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Digital Platform for Environmental and Economic Analysis of Wire Arc Additive Manufacturing

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Abstract. Additive Manufacturing (AM) is gaining attraction due to its benefits such as the ability to fabricate complex shapes, reduced material waste, minimal tooling among others. Wire Arc Additive Manufacturing (WAAM) is an AM process that presents novel opportunities in the fabrication, repair, and refurbishment of products. Nowadays with increased awareness regarding sustainability, assessment of WAAM based on its environmental and economic performance is essential. The popular methods for environmental and economic assessment are Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) respectively. Both these methods are data and time-intensive requiring knowledgeable personnel for their implementation. The objective of this paper is to reduce the time, labour, and costs concerning LCA and LCC procedures by digitalizing them. This paper presents a digital platform where LCA and LCC analyses of WAAM products can be obtained by a user just by entering the geometrical specifications of a product and process parameters.

Keywords: Wire Arc Additive Manufacturing, Life Cycle Assessment, Life Cycle Costing, Sustainability, Digitalization

1 Introduction

The industrial sector is resource intensive, accounting for 37% of the global energy use and responsible for about 24% of the global CO₂ emissions, according to a report by International Energy Agency (IEA) [1]. Increased customer consciousness about the environment and emergence of tougher environmental legislations have pushed the manufacturers to develop sustainable products [2]. Nowadays, adoption of additive manufacturing (AM) is gaining attention due to its ability to fabricate complex shapes and better material utilization [3]. One emerging AM process is Wire Arc Additive Manufacturing (WAAM), where a metal wire is melted using an electric arc and deposited layer by layer. WAAM has a promising sustainability potential as it requires lesser material removal and shorter lead times compared to conventional subtractive manufacturing processes [4]. The environmental and economic sustainability of the WAAM can be evaluated using Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) methodologies respectively. In LCA, the environmental impact of a product is calculated based on the resources and energy consumed over its life cycle. LCC involves economic evaluation of a product over its life cycle. However, conducting LCA and LCC

analyses is a time and labour-intensive task, where the environmental and economic data needs to be collected from various sources and an expert is needed to perform such analyses. This makes the application LCA and LCC methodologies costly.

Digitalization of LCA and LCC methodologies using predictive models that require minimum human effort and expertise can help in reducing the costs of LCA and LCC methodologies. Therefore, the aim of this paper is to digitalize and virtualize the LCA and LCC procedures for WAAM. This paper presents a digital platform where LCA and LCC analyses of WAAM products can be performed by a user just by entering the geometrical specifications of a product and process parameters. This paper is structured as follows: Section 2 links this work with digitalization and virtualization. Section 3 presents the previous work on LCA and LCC studies of AM processes. In Sections 4 and 5, the LCA and LCC models are explained in depth respectively while Section 6 demonstrates the digital platform for LCA and LCC of WAAM. Finally, the conclusions are discussed in Section 7.

2 Relation to Digitalization and Virtualization

The fourth industrial revolution or Industry 4.0 is leveraging digitalization across the whole life cycle of the products. Digitalization in manufacturing can be accomplished by digitalization of its supply, production, and delivery operations [5]. This is achieved using the principle of virtualization, where the real-world data is transformed into digital simulation-based models [6]. In manufacturing, digitalization has found applications in different operations like sensing, control, modelling and simulation, predictive maintenance among others [7]. As mentioned in the previous section, sustainability of products is gaining attention in the industrial sector in response to the strict environmental regulations and growing environmental awareness among the consumers. Therefore, the environmental and economic assessment of products need to be performed using LCA and LCC methodologies respectively.

In this paper, the environmental and economic assessment activities are digitalized. Using the real-world experimental data, predictive LCA and LCC models for environmental impact and production cost calculations, respectively are developed. Using these models, a digital platform is developed where even a non-expert user with minimal background in LCA or LCC can get the environmental impacts and production costs of WAAM by entering the geometrical and process parameters (see Fig.1.). Therefore, this digital platform will help in reducing the time, effort and labour cost associated with the environmental and economic assessment of WAAM products. This platform can offer new opportunities for prediction and improvement of environmental and economic performance of WAAM products. The designers can simulate different parts to be fabricated in future and assess their environmental footprint and production costs digitally.

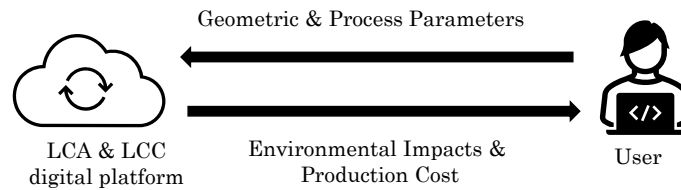


Fig. 1. Schematic representation of the digital platform for LCA and LCC of WAAM.

3 Related Work

Several LCA studies for different AM processes have been conducted in the past [8]. However, most of them are individual case specific studies and fewer studies focus on developing predictive LCA models that can be used to estimate the environmental performance of an AM process in advance. Bourhis et al. developed a predictive model to estimate the environmental impacts of manufacturing products by additive laser manufacturing (ALM) process [9]. Kellens et al. established parametric models to estimate the environmental footprint of Selective Laser Melting (SLM) process [10]. Meteyer et al. presented predictive models for material and energy consumption in binder jetting (BJ) process which then can be used to estimate the life cycle inventory data for LCA studies [11]. Yao and Huang integrated parametric LCA, LCC and optimization models to identify which parameters can affect the environmental impact and life cycle costs of emerging technologies including AM [12]. Ingarao et al. presented LCA models for aluminium parts made by AM, machining and forming routes [13]. Similarly, several studies based on cost modelling of different AM processes have been done in the past [14]. Ruffo [15], Rickenbacker [16] and Lindemann [17] have developed cost models for laser based AM processes. As far as WAAM is concerned, only a few studies performing LCA of WAAM [18–20] or its cost modelling [21] were reported.

Based on the above literature review, it was realized that LCA or LCC of any AM process is a data and time intensive process. One needs to record the amount resources and energy consumed during the process and collect their costs. Moreover, it needs to be carried out by an expert. This makes such assessments more costly. However, with growing emphasis on sustainable development, conducting LCA and LCC to understand environmental and economic aspects of a product/process is essential. Therefore, there is a need to develop predictive LCA and LCC models that can establish a relation between process/geometric parameters and environmental impacts/life cycle costs of AM processes. Digitalizing these models where a user without much knowledge about LCA and LCC methodologies can compute life cycle impacts and costs will further ease their adoption in early stages of product/process development. In this paper, analytical models are developed to predict the resource consumption, environmental impacts, and costs for producing components using WAAM process. Furthermore, a digital platform is developed where a user can enter geometric and process parameters to get the environmental impact and cost of WAAM production.

4 LCA Model

The goal of the LCA study is to determine the environmental impacts caused to due to manufacturing a part by WAAM process. The scope of this study has been limited to the production of a part geometry by WAAM process as illustrated in Fig.2. The scope begins with raw material production where feed wire is produced by subjecting a billet to hot rolling followed by wire drawing. The feed wire, electricity and shielding act as inputs to WAAM process where the part is fabricated by depositing material layer by layer. After printing each layer, it is subjected to cooling while electric arc is turned off. Further, the part is subjected to CNC milling for post processing to achieve the required dimensions and tolerances.

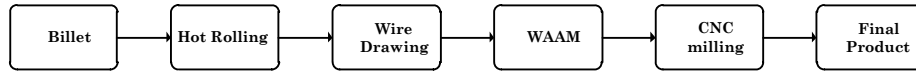


Fig.2. Scope of the LCA model.

The WAAM process time can be divided into two categories: printing time (t_{printing}) and cooling time (t_{cooling}). The printing time is the time when the material is deposited while the machine is idle in cooling time and the printed layer is allowed to be cooled. The build rate (BR) of the WAAM process is calculated as follows:

$$BR = \left(\pi d_{\text{wire}}^2 / 4 \right) \times WFS . \quad (1)$$

where d_{wire} is the feed wire diameter and WFS is the wire feed speed.

The printing time is calculated by dividing the part volume (V_{part}) with the build rate.

$$t_{\text{printing}} = V_{\text{part}} / BR . \quad (2)$$

The cooling time (t_{cooling}) is calculated by multiplying interlayer cooling time ($t_{\text{cooling layer}}$) with the total number of layers. The total number of layers is calculated by dividing the part height (h_{part}) with height of 1 layer (h_{layer}).

$$t_{\text{cooling}} = t_{\text{cooling layer}} \times \left(h_{\text{part}} / h_{\text{layer}} \right) . \quad (3)$$

Therefore, the total time for WAAM process (t_{WAAM}) is the sum of printing and cooling times.

$$t_{\text{WAAM}} = t_{\text{printing}} + t_{\text{cooling}} . \quad (4)$$

The post-processing time i.e., CNC milling time ($t_{\text{post-processing}}$) is obtained by dividing the mass of the material removed by the material removal rate (MRR).

$$t_{\text{post - processing}} = (BTF - 1) \times m_{\text{part}} / MRR . \quad (5)$$

where, BTF is the buy to fly ratio of WAAM and m_{part} is the final part weight. BTF ratio is the ratio of the final part weight after post-processing and the part weight before post-processing.

The inventory flows considered in WAAM process are raw material, electricity, shielding gas and the post-processing operation in the form of CNC milling. The amount of raw material (m_{material}) i.e., feed wire consumed in WAAM is calculated by multiplying BTF ratio of WAAM process and the mass of the final part (m_{part}) as

follows

$$m_{material} = BTF \times m_{part} . \quad (6)$$

The environmental impact of raw material is calculated by multiplying the mass of material consumed by characterization factor of that material ($cf_{material}$) and is expressed in milli points (mPts).

$$EI_{material} = m_{material} \times cf_{material} . \quad (7)$$

Electricity is used for producing an electric arc which melts the feed wire in WAAM. The electricity consumed in part production (e_{part}) is computed by multiplying the power of the electric arc (P_{arc}) and time taken for printing ($t_{printing}$).

$$e_{part} = P_{arc} \times t_{printing} . \quad (8)$$

The environmental impact of the electricity consumed ($EI_{electricity}$) is calculated as a product of e_{part} and characterization factor for electricity ($cf_{electricity}$), as follows

$$EI_{electricity} = e_{part} \times cf_{electricity} . \quad (9)$$

The shielding gas is used during the process to protect the molten metal from interaction with atmospheric gases. The volume of shielding gas used in part manufacture is determined as a product of the gas flow rate (f_{gas}) and the printing time ($t_{printing}$).

$$g_{part} = f_{gas} \times t_{printing} . \quad (10)$$

The environmental impact of shielding gas (EI_{gas}) is given by multiplying g_{part} with the characterization factor for shielding gas (cf_{gas}).

$$EI_{gas} = g_{part} \times cf_{gas} . \quad (11)$$

Similarly, the environmental impact of CNC milling is determined as the product of amount of material removed and the characterization factor for CNC milling ($cf_{CNCmilling}$).

$$EI_{CNCmilling} = (BTF - 1)m_{part} \times cf_{CNCmilling} . \quad (12)$$

The total environmental impact of the production of a part (EI_{part}) is the sum of the environmental impacts of raw material, electricity, shielding gas and post-processing.

$$EI_{part} = EI_{material} + EI_{electricity} + EI_{gas} + EI_{CNCmilling} . \quad (13)$$

The characterization factors (cf) for individual inventory flows obtained from Ecoinvent 3 database [22] are listed in Table 1.

Table 1 Characterization factors of inventory flows based on Ecoinvent 3 database [22].

| Element | Characterization factor (cf) | Unit |
|------------------------------|------------------------------|---------------------|
| Steel Wire | 157 | mPts/kg |
| Electricity (Portuguese mix) | 20.6 | mPts/kWh |
| Shielding gas (Argon) | 106 | mPts/m ³ |
| CNC milling | 84.6 | mPts/kg |

To characterize the inventory of WAAM process experimentally, a single steel wall of 120 mm in length, 40 mm in height and 5 mm in thickness was fabricated using WAAM. The voltage was set to 21 V and a feed wire of 1 mm in diameter was used.

The wire feed speed of 3 m/min, travel speed of 240 mm/min and layer height of 1.3 mm was used. The shielding gas flow rate was fixed at 15 l/min. The deposited mass was milled to required dimensions. The weight of the material deposited by WAAM was measured to be 260 grams. The final weight of the wall after milling was recorded to be 134 grams. Hence, the BTF ratio calculated was 1.96. It took 17 minutes to print the wall consuming 0.483 kWh of electricity. The cooling time was 64 minutes. Thus, the power of the electric arc calculated is 1.7 kW.

5 LCC Model

A LCC model for WAAM process is formulated using the guidelines given by IEC 60300-3-3 Dependability management–Part 3-3: Application guide–Life cycle costing standard [23]. The scope is limited to production phase and following cost elements are considered: machine cost, material cost, consumables cost, post-processing cost and labour cost. The machine cost (C_{machine}) includes the cost of WAAM machine tool (C_{mct}), its maintenance (C_{mt}) and tooling (C_{tooling}). The WAAM machine is assumed to be available for 3 shifts of 8 hours a day, for 250 days a year with 80% availability for a depreciation period of 7 years. Therefore, the hourly cost of using machine (MCC_{1h}) is given as follows

$$MCC_{1h} = (C_{\text{mct}} + C_{\text{mt}} + C_{\text{tooling}}) / t_{\text{available}} . \quad (14)$$

The machine cost (C_{machine}) is computed by multiplying the hourly machine cost (MCC_{1h}) with the total time of the WAAM process (t_{WAAM}) as given by

$$C_{\text{machine}} = MCC_{1h} \times t_{\text{WAAM}} . \quad (15)$$

The material cost (C_{material}) is the cost of raw material i.e., the feed wire consumed in WAAM. It is determined as by multiplying the amount of wire consumed (m_{material}) and the cost of 1 kg wire ($MC_{1\text{kg}}$) as follows

$$C_{\text{material}} = m_{\text{material}} \times MC_{1\text{kg}} . \quad (16)$$

The consumables cost ($C_{\text{consumables}}$) is the cost of process consumables like electricity and shielding gas. It is calculated by the multiplying the amount of electricity (e_{part}) and shielding gas consumed (g_{part}) with their respective costs per unit ($EC_{1\text{kWh}}$ & $GC_{1\text{m}^3}$).

$$C_{\text{consumables}} = e_{\text{part}} \times EC_{1\text{kWh}} + g_{\text{part}} \times GC_{1\text{m}^3} . \quad (17)$$

The post-processing cost ($C_{\text{post-processing}}$) is the cost of post processing operation associated with WAAM i.e., CNC milling in our case. It is the product of hourly cost of post-processing operation (PPC_{1h}) and post processing time ($t_{\text{post-processing}}$).

$$C_{\text{post-processing}} = PPC_{1h} \times t_{\text{post-processing}} . \quad (18)$$

The labour cost is the cost of WAAM operator and is determined by multiplying hourly labour rate (LC_{1h}) and time required by the operator (t_{labour}).

$$C_{\text{labour}} = LC_{1h} \times t_{\text{labour}} . \quad (19)$$

The production cost ($C_{\text{production}}$) for a part is the sum of all the above costs.

$$C_{\text{production}} = C_{\text{machine}} + C_{\text{material}} + C_{\text{consumables}} + C_{\text{post-processing}} + C_{\text{labour}} . \quad (20)$$

The values of the above cost elements with their respective units and sources are presented in Table 2 below.

Table 2. Values of different cost elements used in this study.

| Costs | Value | Unit | Reference |
|----------------------|--------|------------------|------------|
| Machine Tool Cost | 300000 | € | Quotation |
| Machine Cost | 12 | €/h | Calculated |
| Material Cost | 13 | €/kg | Quotation |
| Electricity Cost | 0.13 | €/kWh | [24] |
| Shielding Gas Cost | 2.3 | €/m ³ | Quotation |
| Post-processing Cost | 30 | €/h | Quotation |
| Labour Cost | 15 | €/h | [25] |

6 Digital Platform for LCA and LCC: Example of a Part Geometry

Based on the above LCA and LCC models, a digital platform is developed where the user can compute the environmental impacts and production cost of a part that is intended to be fabricated by WAAM. In this section, a demonstration of LCA and LCC analysis of a part (see Fig.3.) to be manufactured by WAAM using the digital platform is presented. The part in consideration has a volume of 15 cm³ and height of 13 mm. It has a wall thickness of 4 mm and a pocket of 9 mm depth.

The process parameters for WAAM and geometrical parameters of the part are entered in the input interface of the platform as indicated in Fig.4. The wire feed speed and travel speed are set at 300 cm/min and 24 cm/min respectively. The steel wire of 1 mm diameter is employed as feed wire input. The shielding gas i.e., pure argon flow rate of 15 l/min is used. The interlayer cooling time of 120 seconds is being utilized and layer height is set at 1.3 mm. Based on these input parameters and the LCA and LCC models described previously, environmental, and economic analyses of the given part geometry are carried out on the digital platform. The results of analyses are displayed on the output interface, as depicted in Fig.4.

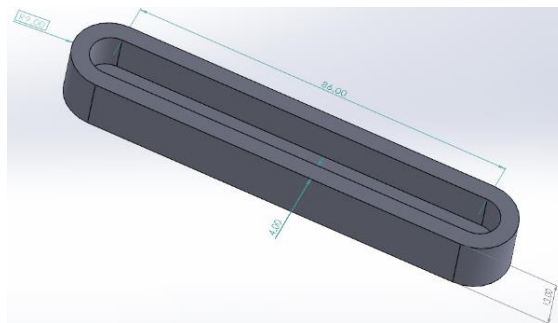


Fig. 3. Part to be manufactured by WAAM.

The environmental impact caused by production of the above part using WAAM process is 88.73 milli points (mPts). The production cost of this part is 20.60 €. The feed wire is the major contributor (52.52 mPts) to the total environmental impact followed by shielding gas (19.65 mPts). Labour is the main cost driver accounting for 8.09 € followed by the machine cost of 6.47 €. Therefore, using this digital platform, the ecological and economic performance of WAAM process can be predicted. This is helpful for designers and manufacturers, especially in the early phases of product development. Such platform can be used to simulate the environmental impact and costs of WAAM products, integrating the environmental and economic considerations in the design phase. Also, the platform is simple to use, and the user does not need extensive knowledge about LCA and LCC methodologies.

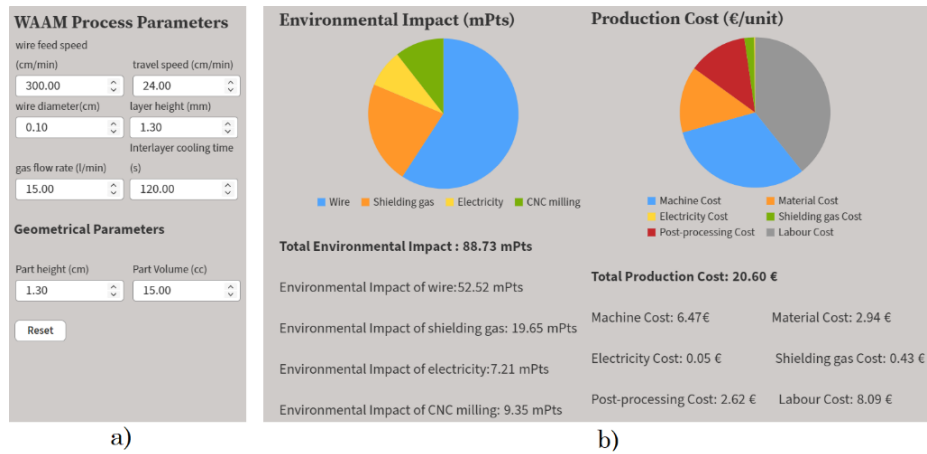


Fig.4. a) Input interface b) Output interface of the digital platform.

However, it must be noted that currently the platform can be used only for WAAM process where steel wire is used as feed wire input. Efforts need to be done for compiling the environmental and cost data for other materials. The scope of this investigation needs to be extended further to the use, transport, and disposal life cycle stages. Furthermore, the interface of the digital platform lacks features like choosing between different feed wire materials and exporting the LCA and LCC results to the user. Future works will involve the expansion of this work to different materials and life cycle stages along with features to export the results.

7 Conclusions

A digital platform to conduct LCA and LCC analyses of WAAM process was developed in this paper. Analytical models to predict the environmental impact and production costs using process and geometrical parameters of a part design were developed. Using these models, a digital platform was created, where a user can

calculate environmental impact and cost of WAAM process by entering process and geometrical parameters. This digitalization of LCA and LCC methodologies will reduce the time, effort, and cost of economic and environmental assessment of WAAM products. The current work involved modelling of environmental impacts and costs for the production of steel parts. Future works will incorporate the further life cycle stages of a product and inclusion of more raw materials. Additionally, advanced features such as exporting the results of the analyses need to be added in the digital platform.

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