Additive Manufacturing 61 (2023) 103316

Contents lists available at ScienceDirect

Additive Manufacturing

journal homepage: www.elsevier.com/locate/addma

Research paper

Environmental and economic assessment of a steel wall fabricated by wire-based directed energy deposition

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ARTICLE INFO

Keywords:
Life cycle assessment
Life cycle costing
Wire arc additive manufacturing
Steel wall

ABSTRACT

Over the past few decades, adoption of different Additive Manufacturing (AM) processes has gained momentum in the manufacturing industry. One such emerging AM process is wire-based directed energy deposition. Environmental impacts and costs are important criteria for adoption of any manufacturing process. Therefore, the aim of this paper is to evaluate the environmental and economic performance of Wire and Arc Additive Manufacturing (WAAM) using Life Cycle assessment (LCA) and Life Cycle Costing (LCC) methodologies. In this paper, an integrated methodology to conduct a cradle-to-gate LCA based on the guidelines of ISO 14044 and LCC based on IEC 60300–3–3 standards is proposed. A case study of a single steel wall manufactured by WAAM was analysed. The environmental impacts and production costs for wire-based directed energy deposition process were compared to laser powder bed fusion (LPBF) and Computer Numeric Control (CNC) milling processes. For the steel wall analysed, CNC milling was the most economical and ecological option followed by the wire-based directed energy deposition and LPBF. However, the performance of a process depends on product complexity and the manufacturing process's material efficiency. Raw material production and labour were identified as major environmental hotspot and cost driver, respectively, in wire-based directed energy deposition. The methodology used in this paper can be extended to other manufacturing processes. The results of this study can help manufacturers in selecting manufacturing processes based on environmental impacts and production costs

1. Introduction

Additive Manufacturing (AM) technologies build a part depositing material layer by layer as opposed to conventional moulding, deformation, or subtractive manufacturing processes. AM processes have gained popularity due to their benefits like freedom of design, mass customization, minimal or no need of tooling, shorter lead times, waste reduction to name a few [39,2]. Considering the four fundamental evaluation criteria of any manufacturing process, AM presents very high flexibility, good quality, and low cost (depending on the AM variant), but typically, it has a very low deposition rate. Wire Arc Additive Manufacturing (WAAM), formally classified as a Direct Energy Deposition (DED), is an emerging AM technique where metal wire is used as the feedstock material and an electric arc is used as heat source to melt the wire and the molten material is deposited layer by layer to fabricate a given geometry [45]. WAAM also presents one of the highest deposition rates among all AM technologies. The research and development in WAAM has been gaining momentum since the 1990 s although its first patent was filed in 1920 [12]. WAAM requires considerably less material removal as opposed to conventional subtractive processes, enabling material savings and shorter lead times [47]. Compared to other AM processes, WAAM has a higher deposition rate (50–130 g/min) as opposed to the deposition rate of laser-based AM processes (2–10 g/min) and hence it is more suitable for building medium to large components [53]. Other advantages of WAAM include low capital costs, open architecture, higher material utilization and lower material costs [52].

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[1] One of the authors of this article is part of the Editorial Board of the journal. To avoid potential conflicts of interest, the responsibility for the editorial and peer-review process of this article lies with the journal's other editors. Furthermore, the authors of this article were removed from the peer review process and had no, and will not have any access to confidential information related to the editorial process of this article.

https://doi.org/10.1016/j.addma.2022.103316
Received 2 July 2022; Received in revised form 31 October 2022; Accepted 22 November 2022

Major drawbacks of WAAM include high residual stresses, poor dimensional accuracy and the requirement of surface finish post-processing operations [13]. WAAM has found applications in several domains including aerospace [55], defence [5], shipbuilding [50] and construction [38] sectors.

In recent years, increased awareness regarding climate change and the emergence of stricter environmental commitments have emphasized the need for manufacturing industries to develop more environmentally friendly manufacturing technologies [36]. WAAM, given its advantages over traditional and laser-based manufacturing processes discussed earlier, has a promising sustainability potential. However, this sustainability potential must be verified quantitatively. Also, production cost is a significant factor in adopting a manufacturing process. Therefore, WAAM must be quantitatively evaluated based on its environmental and economic performance. Several research studies computing the environmental impacts [46] and costs of AM processes [9] have been reported. However, studies considering both environmental impacts and costs simultaneously are scarce. Therefore, in this paper an integrated environmental and economic analysis of WAAM using Life Cycle assessment (LCA) and Life Cycle Costing (LCC), respectively, has been conducted. The environmental impact and cost of WAAM is also compared with traditional CNC milling and powder bed fusion (PBF)-based AM, namely Selective Laser Melting (SLM).

This paper is structured into the following sections: Section 2 presents a literature review on environmental impact and cost assessments of DED processes including WAAM. In Section 3, an integrated framework for conducting LCA and LCC is described. Section 4 contains the case study performed within the scope of this paper. It includes the LCA and LCC models, their inputs, and results in the form of environmental impact (in milli points) and production cost (in €). Finally, the conclusions and the future directions of this study are discussed in Section 5.

2. Literature review

A systematic literature review of LCA and cost modelling techniques applied to DED additive manufacturing processes including WAAM is presented in this section. The current state of the art on the application of LCA and cost assessment methods are described in the following subsections.

2.1. LCA of DED processes

The application of LCA methodologies to evaluate the environmental impacts of additive manufacturing processes have gained attention in recent years. However, most of the LCA studies in metal additive manufacturing are focused on powder bed fusion type AM processes such as SLM, Electron Beam Melting (EBM) and Direct Metal Laser Sintering (DMLS). DED processes have received significantly lesser attention, as indicated in a review study by Saade et al. [46]. Some studies implementing LCA of powder-based DED processes were reported in previous years [48,4,14,40,33]. Serres et al. [48] performed a comparative cradle to grave LCA of a powder-based Direct Additive Laser Manufacturing (DALM) process and conventional machining for manufacturing a Ti6Al4V mechanical part where the environmental impact was expressed in eco-points. The DALM process showed 70% environmental impact reduction due to production of lesser material waste than the machining process. Bourhis et al. [4] proposed a methodology to predict the environmental impact of the DALM process in eco-points by developing a model to calculate the existing environmental flows as the raw material, electricity and fluids. Doran et al. [14] assessed the environmental performance expressed in greenhouse gas (GHG) emissions for DED and CNC milling for different part volumes. It was observed that milling shows better environmental performance when smaller volumes of material are removed. DED becomes a sustainable process for parts which require larger material removal. Peng et al. [40] studied the environmental impacts of a titanium alloy for the production of an impeller using 3 approaches: CNC milling, Laser Cladding, and additive remanufacturing. The additive remanufacturing was the most environmentally friendly option in this study. However, the environmental impact of pure AM i.e., Laser Cladding is approximately double the environment impact of CNC milling due to high electricity and powder consumption. Liu et al. [33] carried out a comparative LCA of powder-based DED and traditional manufacturing processes for manufacturing a AISI 4140 gear wheel. The DED process showed higher impacts than the traditional process in five out of the six impact categories considered due to higher energy consumption and higher powder consumption resulting from the lower powder efficiency.

As far as wire-based DED process is considered, less than a handful of studies focusing on its environmental sustainability were reported [42,6,3]. Priarone et al. [42] compared the cumulative energy demand and manufacturing costs of aluminium, titanium and steel parts using WAAM and CNC machining. For all three parts, WAAM showed lesser cumulative energy demand but higher manufacturing times than the CNC machining process. Campatelli et al. [6] compared the energy demand for fabricating a steel blade using an integrated WAAM-CNC milling and pure CNC milling approaches. Here the integrated WAAM-CNC milling approach exhibited about 60% material saving and 34% energy saving compared to the pure CNC milling approach. Bekker and Verlinden [3] compared the environmental impacts of WAAM, CNC milling and green sand casting to produce 1 kg 308 L stainless steel components. In that work, WAAM demonstrated slightly lesser environmental impact (expressed in eco-points) than green sand casting but significantly lower impact than CNC milling. However, this study did not include the post-processing operations for WAAM such as machining operations used to eliminate surface waviness and achieve the required dimensional accuracy. Sand blasting was used to remove the oxidation layer on the surface as the only post-processing operation. Therefore, more LCA studies on wire-based DED processes that include post processing operations like machining need to be carried out to fully the understand the environmental impacts of WAAM and the hotspots driving these impacts.

2.2. Cost models of DED processes

Multiple cost estimation models for different metal additive manufacturing techniques have been developed, as summarized by Kadir et al. [28]. After analysing the cost models reported in this paper, it is realized that most of the cost models focus on PBF processes as SLM, SLS and DMLS. Fewer cost models for DED processes were reported in the literature [42,19,10,17]. Gouveia et al. [19] developed a LCC model for a powder-based DED process that includes equipment, material, energy, shielding gas and labour costs. As far as wire-based DED process is considered, three studies developed a cost model for WAAM [42,10,17]. Priarone et al. [42] developed a cradle-to-gate cost model for medium to large industrial components manufactured by WAAM and CNC machining. The process time calculations were not described in depth. WAAM and machining times were estimated based on certain deposition rates and material removal rates recommended by the cutting tool manufacturer respectively. However, it remains unclear how process times were estimated for other activities such as setup, work frame calibration and substrate preparation. Process time estimation is important in a costs model as it influences the quantity of resources consumed in that process. Cunningham et. al. [10] developed a cost model for WAAM using an activity-based costing (ABC) approach that considered substrate preparation, deposition, heat treatment and post processing operations. However, this study did not mention maintenance, tooling and energy costs for WAAM and calculated the machining times based on an assumed buy to fly (BTF) ratio of 1.5 and material removal rate, not considering the machining strategy and parameters. Moreover, the labour input in each step was approximated. WAAM was found to be more economical than EBM and DMLS processes. However, when compared to CNC machining, WAAM was economical only for BTF ratios above 5. Facchini et al. [17] developed a cost model for WAAM focusing on non-recurring engineering (NRE) costs i.e. one-time cost for research, design and development of products. However, this model did not include tooling, set-up, post-processing, inspection, and energy costs. Therefore, based on the current state of the art, there is a clear need to focus more on the detailed cost modelling for wire-based DED process.

2.3. Motivation for present study

Based on the literature review presented above, it can be concluded that powder bed fusion processes have gained significant attention for the application of LCA and LCC models. Fewer studies analysed the environmental impacts and economic impacts of wire-based DED process like WAAM. The environmental and economic impacts were studied separately. Studies focusing on carrying out an integrated environmental and economic assessment for DED processes in general are scarce [42,19]. Therefore, the aim of this study is to conduct an integrated environmental and economic assessment of WAAM process using LCA and LCC methodologies respectively. In this paper, we have carried out a comparative LCA and LCC analysis of WAAM where the process performance is compared to SLM and CNC milling processes. SLM is chosen as a representative process for PBF AM processes due to availability of its life cycle inventory data in the literature. CNC milling is chosen as a representative of conventional manufacturing (CM) processes.

3. Methodology

Life Cycle Assessment is a well-known method to calculate the environmental impacts of a product or process across its life cycle stages. Environmental impacts are calculated based on the life cycle inventory data in the form of raw materials, energy, other resources consumed, wastes and emissions associated with a given product or process. Life Cycle Costing is a systematic methodology to compute the life cycle costs of an asset over a given period. Here, the relevant cost elements are determined, a cost model is established, cost data is collected and finally, the different cost elements are summed up to compute the aggregated cost. The methodology used in this work is based on the LCA framework defined ISO 14044 [27] standard and the LCC framework defined by IEC 60300–3–3 standard [26]. The methodology is schematically detailed in Fig. 1.

Firstly, the goal and scope of the LCA and LCC study is defined. The goal of our study is to calculate the environmental impacts and production costs associated to the WAAM process. The scope represents the time (life cycle stage(s)) considered in the study. The LCA and LCC methods, environmental impact categories, cost elements, assumptions and limitations should be defined in this step. Additionally, the functional unit on which the analysis is conducted should also be defined at this moment.

The second step is the collection of environmental and economic inventories. Environmental inventory involves raw materials, electricity, process consumables, waste, and emissions. It is collected from experiments, literature, and professional databases. Economic inventory involves costs per unit for different resources and processes involved in the study from various sources like quotations and research literature.

The third step involves the computation of the environmental impacts and costs from the inventory data collected in the previous step. Finally, in the fourth step, the results of the assessment are interpreted, and environmental hotspots and cost drivers are identified, and conclusions are drawn accordingly.

4. Case study

A flat wall of High Strength Low Alloy (HSLA) steel ER70 of final dimensions 100 × 40 × 3 mm^3 was produced by WAAM. Owing to lower dimensional accuracy and surface waviness associated with WAAM, an as-built WAAM wall of dimensions 121.2 × 41.6 × 6.7 mm^3 was obtained. Therefore, the wall was subjected to milling to remove the typical surface waviness associated with the process followed by surface grinding to achieve a smooth surface (see Fig. 2). Such geometry finds application as flat turbine blades used in some impellers as illustrated in Fig. 3. The parameters used for WAAM are detailed in Table 1. Additionally, the environmental impacts of WAAM are also compared with Selective Laser Melting (SLM) and CNC milling. LCA and LCC models for WAAM, SLM and CNC milling were created based on the methodology described in the earlier section.

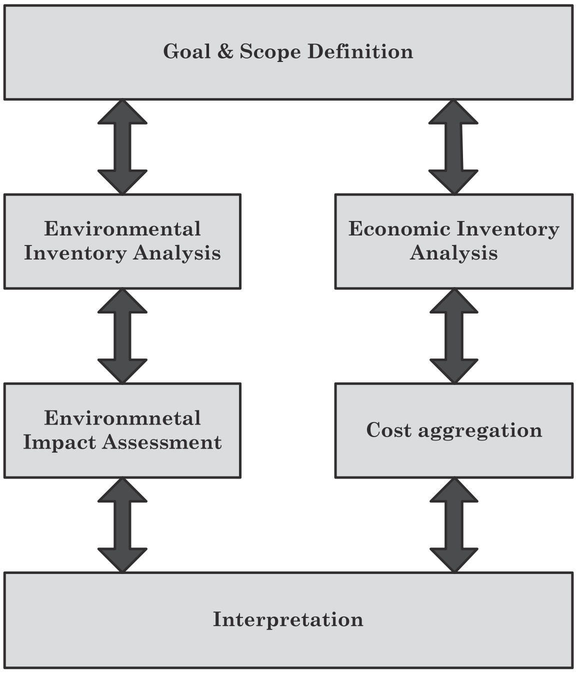

Fig. 1. Integrated LCA and LCC methodology used in this study based on [27,26].

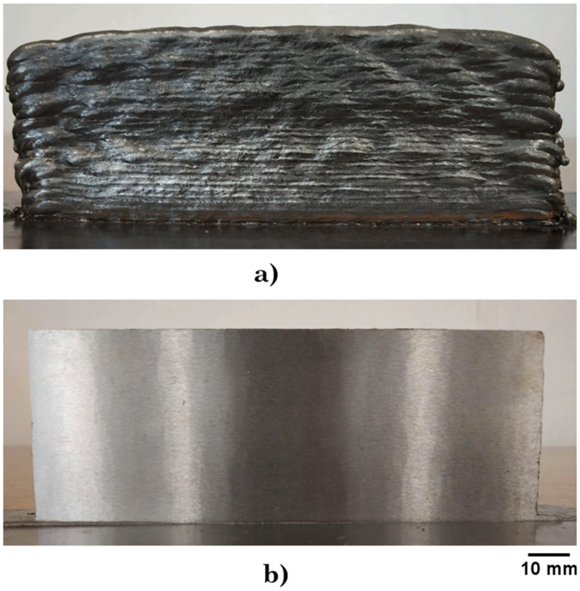

Fig. 2. ER70 Steel wall: a) after WAAM b) after milling and grinding.

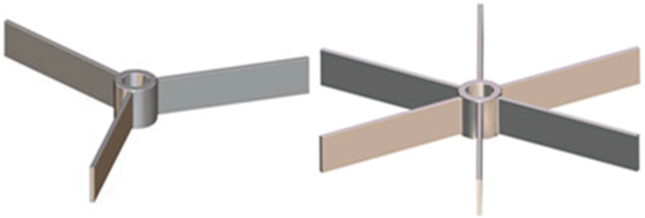

Fig. 3. Impellers using flat blade turbines [8].

Table 1
WAAM process parameters.

Process parameters	Value
WAAM	
Wire diameter (mm)	1
Voltage(V)	19
Wire feed speed (m/min)	3
Travel speed (mm/min)	360
Layer length (mm)	120
Layer height (mm)	1.3
Interlayer cooling time (s)	120
No. of layers	32
Preparation time (min)	30
Printing time (min)	12
Cooling time (min)	64
Total time (min)	106
Milling	
Spindle speed (RPM)	780
Feed rate (mm/min)	365
Depth of cut (mm)	0.1
Set up & cleaning time (min)	5
Milling time (min)	15
Surface Grinding	
Wheel speed (RPM)	3000
Depth of cut (mm)	0.02
Set up & cleaning time (min)	5
Grinding time (min)	7
Total post processing time	32

4.1. *Life cycle assessment*

A LCA model for all three analysed processes was developed in accordance with ISO 14044: Environmental management - Life cycle assessment - Requirements and guidelines [27]. The environmental inventory was collected from experiments, different literature sources and the Ecoinvent database 3 [15]. The following subsections describe the implemented LCA model in detail.

4.1.1. *Goal & scope definition*

The main objective of this study is to quantify the environmental impacts of WAAM. Additionally, the impacts of WAAM are compared with those of traditional CNC machining and SLM. The system boundaries of this study are illustrated in Fig. 4. This is a cradle to gate study and includes extraction of natural resources, production of raw feedstock materials, transportation of the raw materials to the production site and fabrication of given a product. As-built WAAM products can exhibit good mechanical properties [44]. SLM parts show comparable mechanical properties to those of bulk materials, except for a typical ductility reduction [32]. Therefore, the need for the heat treatment is excluded in this study. The inspection procedures for all 3 processes are excluded from this study as the final part is identical in all 3 cases. The base plate in WAAM and SLM on which the part is printed is also excluded from this study to ensure fair comparison with CNC machining. The shipping, utilization and disposal phases of the final part are also excluded from this study. The functional unit of this study is manufactured with ER70 steel wall with dimensions of 100 × 40 × 3 mm^3. This study was carried out using ReCipe 2016 (Hierarchical) method in commercial LCA package SimaPro 9.2 [41].

4.1.2. *Environmental inventory analysis*

Life Cycle Inventory (LCI) data for WAAM was collected from onsite experiments and Ecoinvent 3 database. LCI data for SLM and CNC machining was collected from various literature sources and from the Ecoinvent 3 database. The inventory collection for each process is described next.

4.1.2.1. WAAM. For the WAAM process, the manufacturing steps similar to [3] are considered. Prior to WAAM is performed there is a need to obtain the wire feedstock. This requires a steel billet which is then hot rolled into a rod shape. Material loss of 5% is considered for hot rolling stage based on Ecoinvent 3 database. The metal rod is subjected to successive wire drawing and the final material condition is obtained. A material loss of 4% is assumed in this case based on Ecoinvent 3 data. The shielding gas used is a mixture of 82% Ar and 18% CO_2. The steel billet, steel wire and shielding gas are assumed to be transported to the production site over 500 km distance using lorry of the size class > 32 metric tons gross vehicle weight (GVW) and Euro VI emissions class from the Ecoinvent 3 database. Then the wire is used during WAAM to be melted and deposited layer by layer until the prescribed geometry is obtained. The interlayer cooling time was set to 120 s to allow for the part temperature to reach less than 100 °C. In the present case study, the mass of deposited material was of 0.220 kg. No relevant spatter was observed during WAAM. A previous study by Rodrigues et al. [44]

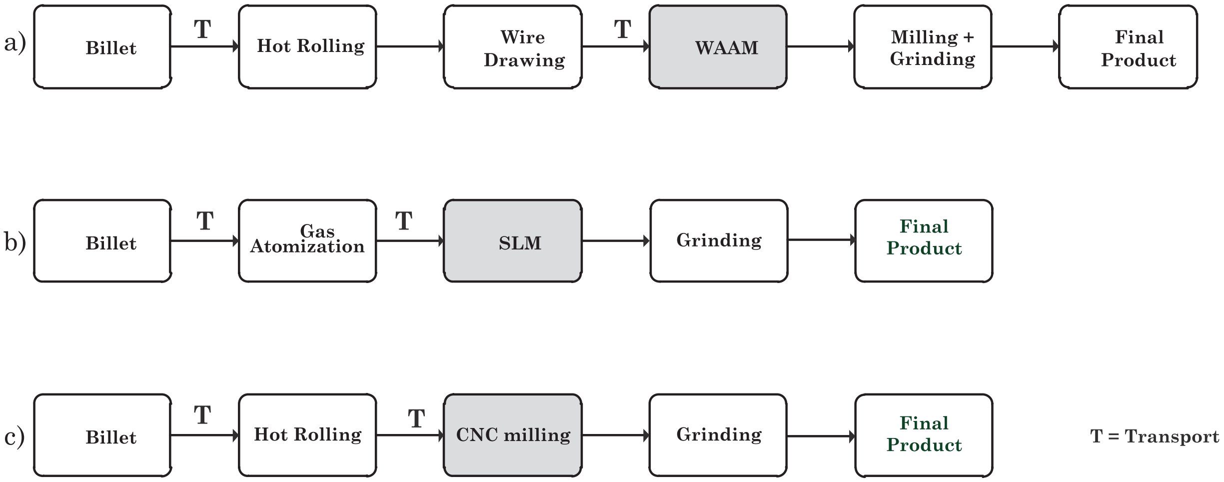

Fig. 4. System Boundaries for a) WAAM b) SLM c) CNC milling.

showed that the mechanical response of the as-built WAAM part of ER110S-G showed excellent ductility and high mechanical strength. Based on this study and material similarity, it is assumed that the ER70 product built in this study has similar properties and hence, requires no heat treatment.

Machining of the WAAM built part was performed using a Holke F1010 3 axis vertical milling machine. The values of spindle speed, table feed rate and depth of cut were set to be 780 rpm, 365 mm/min, and 0.1 mm respectively. The milling took 15 min and additional 5 min were required for setup, initialization, and cleaning. Further, the machined WAAM part was subjected to surface grinding to improve its surface finish. The grinding wheel rotation speed of 3000 rpm and a small depth of cut of 0.02 mm per pass was used. The total grinding time along with the setup and cleaning time was 12 min. The final product weighed 0.78 kg. Thus, the manufacturing material efficiency i.e., ratio of mass of final product compared to mass of raw material consumed (wire in this case) is 0.35 (or 35%) in this case. The shielding gas and energy consumed in the process were measured on site. The main source of energy consumption is the electric arc. The current and voltage were recorded using National Instruments USB 6008 data acquisition device in LabVIEW software. Based on this data, power consumption of the electric arc was calculated. The power ratings for milling and surface grinding machines were 2 kW and 1.5 kW respectively. Hence, the energy consumed in this process was calculated by multiplying the power rating and the process time. The detailed inventory analysis of WAAM process is depicted in Table 2. Note that the amount of material indicated for hot rolling and wire drawing processes is the amount of input material and not the amount of output material from these processes.

4.1.2.2. SLM. As for the SLM process, it begins with melting the billet and production of the steel powder using gas atomization process. Material loss of 10% is assumed during the gas atomization step based on the % yield of atomization of low carbon steel powder reported by Yenwiset and Yenwiset [54]. The specific energy for gas atomization considered in this study was 1 MJ/kg based on the value reported by Morrow et al. [37] for gas atomization of tool steel. Argon gas consumption is assumed to be 2 m^3/kg as used by Kamps et al. [29] for powder atomization of steel. The steel billet, steel powder and inert gas are assumed to be transported to the production site over 500 km distance using lorry of the size class > 32 metric tons gross vehicle weight (GVW) and Euro VI emissions class from the Ecoinvent database. For SLM, the following process parameters values were selected: scanning speed of 1100 mm/s, hatch distance of 100 μm and layer thickness of 50 μm, similar to the previous studies involving SLM of carburizing steel 16MnCr5 [29] and Stainless Steel 316 L powders [20]. The building rate calculated as product of these 3 parameters was 19.8 cm^3 per hour assuming a single laser operation mode of the machine. The recoating time is assumed to be 7 s for each layer. As mentioned earlier in Section 4.1.1. earlier, the base plate or building platform on which the part is SLMed is excluded in this study. However, the supporting structures built for the part need to be considered as these supporting structures are built during the SLM process to support the part being printed. Hence, their material and energy consumption need to be accounted in the inventory data. The supporting structure weight and powder losses were conservatively assumed to be 20% and 10% of the part weight, respectively based on SLM of stainless steel X12Cr13 performed by Gebbe et al. [18]. Therefore, the manufacturing material efficiency is 0.76 in this case. A preparation time of 30 min and a preheating time of 30 min is assumed. The exposure and recoating times can be calculated as follows

$$Exposure\ time = \frac{Volume\ part + Volume\ support}{Build\ Rate} \tag{1}$$

$$Recoating\ time = \frac{height\ part}{layer\ thickness} \times recoating\ time\ layer \tag{2}$$

Table 2
LCI data for WAAM process.

Material /Process	Amount	Unit	Reference
Steel billet	0.243	kg	Calculated based on Ecoinvent 3 database
Hot Rolling	0.243	kg	
Wire Drawing	0.231	kg	
WAAM Deposition	0.222	kg	Measured/calculated based on site data
Electricity	0.26	kWh	
Shielding gas	0.344	kg	
Electricity (Milling)	0.667	kWh	
Electricity (Surface Grinding)	0.3	kWh	
Final product	0.078	kg	

Additionally, a cooling time of 2 h was assumed conservatively based on the cooling time reported in previous studies [18,31]. The post-processing involves removal of the SLM part and its support structures using sawing and surface grinding of the part. The surface roughness for SLM parts is lower, generally in the range of 5–50 μm [35]. Löber et al. [34] studied the different post processing techniques for SLMed Stainless Steel 316 L parts and found that the surface quality of simple geometries can be improved using simple post-processing such as grinding. Therefore, surface grinding was considered as the post processing operation owing to the simplicity of the steel wall geometry fabricated in this work. The energy, compressed air, and argon requirements for SLM in different modes were taken from a study by Gebbe et al. [18] involving SLM of stainless steel X12Cr13 powder. The calculations of energy compressed air and argon gas consumed in SLM are presented in Table 3. The detailed inventory analysis of SLM is further detailed in Table 4.

4.1.2.3. CNC milling. For CNC milling, it is assumed that a steel billet is hot rolled to a bar. Material loss of 5% is considered for hot rolling stage based on Ecoinvent 3 database The bar is then milled to the required dimensions. The bar is subjected to roughing followed by finishing to achieve the targeted dimensional accuracy. The surface grinding procedure like that for WAAM is considered for CNC milling. The steel billet and steel bar are assumed to be transported to the production site over 500 km distance using lorry of the size class > 32 metric tons gross vehicle weight (GVW) and Euro VI emissions class from the Ecoinvent database. The milling parameters were taken from a study by Campatelli et al. [7] involving CNC milling of a thin structural steel aerofoil and are depicted in Table 5. Based on this study, it is assumed that 80% of the volume to be machined is removed by roughing and the rest is removed by finish milling. The milling time calculated was of 8.8 min. Additional 30 min are assumed for CNC code preparation and set up time. The SEC in J/mm^3 for CNC milling in was calculated using the equation proposed by Kara and Li [30]:

$$SEC = C_0 + \frac{C_1}{MRR} \tag{3}$$

where, MRR (in mm^3/s) stands for material removal rate and C_0 and C_1 are machine specific constants. The values of C_0 (=3.524) and C_1 (=2066) are taken from [7]. Based on the MRRs calculated for roughing and finishing in Table 4, the SEC values for roughing and finishing are calculated as 27.83 J/mm^3 and 132.65 J/mm^3 respectively. The input values for compressed air and cutting fluid were taken from the Ecoinvent flow of {Chromium *steel removed by milling, average {RER}| chromium steel milling, average | Cut-off, U}*. As the geometry considered in this study is simple, the manufacturing material efficiency for the CNC milled fabricated part is assumed to be 0.5. For complex geometries, the manufacturing material efficiency for CNC milling will be lower due to high amounts of material removal. The LCI data used for CNC milling is presented in Table 6. The electricity input for each process used was *{Electricity, low voltage {PT}| electricity voltage transformation from medium to low voltage | Cut-off, U}*. It must be noted that the same steel billet input from Ecoinvent database i.e. *{steel billet (Steel, low-alloyed {RER}|*

Table 3
Calculations of energy, compressed air and argon gas consumed in SLM based on [18].

SLM Production Mode	time (h)	Energy		Compressed Air		Argon	
		Power (kwh)	Energy (kWh)	Flow rate (l/min)	Total (m^3)	Flow rate (l/min)	Total (m^3)
Preparation	0.5	0.36	0.18	0	0	0	0
Preheating	0.5	2.52	1.26	0	0	40	1.2
Exposure	1.45	2.625	3.81	16.7	1.45	0	0.00
Recoating	1.55	2.625	4.07	16.7	1.55	0	0.00
Cooling	2	0.36	0.72	0	0	0	0
Total	6		10.035		3.01		1.2

Table 4
LCI data for SLM process.

Material /Process	Amount	Unit	Reference
Steel billet	0.113	kg	Calculated based on Ecoinvent data assuming manufacturing material efficiency of 0.76
Gas Atomization			Calculated based on[54,37]
Electricity	0.103	MJ	
Argon	0.367	kg	
SLM			Calculated based on[18]
Electricity	10.035	kWh	
Compressed air	3.01	m^3	
Argon	2	kg	
Electricity (Surface Grinding)	0.3	kWh	Calculated based on site data

Table 5
CNC milling process parameters based on [7].

Process parameter	Roughing	Finishing
Cutting tool	8 mm endmill	8 mm endmill
Cutting speed (m/min)	200	200
Depth of cut (mm)	2	1
Width of cut (mm)	2	1
Feed per tooth (mm/tooth)	0.04	0.03
No. of teeth	4	4
Material Removal Rate (cc/min)	5.1	0.96
Volume to be removed (cm)	19.2	4.8
Milling time (min)	4	5
Preparation time (min)	30	
Set up time (min)	5	
Total time (min)	44	

Table 6
LCI data for CNC milling process.

Material /Process	Amount	Unit	Reference
Steel Billet	0.164	kg	Calculated based on Ecoinvent 3 database assuming manufacturing material efficiency of 0.5
Hot Rolling	0.164	kg	
Compressed Air	0.099	m^3	
Lubricating Oil	0.297	g	
Water	0.0013	m^3	
Electricity	0.325	kWh	
Electricity (Surface Grinding)	0.3	kWh	Calculated based on site data

steel production, converter, low-alloyed | Cut-off, U)} was used for all 3 processes as it could not be confirmed with the manufacturers of raw material if the billet of same grade and dimensions is used in production of wire, powder and bar. Therefore, it is assumed that all three raw materials are produced from the same type of steel billets.

4.1.3. Environmental impact assessment

The environmental impact assessment was carried out using ReCiPe 2016 (Hierarchist) method. Using ReCiPe 2016 Midpoint (Hierarchist) method, the environmental impacts for 18 different impact categories are calculated. Using characterization factors available in this method, each LCI input is converted into an indicated result i.e. a single numerical value of an impact category The indicated result for each impact category is calculated as follows [11]:

$$I_c = \sum_i CF_{c,i} \times m_i \tag{4}$$

where I_c is the indicated result of impact category c, $CF_{c,i}$ is the characterisation factor of inventory i for impact category c and m_i is the amount of inventory i consumed. The impact category wise results are listed in Table 7.

Weighting was carried out to aggregate the indicator results of 18 impacts categories into a single score using ReCiPe 2016 Endpoint

Table 7
ReCiPe Midpoint Impact Assessment Results.

Impact category	Unit	WAAM	SLM	CNC Milling
Global warming	kg CO_2 eq	1.74	9.51	6.74×10^{-1}
Stratospheric ozone depletion	kg CFC11 eq	6.06×10^{-7}	3.88×10^{-6}	2.15×10^{-7}
Ionizing radiation	kBq Co-60 eq	2.81×10^{-1}	2.15	9.71×10^{-2}
Ozone formation, Human health	kg NO_x eq	3.89×10^{-3}	2.16×10^{-2}	1.58×10^{-3}
Fine particulate matter formation	kg PM2.5 eq	2.73×10^{-3}	1.51×10^{-2}	1.12×10^{-3}
Ozone formation, Terrestrial ecosystems	kg NOx eq	4.02×10^{-3}	2.18×10^{-2}	1.66×10^{-3}
Terrestrial acidification	kg SO_2 eq	6.54×10^{-3}	4.22×10^{-2}	2.37×10^{-3}
Freshwater eutrophication	kg P eq	9.49×10^{-4}	5.62×10^{-3}	3.78×10^{-4}
Marine eutrophication	kg N eq	7.17×10^{-5}	3.91×10^{-4}	2.68×10^{-5}
Terrestrial ecotoxicity	kg 1,4-DCB	5.13	14	2.58
Freshwater ecotoxicity	kg 1,4-DCB	8.67×10^{-2}	3.31×10^{-1}	5.08×10^{-2}
Marine ecotoxicity	kg 1,4-DCB	1.18×10^{-1}	4.42×10^{-1}	6.82×10^{-2}
Human carcinogenic toxicity	kg 1,4-DCB	5.57×10^{-1}	7.33×10^{-1}	3.13×10^{-1}
Human non-carcinogenic toxicity	kg 1,4-DCB	1.68	8.67	0.733
Land use	m^2a crop eq	4.34×10^{-2}	2.17×10^{-1}	3.01×10^{-2}
Mineral resource scarcity	kg Cu eq	3.49×10^{-2}	2.43×10^{-2}	2.31×10^{-2}
Fossil resource scarcity	kg oil eq	4.44×10^{-1}	2.63	1.69×10^{-1}
Water consumption	m^3	3.34×10^{-2}	2.1×10^{-1}	6.9×10^{-3}

(Hierarchist) method. A single score result is calculated as follows

$$S = \sum_{c} WF_c \times I_c \tag{5}$$

where S is the single score result and WF_c is the weighting factor for impact category c. The single score result of each process expressed in millipoints (mpts) are illustrated in Fig. 5. SLM has the highest environmental impact (402.5 mpts) followed by WAAM (96.7 mpts) and CNC milling (43.6 mpts). Thus, CNC milling is the most sustainable option for fabricating this geometry followed by WAAM and SLM.

4.1.4. *Interpretation of LCA results*

The contributions of different inventory inputs to WAAM, SLM and CNC milling were also analysed. The results of contribution analysis are displayed in Figs. 6–8. Within the production of the part by WAAM, the production of the steel billet causes most of the impact (45%) followed by post processing operations (21%) and shielding gas consumption (20%) during the process. The energy consumed during WAAM contribute roughly 6% to the total impact. In the SLM process, the energy consumed was the major contributor to the environmental impact (51%) followed by argon (31%). Gas atomization for powder production, steel billet consumption (including the part, supporting structure and material losses) and compressed air consumption have relatively lower contributions of 6%, 5% and 3% respectively. In CNC milling, 67% of the total impact originates from the steel billet production. CNC milling and hot rolling contribute 14% and 4% respectively. From the contribution analysis, the raw material i.e., steel billet production, causes majority of the total impact in WAAM and CNC milling while in SLM, the energy consumed during the process contributes to most of the total impact.

4.2. *Life cycle costing*

A LCC model for all three processes was developed in accordance with IEC 60300–3–3 Dependability management–Part 3–3: Application guide–Life cycle costing standard [26]. The economic inventory was collected from quotations and existing research articles focused on cost assessment of manufacturing processes. The following subsections describe the LCC model in more detail.

4.2.1. *Goal and scope definition*

The objective of this analysis is to develop a LCC model for WAAM, SLM and CNC milling process used for manufacturing a given part geometry to evaluate the most economical alternative and to identify the main cost drivers in each process that influence the cost of each alternative. The scope of this analysis is limited to the production phase as shown in Fig. 9. Time driven Activity Based Costing incorporating activity-based costing and costs per unit time for each activity is used to calculate the production costs of WAAM, SLM and CNC milling processes.

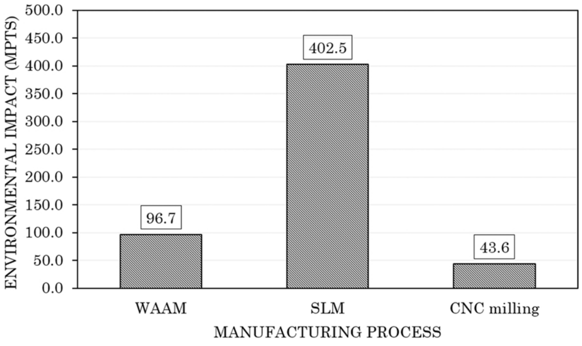

Fig. 5. Overall environmental impacts of SLM, WAAM and CNC milling.

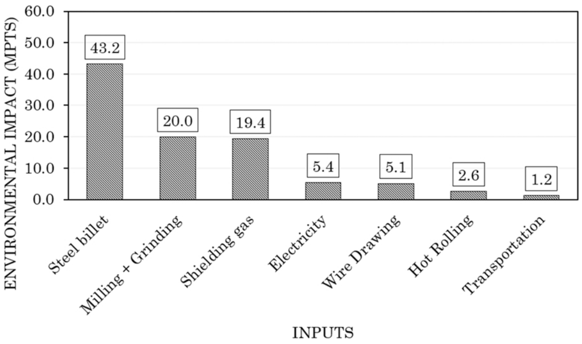

Fig. 6. WAAM environmental analysis.

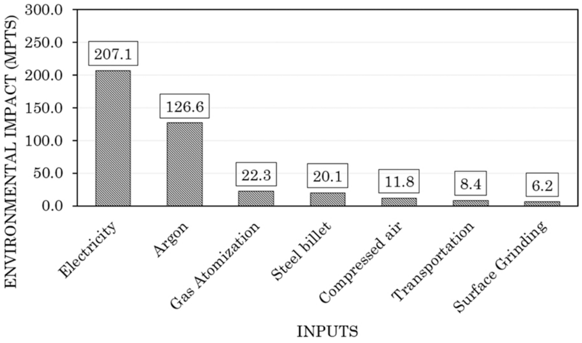

Fig. 7. SLM environmental analysis.

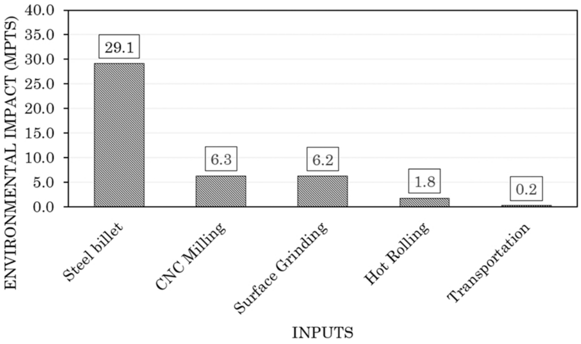

Fig. 8. CNC milling environmental analysis.

The cost elements considered in this study include:

- Machine Cost: which includes the purchasing cost of machine tools, its maintenance and tooling costs.
- Material Cost: encompasses the cost of raw material consumed in manufacturing of a given part.
- Consumables Cost: includes the cost of consumables such as shielding gas, compressed air, energy consumption and cooling fluid used in manufacturing of a given part.
- Post-processing Cost considers the cost of post processing operations like milling and surface grinding to achieve the required dimensional tolerances in the fabricated part.
- Labour Cost: includes the cost of operator activities such as preparation time, machine set-ups and process supervision.

4.2.2. *LCC model*

A LCC model was constructed based on the cost elements considered in the previous sub-section. The methods for calculating these cost elements and their calculations are detailed in this sub-section.

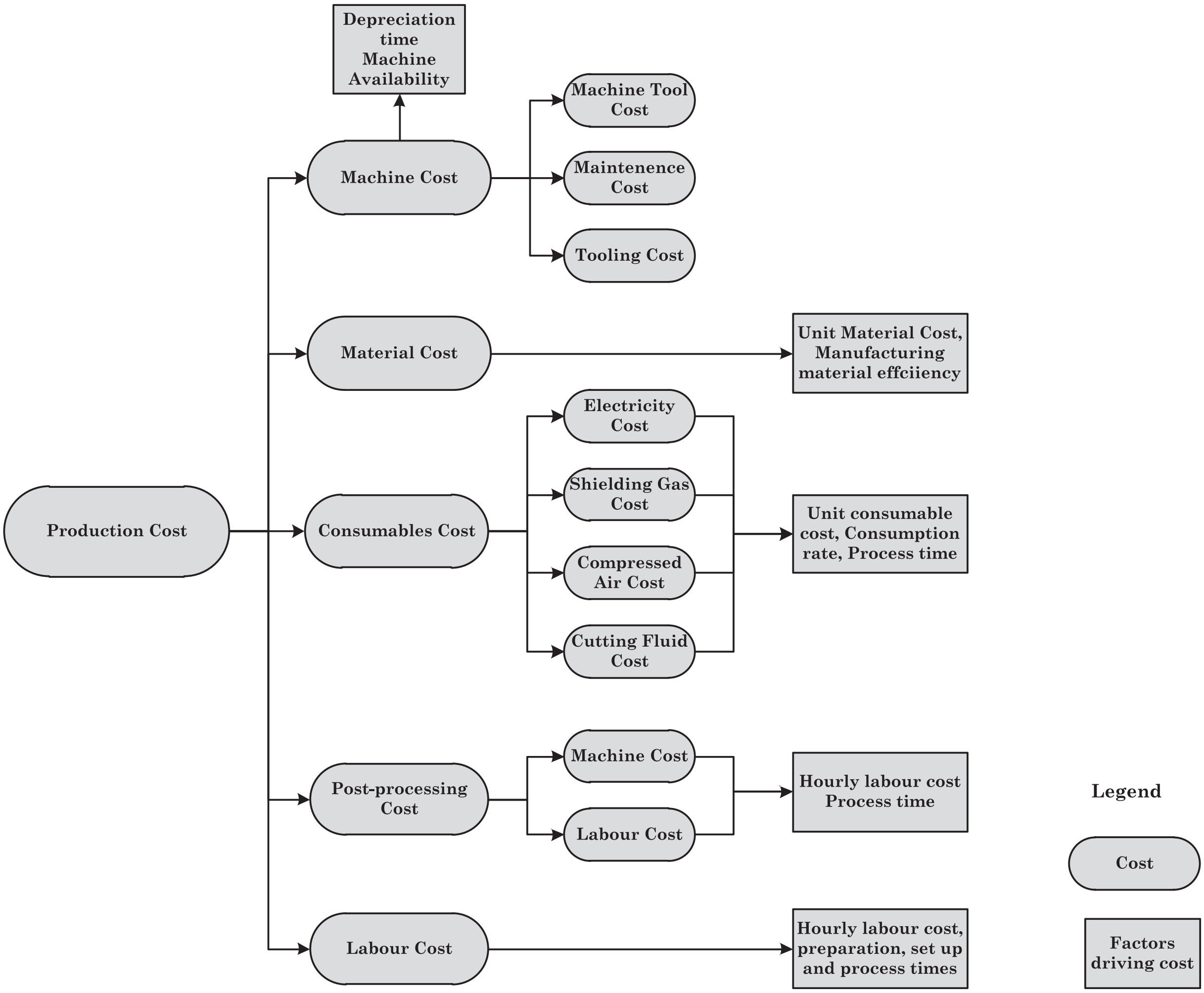

Fig. 9. LCC model developed for this study.

4.2.2.1. Machine cost. The machine cost per hour for WAAM, SLM and CNC milling were calculated considering the cost of machine tool (C_{mct}), with its maintenance cost (C_{mt}) of 3% and tooling costs ($C_{tooling}$) of 2% per anum of the machine tool cost for a depreciation period of 7 years, as reported by Pusavec et al. [43]. The machines were assumed to be used for 3 shifts of 8 h each for 250 days a year for 7 years with 80% availability. Therefore, hourly machine cost ($MCC_{1\,h}$) is computed by dividing the sum of machine tool, maintenance, and tooling costs with total time for which the machine is available ($t_{available}$).

$$MCC_{1h} = \frac{C_{mct} + C_{mt} + C_{tooling}}{t_{available}} \tag{6}$$

Table 8
Calculation of machine cost for WAAM, SLM and CNC milling.

Process	Costs	Value	Unit	Reference
WAAM	Machine Tool Cost	300,000	€	Quotation
	Maintenance Cost	9000	€/yr	Calculated based on [43]
	Tooling Cost	6000	€/yr	
	Machine Cost	12	€/h	
SLM	Machine Tool Cost	500,000	€	Quotation
	Maintenance Cost	15,000	€/yr	Calculated based on [43]
	Tooling Cost	10,000	€/yr	
	Machine Cost	20	€/h	
CNC Milling	Machine Tool Cost	150,000	€	Calculated based on [43]
	Maintenance Cost	4500	€/yr	
	Tooling Cost	3000	€/yr	
	Machine Cost	6	€/h	

The hourly machine costs for each process are reported Table 8. The machine cost ($C_{machine}$) for each process can be calculated by multiplying its hourly rate ($MCC_{1\,h}$) and time for which the machine was used ($t_{machine}$).

$$C_{machine} = MCC_{1h} \times t_{machine} \tag{7}$$

4.2.2.2. Material cost. The amount of raw material required for a process can be calculated by multiplying the mass of final product (m_{part}) and manufacturing material efficiency (ε) of that process. The material cost ($C_{material}$) is the product of amount of raw material required and cost of raw material per kg ($MC_{1\,kg}$).

$$C_{material} = \varepsilon \times m_{part} \times MC_{1kg} \tag{8}$$

4.2.2.3. Consumables cost. Consumables include energy consumed, shielding gas, compressed air and cutting fluid consumed during a process. A consumableś cost is calculated by simply multiplying the amount of consumable used and its cost per unit. Electricity cost ($C_{electricity}$) is the product of electricity consumed per product (e_{part}) and cost of 1 kWh electricity (EC_{1kWh}).

$$C_{electricty} = e_{part} \times EC_{1kWh} \tag{9}$$

Similarly, shielding gas cost ($C_{shieldinggas}$) and compressed air cost ($C_{compressed\ air}$) are computed by multiplying their amounts consumed per part (g_{part} and a_{part}) with their costs per cubic metres ($GC^{3}_{1\ m}$ and $AC^{3}_{1\ m}$) respectively.

$$C_{shieldinggas} = g_{part} \times GC_{1m^3} \tag{10}$$

$$C_{compressed\ air} = a_{part} \times AC_{1m^3} \tag{11}$$

The total consumables cost ($C_{consumables}$) is the sum of all consumable costs and is given by:

$$Cconsumables = C_{electricity} + C_{inert\ gas} + C_{compressedair} \tag{12}$$

4.2.2.4. Post-processing cost. Post-processing cost ($C_{post\text{-}processing}$) can be calculated by multiplying hourly post-processing cost ($PPC_{1\ h}$) and post processing time ($t_{post\text{-}processing}$). The hourly rates for post processing operations were calculated like the machine cost with additional labour cost of 15 € per hour.

$$C_{post-processing} = PPC_{1h} \times t_{post-processing} \tag{13}$$

4.2.2.5. Labour cost. Labour cost (C_{labour}) is the product of labour rate per hour ($LC_{1\ h}$) and time spend by the labour (t_{labour}). Labour time consists of preparation time, set up time and processing time.

$$C_{labour} = LC_{1h} \times t_{labour} \tag{14}$$

The total production cost ($C_{production}$) is the summation of all the above costs.

$$C_{production} = C_{machine} + C_{material} + C_{consumables} + C_{post-processing} + C_{labour} \tag{15}$$

4.2.3. Economic inventory analysis

The economic inventory includes the cost of different resources and activities involved in WAAM, SLM and CNC milling processes. The data for different cost elements considered in this study was collected from quotations, literature and some were theoretically calculated. The cost data for all three processes are summarized in Table 9. The labour and electricity costs for Portugal, where the experiments were performed, were used in this study.

4.2.4. Cost aggregation

Based on this cost data collected, LCC analysis of WAAM, SLM and CNC milling was performed. The individual costs were summed up and the production cost for each process was calculated. The production cost per unit for WAAM, SLM and CNC machining were 60 €, 236.7 € and 19.7 € respectively. Thus, CNC milling is the cheapest alternative while SLM is the most expensive alternative. The results of cost aggregation are summarized in Table 10.

Table 9
Cost data for WAAM, SLM and CNC milling.

Process	Costs	Value	Unit	Reference
WAAM	Machine Cost	12	€/h	Calculated
	Material (wire) Cost	16	€/kg	Quotation
	Electricity Cost	0.13	€/kWh	[16]
	Inert gas/Compressed air Cost	2.3	€/m^3	Quotation
	Post-processing Cost	16	€/h	Calculated
	Labour Cost	15	€/h	[49]
SLM	Machine Cost	20	€/h	Calculated
	Material (powder) Cost	33	€/kg	Quotation
	Electricity Cost	0.13	€/kWh	[16]
	Inert gas/Compressed air Cost	2.3	€/m^3	Quotation
	Post-processing Cost	16	€/h	Calculated
	Labour Cost	15	€/h	[49]
CNC Milling	Machine Cost	6	€/h	Calculated
	Material (bar) Cost	5	€/kg	Quotation
	Electricity Cost	0.13	€/kWh	[16]
	Compressed air Cost	2.3	€/m^3	Quotation
	Cutting fluid cost	50	€/kg	Quotation
	Post-processing Cost	16	€/h	Calculated
	Labour Cost	15	€/h	[49]

Table 10
Production Cost per unit product for WAAM, SLM and CNC milling processes.

Costs (€)	WAAM	SLM	CNC Milling
Machine Cost	21.2	120	4.4
Material Cost	3.6	3.7	0.82
Consumables Cost	0.4	11.0	0.27
Post-processing Cost	8.4	14.2	3.2
Labour Cost	26.4	97.5	11
Production Cost	60.0	236.7	19.7

4.2.5. Interpretation of LCC analysis

From the results of LCC, the main cost drivers in all these processes are machine and labour costs. In WAAM, labour and machine costs account for 44% and 35% of the production cost respectively. The contributions of machine and labour costs in the production costs of SLM are 51% and 41%, respectively. In CNC milling, labour contributes to 56% of the production cost while machine costs are 22% of the production cost.

4.3. Influence of material efficiency

A manufacturing material efficiency (ε) of 50% was considered for CNC milling in this study owing to simplicity of the part geometry. However, it is highly affected by the complexity of the part geometry. For instance, the manufacturing material efficiency of some aero engine components manufactured by conventional methods vary between 5% and 17% [1]. For aircraft components made up of titanium and aluminium alloys by traditional manufacturing processes, the manufacturing material efficiency can be as low as 4–8% [23].

The effect of the manufacturing material efficiency on the environmental and economic performances of CNC milling is also studied. A flat wall with no curvature is fabricated in this study. The manufacturing material efficiency for CNC milling will vary as the curvature profile of the wall varies (assuming wall thickness, height, length and material remains the same). The manufacturing material efficiencies for WAAM and SLM are assumed to be constant due to their enhanced ability to fabricate complex shapes. Increased product complexity due to increased wall curvature will lead to lower manufacturing material efficiency for CNC machining. The lower manufacturing material efficiency corresponds to increased amounts of material removal and resource consumption. The MRRs for roughing and finishing in CNC machining are assumed to be constant for all manufacturing material efficiencies. Based on the above assumptions, the environmental impacts and production costs of CNC milling for different values of manufacturing material efficiency ranging from 5% to 50% are calculated and presented in Figs. 10 and 11.

From Fig. 10, it can be observed that the environmental impact of CNC milling matches to that of SLM and WAAM at Break Even Point 1 (ε = 5.6%) and Break Even Point 2 (ε = 25%) respectively. Similarly,

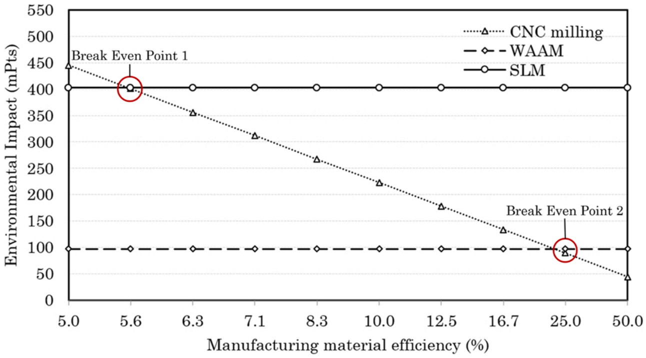

Fig. 10. Influence of manufacturing material efficiency on environmental impact.

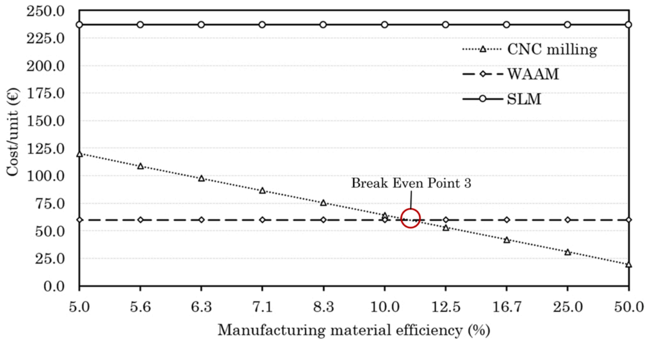

Fig. 11. Influence of manufacturing material efficiency on production cost.

the cost of CNC milling matches that of WAAM at Break Even Point 3 (see Fig. 11) where the manufacturing material efficiency is about 11%. However, SLM is the costliest process irrespective of the manufacturing material efficiency ranging from 5% to 50%. For the flat wall considered in this study (ε = 35%) CNC milling is the most ecological and economical option. For similar steel walls with same dimensions but varying curvature, when the manufacturing material efficiency for CNC milling is between 11% and 25%, WAAM is the most ecological alternative, but CNC milling is the most economical alternative. For such walls, when manufacturing material efficiency is less than 11% for CNC milling, WAAM is the most ecological and economical approach. SLM does not appear to be the most ecological and economical option owing to its high energy consumption and processing time respectively.

The above analysis cannot be generalized for all geometries. For instance, geometries with complex features but small height can still have higher manufacturing material efficiency for CNC milling. This analysis can only be applied to walls of differing curvature profiles but of same dimensions and raw material considered in this study. For example, consider a wall with a complex curvature profile with same dimensions and material as that of the flat wall fabricated in this study (see Fig. 12a). To determine the input stock for CNC milling of this part, the Stock manager option in Solidworks CAM add-on is used. According to this option, this geometry requires an initial stock with dimensions of 77 mm × 82 mm × 40 mm. Based on the stock volume required, the manufacturing material efficiency for CNC machining in this case is calculated to be 9.5%. As discussed previously, WAAM will be the most ecological and economical option to manufacture this complex geometry as the manufacturing material efficiency for CNC milling is 9.5%

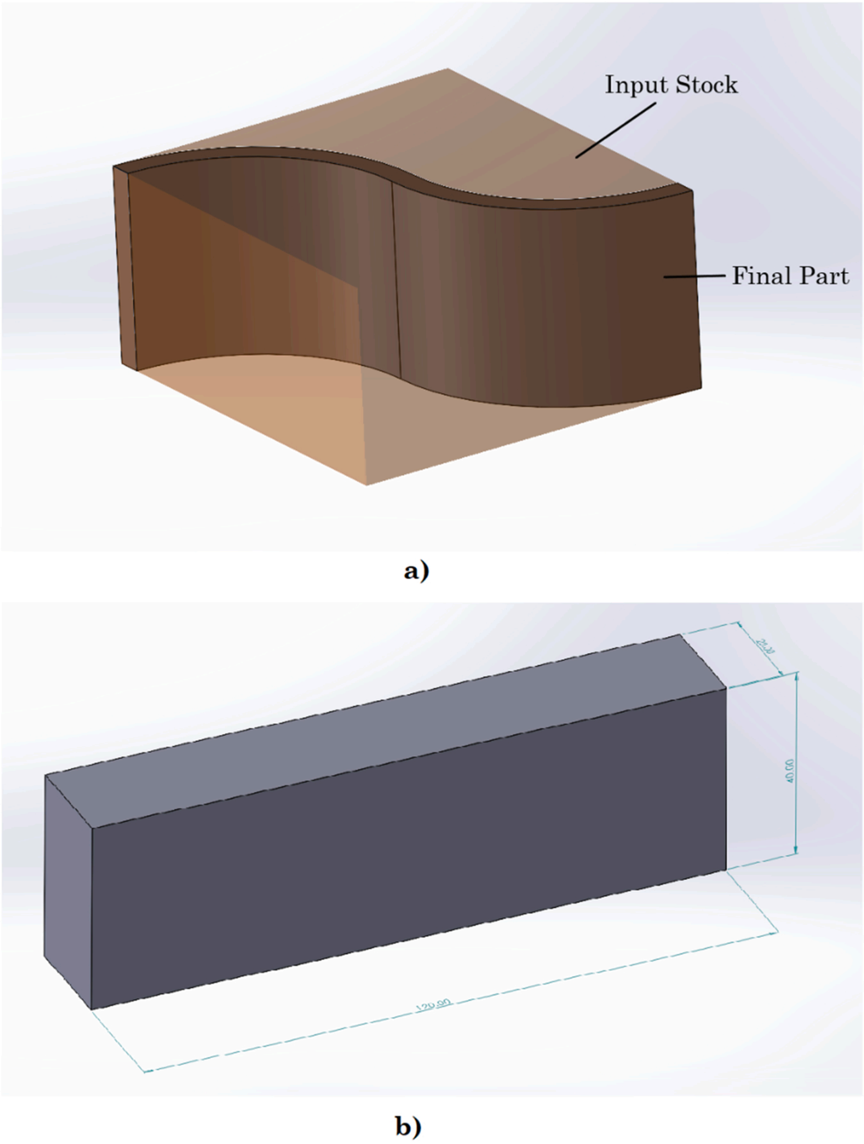

Fig. 12. a) A curved wall part of length 120 mm, height 40 mm and width 5 mm b) A thick wall geometry of length 100 mm, height 40 mm and width 20 mm.

(<11%) in this case.

As mentioned earlier, the results of the above analysis cannot be used for walls of different dimensions and materials. For example, consider a thick wall geometry of dimensions 100 mm in length, 40 mm in height and 20 mm in width being fabricated using WAAM (see Fig. 12b). Based on the present WAAM experiment described in Section 4. Case Study, this geometry will require milling up to 1.8 mm depth on all the sides to achieve dimensional accuracy, assuming no surface and sub surface defects. The manufacturing material efficiency of WAAM process in this case will be about 75%. Therefore, for such thick-walled geometries, the break-even points for WAAM and CNC milling will arrive at higher manufacturing material efficiencies.

It must also be noted that the scope of the analysed case study and above breakeven point analyses was limited up to production of the part geometry. Also, the break-even points will be different for different materials. Studies have demonstrated reduction in material, and energy savings by achieving part weight reduction by readapting the part design for AM processes [24,22]. Weight reduction enabled by AM was not considered in this study. Weight reduction in turn may decrease the emissions and cost per part not only in the production phase but also in subsequent phases like transportation to customers as shown by Ingarao et al. [25]. Therefore, the environmental and economic performance of WAAM and SLM can further be improved by weight reduction of the part enabled by more AM-oriented geometry. It must also be noted that one may not always have an option to manufacture a geometry by both conventional and additive manufacturing routes. For manufacturing some practical geometries, only a hybrid conventional and additive manufacturing route is feasible. Hence, the environmental and economic indicators are not simply a function of manufacturing material efficiency. The environmental and economic indicators can be expressed as a function of manufacturing material efficiency only in a few cases, as discussed previously. Additionally, WAAM requires manual supervision for the entire process duration. As WAAM technology matures, it is expected that manual intervention will be reduced which will reduce the labour costs for WAAM. This may lead to arrival of break even points at higher manufacturing material efficiencies of CNC machining.

4.4. Uncertainty and sensitivity analysis

4.4.1. Uncertainty analysis

An uncertainty analysis was carried out to determine how the uncertainties in the inventory data affect the environmental impact. The uncertainty analysis was carried out in SimaPro software using Monte-Carlo Analysis method. The inventory data collected may have uncertainties and these uncertainties can seriously affect the LCA results. Therefore, it is necessary to determine if the environmental impact of all 3 processes is significantly different even on considering the uncertainties in input data. The uncertainty in each inventory data is modelled by assuming normal distribution for each LCI input with a standard deviation (SD) of 10% of the mean value and 95% confidence level. A sufficiently high number of runs i.e., 10,000 runs were performed for each process based on the Monte-Carlo runs reported by Heijungs [21] in different LCA case studies. In each run, SimaPro assigns a random value to a LCI input based on its defined uncertainty distribution and calculates the environmental impact. The results of uncertainty analysis for LCA are illustrated in Figs. 13–15. Here, a higher bar implies a higher probability of having a corresponding environmental impact. From these figures, the 95% confidence intervals of environmental impact for WAAM (87–107 mPts), SLM (352–448 mPts) and CNC machining (37–51 mPts) do not overlap. This means that CNC machining showed the least environmental impact followed by WAAM and SLM in all Monte-Carlo simulations. Therefore, the effect of uncertainties in inventory data does not alter the conclusions drawn from the LCA results.

Additionally, Jarque-Bera (JB) test of normality was performed to check if the results of Monte-Carlo simulations follow a normal distribution [51]. In this test, a test statistic JB is calculated based on the sample size (n), sample skewness (S) and sample kurtosis (K).

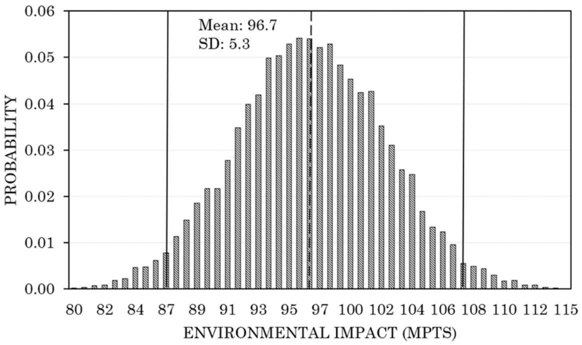

Fig. 13. Uncertainty analysis for environmental impact of WAAM.

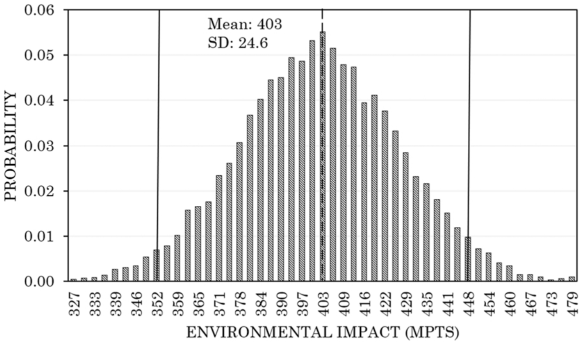

Fig. 14. Uncertainty analysis for environmental impact of SLM.

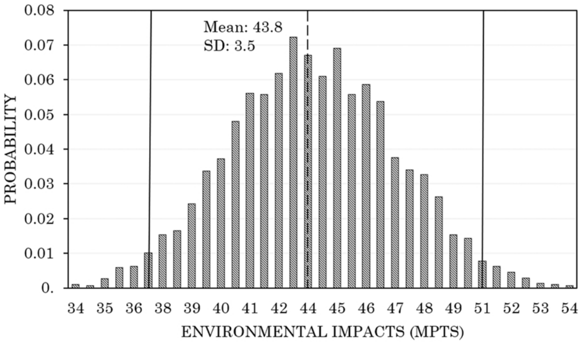

Fig. 15. Uncertainty analysis for environmental impact of CNC milling.

$$JB = \frac{n}{6}\cdot\left(S^2 + \frac{(K-3)^2}{4}\right) \tag{16}$$

The null hypothesis assumes that the given data sample follows normal distribution. In case of normality, the test statistic JB has chi-squared (χ^2) distribution with 2 degrees of freedom. The JB test statistic calculated for Monte-Carlo simulations follows normal distribution as its value (JB = 2.94 for WAAM and SLM, 2.1 for CNC machining) is lesser than the critical chi-square ($\chi^2_{0.95,2} = 5.99$) value at 0.05 significance level and 2 degrees of freedom. Therefore, the null hypothesis is true and there is no sufficient evidence to prove that the given data does not follow normal distribution. Hence, we can assume normal distribution for the results of Monte-Carlo simulations.

4.4.2. Sensitivity analysis

The impact of variation in quantities of environmental and economic inventories on the total environmental impact and production cost of a process was studied by performing a sensitivity analysis where each inventory input amount was systematically varied by ± 10% one at a time. The results of this sensitivity analysis are displayed in Figs. 16 and 17. It is observed that for WAAM and CNC milling, the variation in raw material quantity has the highest influence on environmental impact. For SLM, the variation in amount of electricity consumed has the highest influence on the environmental impact. The production costs have the highest sensitivity for process times, as variation in process times affects the machine cost, electricity cost, consumables cost and labour cost accordingly.

5. Conclusions

The aim of this investigation was to compare the environmental and economic performance of the WAAM process with SLM and CNC milling processes. The cradle-to-gate life cycle assessment and life cycle costing were carried out considering just the production phase of a simple geometry for WAAM, SLM and CNC milling. The following conclusions can be drawn:

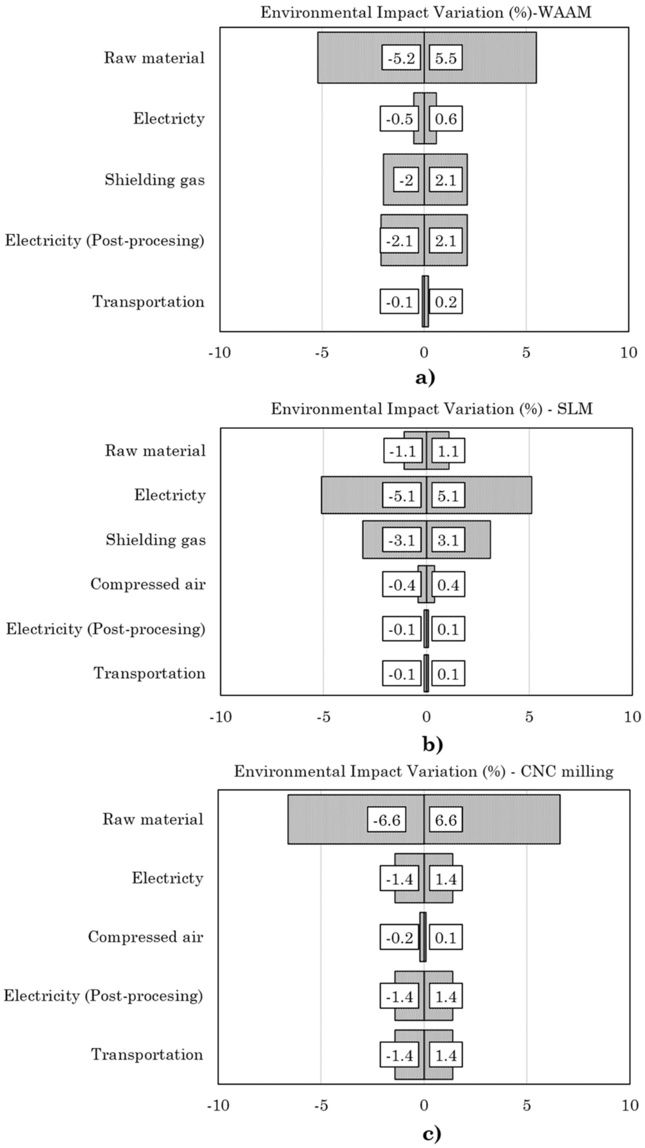

Fig. 16. Sensitivity analysis for environmental impact of a) WAAM b) SLM c) CNC Milling.

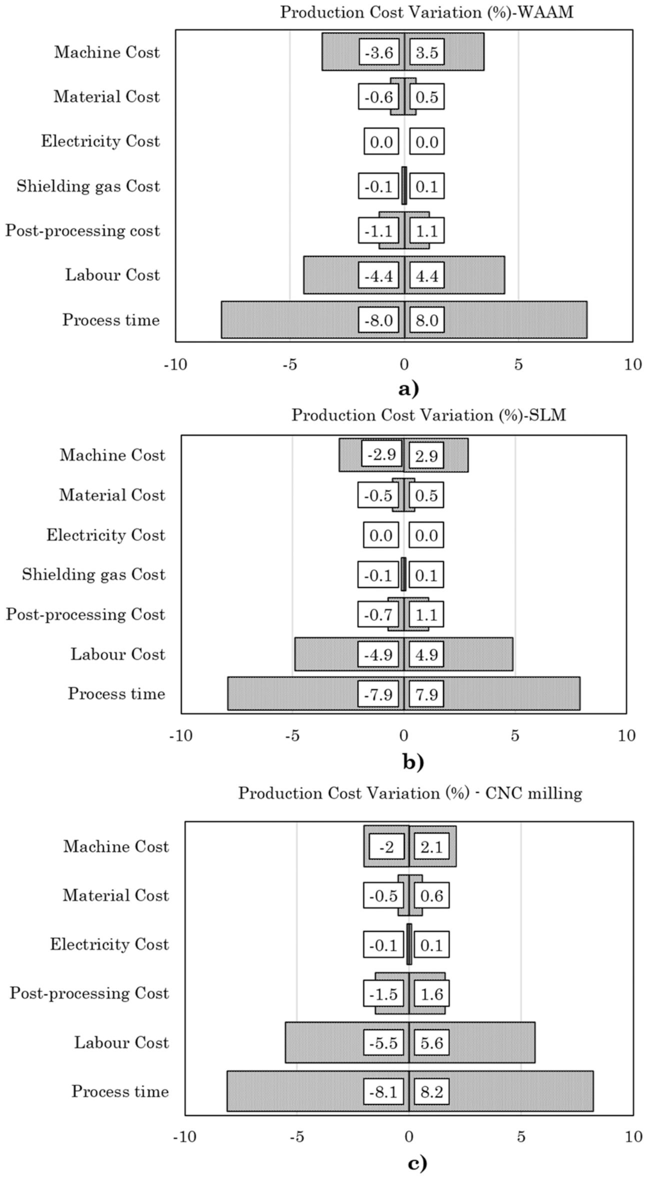

Fig. 17. Sensitivity analysis for production cost of a) WAAM b) SLM c) CNC Milling.

- For the selected part geometry, CNC milling was the most environmentally friendly and economical process followed by WAAM and SLM. CNC milling causes 55% less environmental impact and costs 67% cheaper than WAAM. SLM on the other hand has an environmental impact and cost approximately 4 times that of WAAM.
- The raw material i.e., steel billet was the environmental hotspot in WAAM and CNC machining accounting for 45% and 67% of the total environmental impact respectively. In SLM, the energy consumed during the process was the environmental hotspot causing 51% of the total impact.
- Labour costs were the main cost driver in WAAM and CNC responsible for 44% and 56% of the production cost respectively while machine cost was the major cost driver in SLM with a contribution of 51% of the production cost.
- For walls of same dimensions and material as the wall considered in this study but with complex curvature profiles, WAAM could be the most economical and ecological option only when the manufacturing material efficiency of CNC milling process is less than 11%.
- Uncertainty and sensitivity analyses were performed to study the cumulative effects of input data uncertainty and variability,

respectively. The possible environmental impacts for WAAM, SLM and CNC milling lie in the intervals 87–107 mPts, 352–448 mPts, and 37–51 mPts, respectively. The production costs were the most sensitive to variation in the process times.

Current work included LCA and LCC assessment of a simple geometry with scope limited to production phase. Future works will involve more complex geometries, inclusion of other life cycle stages such as heat treatment, inspection, transportation, utilization, and disposal in LCA and LCC model to fully characterize the environmental and economic performance of WAAM process. Furthermore, it is assumed in this study that the mechanical properties of the flat wall are same for all 3 processes. Some recent studies have simultaneously reported the mechanical, environmental and economic performance of AM processes [42, 20]. Priarone et al. [42] considered cost, time, quality (characterised by ultimate tensile strength) and environmental sustainability in their multi-criteria decision making framework for WAAM and CNC machining. Guarino et al. [20] reported average better tensile strength for a SLMed product than a laser cut product along with their environmental and economic assessment. Both these studies just considered tensile strength. Assessing multiple mechanical properties and their integration with environmental and economic assessment of AM processes should be considered in future works. WAAM is constantly developing and evolving. In addition to environmental and economic assessment, evaluation of its social impacts like health and safety, working conditions, employment generation, to mention a few is also of a greater concern to ensure its sustainable development. Future works will also involve Social-Life Cycle Assessment (S-LCA) of WAAM process.

CRediT authorship contribution statement

Samruddha Kokare: Writing – original draft, Investigation, Formal analysis, Data curation. **Radu Godina:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **J. P. Oliveira:** Writing - review & editing; Validation; Supervision; Resources; Conceptualization. **Telmo G. Santos:** Writing - review & editing; Validation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: One of the authors, J, P, Oliveira, is associated editor of the journal.

Data availability

Data will be made available on request.

Acknowledgements

The authors acknowledge Fundação para a Ciência e a Tecnologia (FCT-MCTES) for its financial support via the project UIDB/00667/2020 (UNIDEMI). JPO acknowledges funding by national funds from FCT - Fundação para a Ciência e a Tecnologia, I.P., in the scope of the projects LA/P/0037/2020, UIDP/50025/2020 and UIDB/50025/2020 of the Associate Laboratory Institute of Nanostructures, Nanomodelling and Nanofabrication – i3N. The authors wish to thank Mr. Igor Felice and Mr. Antonio Campos for their help in conducting WAAM process. This activity has received funding from the European Institute of Innovation and Technology (EIT) – Project Smart WAAM: Microstructural Engineering and Integrated Non-Destructive Testing. This body of the European Union receives support from the European Union's Horizon 2020 research and innovation programme.

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