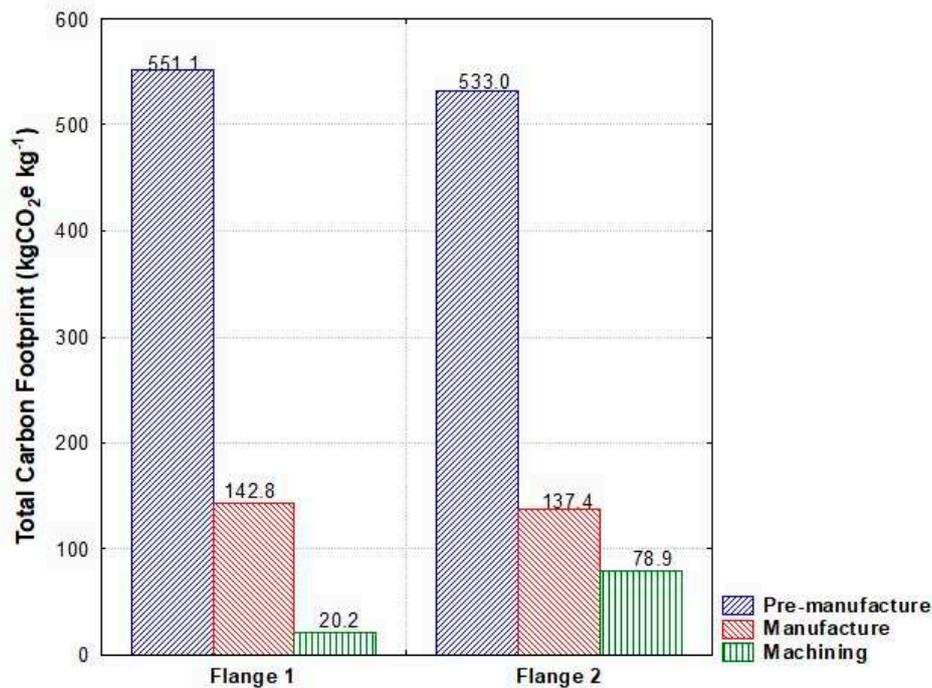
With primary and secondary data, measured, collected and modeled, presented in "Methodology", it was possible to obtain information regarding energy demand and CO<sub>2e</sub> emissions generation in the life cycle of the products manufactured using by WAAM. The total energy demand in flanges 1 and 2 were, respectively, 10,239.0 MJ, 12,754.0 MJ and the WAAM process carried out on flange 2 was approximately 19.7% higher. The results obtained are shown on Figure 4.



**Figure 4.** Total energy demand in Wire and Arc Additive Manufacturing (WAAM).

For both flanges, we observed that the prefabrication stage of flange 1 was the one that consumed the greatest amount of energy, 68% of the total, followed by manufacturing by deposition and the machining stages, with 23% and 9% of energy consumption. The deposition manufacturing phase is dependent on the deposition rate of the welding material and in this work the Pulsed GMAW process was used, with 1.2 mm wire diameter and 1.9 kg h<sup>-1</sup> melting/deposition rate. The machining stage showed lower energy consumption, 9%, as this phase is very efficient, especially when we spend less time. In flange 2, the prefabrication stage was also the one that consumed the greatest amount of energy, 53% of the total, but machining was the second largest consumer of energy, as it consumed more time, as presented in the methodology, 29% and manufacturing by deposition consumes 18% of the total.

The total carbon footprint on flanges 1 and 2 was, respectively, 714.1 kgCO<sub>2e</sub> kg<sup>-1</sup>, 749.3 kgCO<sub>2e</sub> kg<sup>-1</sup> and the WAAM process carried out on flange 2 was approximately 4.7% higher. The results obtained are shown on Figure 5.



**Figure 5.** Total carbon footprint in Wire and Arc Additive Manufacturing (WAAM).

In WAAM, the highest CO<sub>2</sub>e emissions occurred in the prefabrication of flanges 1 and 2, respectively, 77.0% and 71.0%, followed by deposition manufacturing with 20.0% and 18.0%. The machining of flange 2 was 74.4% greater than the machining of flange 1, because more time was added to flange 2 machining, indicating an important factor in the production of the parts.

It is important to highlight that in the deposition stage the gas was used only during deposition and, when the machine was in stand-by mode, the shielding gas was not released from the cylinder. The greater the amount of material used in the manufacturing process, the greater the CO<sub>2</sub>e emission. Reductions in environmental impact are predominantly driven by reduced shielding gas and electricity for fume extraction per kilogram of printed material.

In 2019, Brazil produced about 30 million tons of crude steel (WSA) and the global CO<sub>2</sub> emissions of the steel sector in the same year were approximately 3.6 Gt, representing more than 8% of total energy use and than each ton of crude steel, generating about two tons of CO<sub>2</sub> emissions [60]. In this context, the importance of producing metal parts with low greenhouse gas emissions and lower energy consumption is the major challenge in production using additive manufacturing.

#### 4. Conclusions

The model developed in this work presented similar results in the pre-manufacturing stages and in WAAM, indicating the reliability of the results in terms of greenhouse gas emissions and energy consumption. The model also presented important information during the production stages, when we increase machining time, as at this stage, based on the developed model, special attention should be paid during the preparation of the life cycle analysis.

The steel industry contributes to harmful effects on the environment through the waste of materials, consumption of resources and energy and CO<sub>2</sub> emissions, as well as other greenhouse gases related to climate change. In this sense, developing methodologies that can assist in the calculations of environmental indicators is very important during life cycle assessment.

**Author Contributions:** Claudinei de Souza Guimarães performed the modeling, analyzed the results and wrote the manuscript; Brunna Mothé Mattos carried out the literature review, modeling and calculations; João Payão Filho obtained the experimental results and revised the manuscript.

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**Conflicts of Interest:** The authors declare no conflict of interest.

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