



Advancing sustainable manufacturing decision-making through an online life cycle assessment tool for wire-based directed energy deposition

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Abstract

The manufacturing sector is highly material and energy-intensive, contributing significantly to environmental degradation. Despite its environmental impact, manufacturing is essential for economic growth and social benefits, such as improved living standards and job creation. Therefore, balancing economic, environmental, and social outcomes through sustainable manufacturing practices is crucial. In recent years, additive manufacturing (AM) has transformed the production of complex parts across various sectors by reducing material waste and lowering costs. One prominent wire-based Directed Energy Deposition (DED) type of AM process, commonly referred to as Wire Arc Additive Manufacturing (WAAM) is gaining attention for its ability to produce large-scale parts at higher build rates and lower material and machine costs compared to other metal AM technologies. A comprehensive sustainability assessment of manufacturing technologies, including WAAM, is necessary for informed sustainable decision-making. The Life Cycle Sustainability Assessment (LCSA) method, which integrates Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA), provides a holistic approach to evaluating environmental, economic, and social impacts. Recent advancements in online LCSA tools have improved accessibility and usability, particularly for small and medium enterprises (SMEs) that may lack the financial and human resources to perform sustainability assessments. These tools, tailored for specific sectors, enable quick and user-friendly sustainability assessments, facilitating informed decision-making. This study develops an online LCSA tool for WAAM, integrating LCA, LCC, and S-LCA models. By compiling relevant databases and formulating LCA, LCC, and S-LCA models, an interactive online tool is developed, in which non-experts can visualize and compare the sustainability impacts of WAAM and traditional CNC machining processes. The tool was also validated with data from existing LCA studies, and it predicted environmental and economic impacts with a maximum error margin of 12.5%. A case study of an automotive part is presented to demonstrate the utility of this tool. This approach promotes life cycle thinking from the early stages of product development, supporting sustainable manufacturing practices.

Keywords Wire arc additive manufacturing · Life cycle sustainability assessment · Life cycle assessment · Life cycle costing · Social life cycle assessment

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Nomenclature

a	finish machining allowance for WAAM part [mm]	GC_{1m}^3	cost of $1m^3$ shielding gas [€]
a_c	width of cut [mm]	g_{part}	volume of shielding gas consumed per product [m^3]
a_p	depth of cut [mm]	h_{layer}	layer height in WAAM [mm]
BR	build rate of WAAM [cm^3/h]	h_{part}	height of the final part [cm]
$C_{consumables}$	cost of consumables per unit product [€]	LC_{1h}	hourly cost of operator [€]
$C_{electricity}$	cost of electricity consumed per unit product [€]	m_{bar}	mass of bar consumed [kg]
C_{labour}	cost of operator [€]	MC_{1kg}	cost of 1 kg raw material [€]
$C_{machine}$	cost of machine per unit product [€]	MCC_{1h}	cost of 1 h machine use [€]
$C_{material}$	cost of raw material consumed per unit product [€]	m_{part}	mass of final part [kg]
C_{mct}	cost of machine tool [€]	MRR	material removal rate in CNC machining [mm^3/min]
C_{mt}	cost of machine tool maintenance [€]	m_{scrap}	mass of material removed during finish machining of WAAM parts [kg]
$C_{post-processing}$	cost of post-processing per unit product [€]	m_{wire}	mass of wire consumed [kg]
$C_{tooling}$	cost of tooling [€]	$P_{air-cutting}$	power consumption of a CNC machine in air-cutting mode [kW]
EC_{1kwh}	cost of 1 kWh electricity [€]	$P_{cutting}$	power consumption of a CNC machine in material cutting mode [kW]
$E_{CNC_milling}$	energy consumed during CNC milling [kWh]	$P_{deposition}$	power consumption of WAAM machine while depositing material [kW]
$EI_{bar,c}$	environmental impact of the bar in midpoint indicator c	PPC_{1h}	hourly cost of post-processing operations [€]
EI_c	environmental impact for midpoint indicator c	$P_{stand-by}$	power consumption of a machine tool in stand-by mode [kW]
$EI_{CNC_milling,c}$	environmental impact of CNC milling in midpoint indicator c	Q_i	quantity of life cycle inventory i
$EI_{electricity,c}$	environmental impact of electricity in midpoint indicator c	S	surface area of the final part [cm^2]
$EI_{gas,c}$	environmental impact of shielding gas in midpoint indicator c	S_{EI}	single score environmental impact [Pts]
$EI_{post-processing,c}$	environmental impact of post-processing WAAM part in midpoint indicator c	S_i	score for social indicator i
$EI_{WAAM,c}$	environmental impact of WAAM in midpoint indicator c	S_{SI}	total aggregated score in S-LCA
$EI_{wire,c}$	environmental impact of the wire in midpoint indicator c	$t_{available}$	total time for which machine is available [h]
e_{part}	amount of electricity consumed per product [kWh]	$t_{cooling}$	time required for cooling deposited material in WAAM [h]
E_{WAAM}	energy consumed during WAAM [kWh]	$t_{cooling_layer}$	interlayer cooling time in WAAM [s]
$F_{bar,c}$	characterization factor for bar in midpoint indicator c	$t_{deposition}$	time required for material deposition in WAAM [h]
$F_{electricity,c}$	characterization factor for electricity in midpoint indicator c	t_{labour}	operator time spent per unit product [h]
f_{gas}	shielding gas flow rate during WAAM [L/min]	$t_{machine}$	machine use time per product [h]
$F_{gas,c}$	characterization factor for shielding gas in midpoint indicator c	$t_{post-processing}$	post-processing time per unit product [h]
$F_{i,c}$	characterization factor for life cycle inventory i in midpoint indicator c	t_{set-up}	set-up time for a machine tool [h]
$F_{wire,c}$	characterization factor for wire in midpoint indicator c	V_f	feed rate in CNC machining [mm/min]
		V_{part}	volume of the final part [cm^3]
		W_c	weighing factor assigned for midpoint indicator c
		WFS	wire feed speed [m/min]
		δ	density of part's material [g/cm^3]
		ε_{WAAM}	material efficiency of WAAM
		λ_c	ratio of production costs of WAAM and CNC milling
		λ_e	ratio of environmental impacts of WAAM and CNC milling

ϕ wire diameter [mm]

1 Introduction

In the past few years, additive manufacturing (AM) has emerged as a disruptive technology producing highly complex parts that are difficult to produce by conventional manufacturing technologies [1, 2]. AM has found application in aerospace, automotive, biomedical, defence, and construction sectors among others [3, 4]. Wire Arc Additive Manufacturing (WAAM) is one such wire based Directed Energy Deposition (DED) AM technology that has been gaining popularity recently due to its ability to fabricate large-scale parts, higher build rates, and lower material and machine costs compared to other AM technologies like Laser Powder Bed Fusion (LPBF) [5, 6]. In WAAM, metal wires are used as feedstock materials that are melted using an electric arc and deposited layer-by-layer. Currently, industrial manufacturing is environmentally-intense, accounting for 35–40% of global material consumption and 15% of global energy consumption [7, 8]. However, manufacturing is also essential for economic growth which, in turn, results in social effects like upliftment of living standards, poverty reduction, job creation, and better access to health care and education, among others [9]. Hence, there is a need to balance the economic benefits of manufacturing with its environmental degradation and social implications. Realizing this need, the concept of sustainable development has evolved, aiming for environmentally bearable, economically viable, and socially equitable development [10, 11]. The concept of sustainability is also being integrated into manufacturing through sustainable manufacturing practices for several reasons such as government regulations, customer awareness, improving quality, and lowering costs, among others [12, 13].

From a sustainability perspective, AM technologies may exhibit lower material wastage but may consume more energy than traditional subtractive manufacturing processes. The enhancement of energy efficiency represents a significant concern, particularly within the manufacturing sector [14]. Moreover, additional energy is consumed during the production of AM feedstock materials like powders or wires through atomization or extrusion processes, and post-processing operations, respectively [15, 16]. The as-built WAAM components have surface waviness and low dimensional accuracy, and thus, require finish machining operations to eliminate surface waviness and achieve the required dimensional accuracy [17–19]. A material allowance needs to be considered for WAAM part models to accommodate surface waviness and compensate for the material loss in post-processing finish machining. This limits the material

and energy efficiency of WAAM and incurs additional costs of post-processing. Hence, quantitative sustainability assessment of AM technologies, including WAAM and traditional manufacturing technologies are required to make informed decisions on selecting the most sustainable manufacturing approach from an environmental, economic, and social perspective.

The Life Cycle Sustainability Assessment (LCSA) is a widely agreed methodology used for a holistic sustainability assessment of products and processes from an environmental, economic, and social perspective [20–23]. Klöpffer [24] proposed an LCSA framework for sustainable product development that incorporates Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA) methodologies and calculating life cycle environmental impacts, costs, and social impacts. LCA is a well-known standardized methodology used to calculate the environmental impacts of a product or process [25–27] and is defined by ISO 14044:2006 standard [17]. Complementary to LCA, LCC is used to compute all costs associated with a product or process to make informed financial decisions. Unlike LCA, no common agreed standard exists for LCC, and different standards such as IEC 60300-3-3:2017 [29], SAE AR4293A:2021 [30], AS/NZS 4536:1999 [31], and ISO 15686-5:2017 [32] among others, exist for different application domains. Similarly, S-LCA is used to assess the social impacts of a product or process on its different stakeholders such as society, local community, workers, customers, and value chain actors such as suppliers, contractors, or distributors. S-LCA is carried out in accordance with the guidelines prescribed by the United Nations Environment Programme/Society of Environmental Toxicology and Chemistry (UNEP/SETAC) [33].

Conducting LCSA studies have found several applications in the industry such as identification of product-related environmental issues, cost-saving opportunities and avoiding costs due to future liabilities, product benchmarking, eco-labelling, product/process improvement, supplier screening, marketing, policy formation, among others [34, 35]. However, Johnson and Schaltegger [36] found that lack of awareness, lack of knowledge and expertise, lack of financial and human resources, insufficient incentives from governments, and complexity of existing suitability standards and tools are the major barriers in LCSA implementation especially for small and medium enterprises (SMEs). Hence, the development of user-friendly, cost effective, adaptable, and company-tailored tools was recommended in this study. Online LCSA tools with interactive user interfaces that are dedicated to specific target users and are customized for specific sectors such as machinery [37], packaging food [38] and construction sectors [39] have been developed in the past few years. In contrast to traditional LCA software,

such as SimaPro and GaBi, that need to be installed on desktops and are generic LCA tools that contain a wide range of databases, online LCSA tools could be helpful for LCSA implementation as they are streamlined, can quickly calculate results and can be tailored as per the requirements of a specific sector or company. Krautzer et al. [37] developed a simple tailor-made web tool “LCA to go” to perform LCA of industrial machines and machine tools using Cumulative Energy Demand (CED) as the key environmental impact indicator. Varghese et al. [38] developed a streamlined LCA tool “Packaging Impact Quick Evaluation Tool” (PIQET) that assesses environmental impacts for different packaging scenarios aiding sustainable decision-making during packaging design and development. Ramos et al. [39] presented a web-based LCA tool - SENSE - targeted for food and beverages SMEs that performs environmental impact assessment generated in food production and its entire supply chain. The tool was tested in salmon, beef, dairy, and fruit juice-producing enterprises. Apostolopoulos et al. [40] demonstrated development of an online tool - Virtual integrated platform on Life cycle Analysis (VERIFY) - that performs a dynamic life cycle impact and cost assessment for building renovation scenarios based on calculations of primary energy demand, carbon footprint and life cycle costs. Similarly, Arvizu-Pina et al. [41] developed an online LCA tool – EVAMED - for non-expert users to compute carbon footprint for buildings in their early design stages in Latin America.

As far as the manufacturing sector is concerned, few studies focusing on automating LCSA to reduce the reliance on human expertise have been reported [42–45]. Bourhis et al. [42] developed predictive models based on experimental data to predict the consumption of raw material, energy, fluids, and environmental impacts for the Direct Laser Additive Manufacturing process. Schneider et al. [43] proposed a concept of automated LCA where all the LCA relevant data such as material, energy, produce details, transportation distances, and machine tools are automatically extracted from different IT systems used in manufacturing like plant simulation software, Computer-Aided Design and Manufacturing (CAD/CAM), Manufacturing Execution Systems (MES), Enterprise Resource Planning (ERP), and saved into a JSON file that can be used as an input to openLCA software. An example of a milling process was also demonstrated to evaluate this concept. Similarly, Wang et al. [44] proposed a knowledge-oriented LCA framework where process flow knowledge graphs (PFKG) were used to help non-experts identify the complex relationship between processes and flows and collect LCA-related inventories. The efficiency and user-friendliness of this approach were demonstrated through an example of a product manufactured by aluminum die casting. Naser et al. [45] proposed a Machine

Learning (ML) based LCA where predictive environmental impact assessment models were developed for Fused Filament Fabrication (FFF) products using a dataset with 200 entries. Seven different ML algorithms were tested, and it was found that Extreme Grading Boosting (XGBoost) and Multi-Layer Perceptron (MLP) algorithms showed the best prediction accuracy. Concerning WAAM, the existing LCSA studies follow a case study approach and focus singularly on LCA ignoring LCC and S-LCA assessments (refer to Table 1).

Based on the reviewed literature, it is evident that existing tools such as LCA to go, PIQET, SENSE, and EVAMED primarily integrate LCA models. Consequently, their functionality is limited to evaluating the environmental dimension, while economic and social sustainability dimensions remain largely excluded. A similar pattern is observed in LCSA studies of WAAM components, where the economic and social dimensions are significantly understudied compared to the environmental dimension. Therefore, the main objective of the present study is to develop an online LCSA tool to perform a comprehensive LCSA of WAAM built products integrating tailor made environmental (LCA), economic (LCC), and social (S-LCA) models for a holistic sustainability assessment. The databases covering environmental, economic, and social inventories for WAAM technology are compiled based on experiments (for LCA), cost quotations (for LCC), and socio-economic reports from various public and international organizations (for S-LCA). These databases are then integrated with an online digital tool with an interactive graphical user interface where a non-expert can quickly visualize the environmental, economic, and social impacts of WAAM by entering product and process parameters. The impacts of WAAM are also compared with traditional subtractive machining, enabling the selection of the most sustainable manufacturing process. Additionally, a detailed analysis of impact drivers and scenario comparisons can be performed, facilitating the selection of sustainable parameters, understanding sustainability trade-offs, and thus integrating life cycle thinking right from the early stages of product development.

The remaining paper is structured as follows: Sect. 2 describes the WAAM technology and LCSA framework including LCA, LCC, and S-LCA methodologies in depth. In Sect. 3, the LCA, LCC, and S-LCA models for WAAM and their underlying calculations are presented. Sect. 4 presents a case study that demonstrates the utility of the online LCA tool in calculating environmental, economic, and social impacts for a component fabricated using WAAM. The advantages, limitations and future research directions are also discussed in this section. Finally, the conclusions of this study are drawn in Sect. 5.

Table 1 Review of LCSA studies of WAAM components

Study	Product analyzed	LCA	LCC	S-LCA	Findings
Bekker & Verlinden[46]	1 kg stainless steel 316 product	✓	X	X	WAAM showed 35% lower environmental impact than CNC milling and comparable environmental impact relative to green sand casting.
Campatelli et al. [47]	EN S235JR structural steel blade	✓	X	X	WAAM demonstrated material and energy savings of 60% and 34% respectively, compared to CNC milling
Priarone et al.[48]	Aluminum frame, titanium bracket, and steel beam	✓	✓	X	WAAM consumed lower materials and energy compared to CNC machining. The cost-effectiveness of WAAM was subject to material, process parameters, and processing times.
Reis et al.[49]	High-strength low alloy (HSLA) parts	✓	X	X	WAAM showed an environmental impact reduction between 12%–47%, depending upon part geometry
Shah et al.[50]	Carbon and stainless-steel beams	✓	X	X	WAAM reported upto 24% lower carbon emissions than conventional hot rolling process
Kokare et al.[51]	HSLA wall	✓	✓	X	WAAM was a cost and environmentally efficient option only for walls with complex curvatures, compared to CNC machining
Kokare et al.[52]	HSLA marine propeller	✓	✓	X	WAAM exhibited a 40% lower environmental impact and 8% lower cost relative to CNC machine

2 Methodology

2.1 Wire arc additive manufacturing

In WAAM, metal wire is melted using an electric arc and deposited layer-by-layer to fabricate the required part. The steps involved in part fabrication using WAAM are illustrated in Fig. 1. Firstly, a 3D model of the component is created with Computer Aided Design (CAD) software. The part file is exported in .stl format so that it can be sliced into layers in the slicing software. In the slicing software, a G-code is generated for the WAAM machine based on the selected part orientation process parameters and toolpath strategies. Using this G-code, the WAAM machine prints

the part layer-by-layer, with appropriate cooling time between successive layer depositions. As WAAM parts tend to have thermal distortions, wavy surfaces, and poor dimensional accuracy, they need post-processing operations like finish machining. Before finishing machining, a 3D model of the as-built WAAM part (with distortions and surface waviness) is created using a 3D scanner. Then, using this 3D scanned model as the stock material, finish machining is simulated in Computer Aided Manufacturing (CAM) software [53]. The most suitable cutting parameters and cutting strategies are selected and a G-code for the CNC milling machine is generated. Using this G-code, finish machining is performed, and the required dimensional accuracy is achieved.

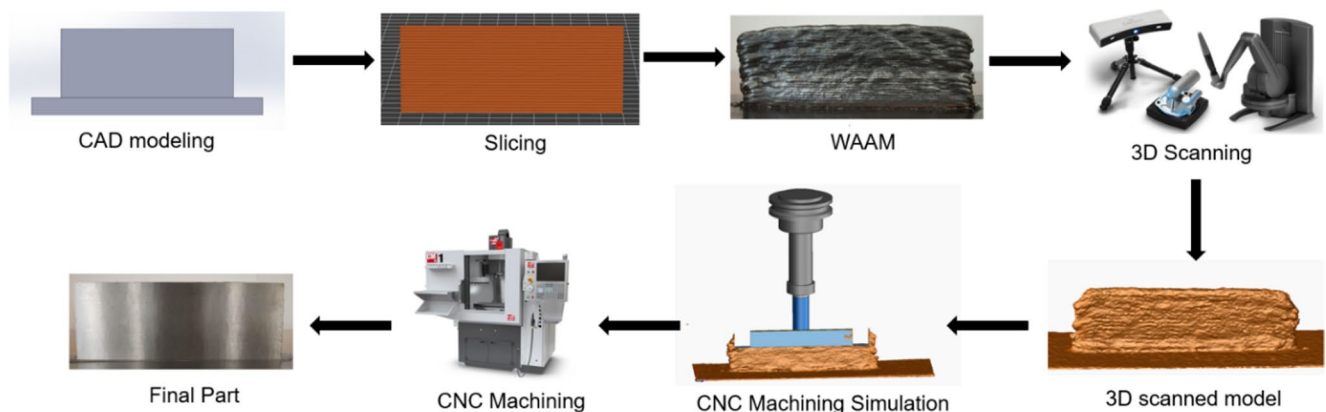


Fig. 1 Steps involved in the WAAM approach

2.2 Life cycle sustainability assessment

The objective of this research is to develop an online LCSA tool to perform a comprehensive LCSA of WAAM built products. To achieve this objective, an LCSA framework for WAAM needs to be defined first. The environmental impacts will be quantified using LCA, economic costs will be computed using LCC, and social impact will be assessed using S-LCA methodologies (refer to Fig. 2). The goal of this integrated sustainability assessment is to identify a manufacturing approach that is environmentally, economically, and socially sustainable. As a result, this project aims to develop an LCA model, LCC model, S-LCA model, and a web tool that integrates these three models and performs a holistic LCSA of WAAM products.

2.2.1 Life cycle assessment (LCA)

The LCA (Life Cycle Assessment) methodology is used to evaluate the environmental impact of a product or service throughout its entire life cycle. The framework of this methodology is based on the ISO 14044 standard [28] and is carried out in four stages. The first stage involves defining the goal and scope, which includes defining the objective of the study, its functional unit, Life Cycle Impact

Assessment methodology, environmental impact indicators, system boundaries, any assumptions, and limitations of the study. The second stage involves conducting a life cycle inventory analysis to quantify the inputs and outputs of the product or service. The inputs include raw materials, electricity, and other process consumables, while outputs include wastes and emissions. The third stage involves performing a life cycle impact assessment whereby the environmental impacts are calculated based on the data collected in the life cycle inventory analysis phase. Finally, the fourth stage involves interpreting the results of the life cycle impact assessment to determine the environmental impact, environmental hotspots, and measures to minimize the environmental impact of the product or service.

2.2.2 Life cycle costing (LCC)

The Life cycle costing (LCC) methodology is used to determine costs associated with an entity over the entire or a portion of its life cycle. The first step here involves defining aims and objectives, system boundaries, and LCC methodology used in the LCC assessment. To analyze the costs of the product, the activity-based costing approach is used as the final cost of a given product. It includes the cost of material and all value-adding activities involved in manufacturing

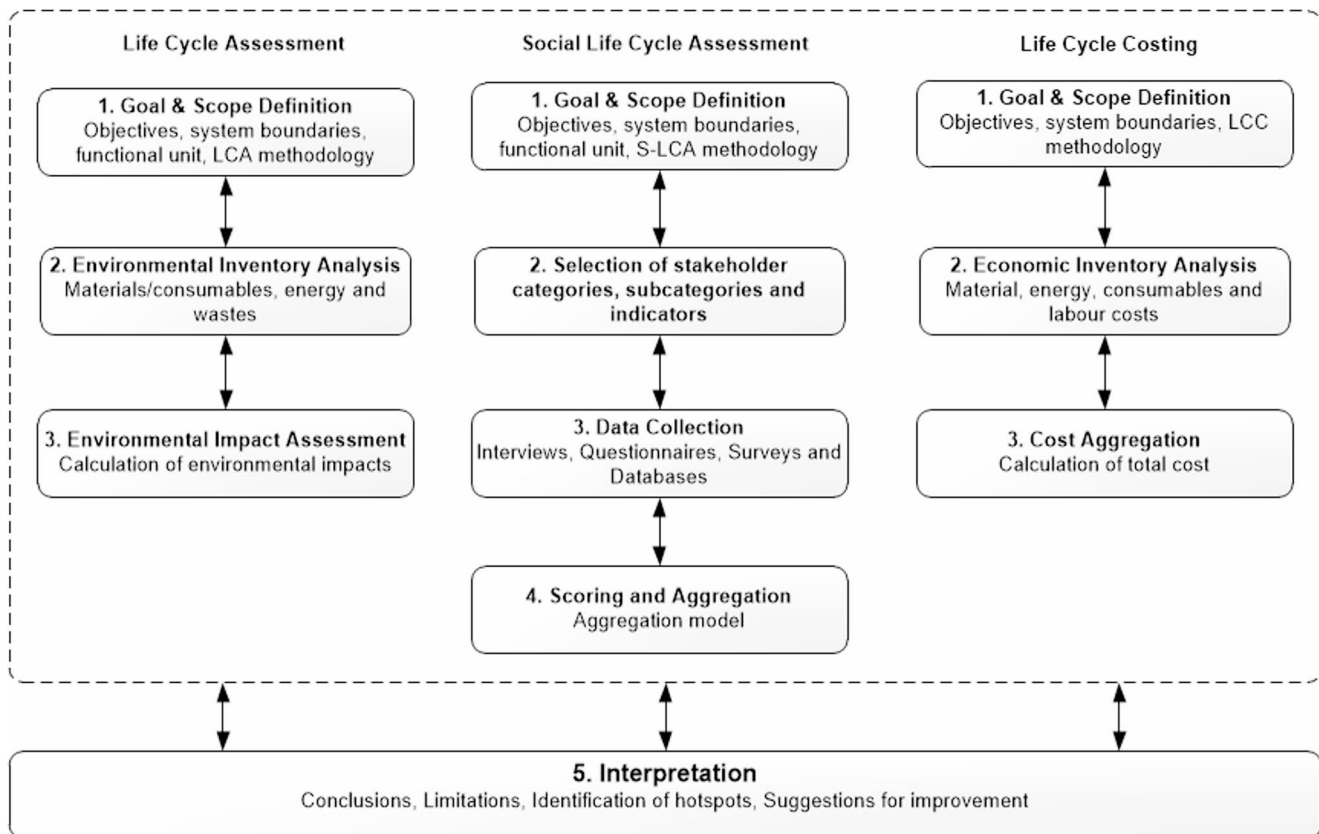


Fig. 2 Life cycle sustainability assessment framework

the given product as opposed to traditional cost accounting methods which take into account only the direct material cost and labour cost [54]. Next, the data inputs required to calculate the direct and indirect costs are collected through vendor quotations or literature in some cases. Finally, the individual costs are aggregated to obtain the total cost. The results of LCC help realize the different cost drivers and take appropriate measures to reduce the costs associated with the given product. An inter-process comparison of cost performance between WAAM and pure subtractive machining is also made so that the user can decide which process is more economical for fabricating a given product.

2.2.3 Social life cycle assessment (S-LCA)

The S-LCA methodology aims to evaluate the social impacts of a product or service throughout its life cycle. In doing so, the guidelines provided by the United Nations Environment Programme/Society of Environmental Toxicology and Chemistry (UNEP/SETAC) are followed [55]. The development of this model involves active participation from various stakeholders, including workers, local communities, and consumers. The first step in S-LCA involves the definition of goal, scope, functional unit, assumptions, and limitations. The next step involves identifying subcategories and indicators such as working conditions, health and safety, and respect for intellectual property rights, among others. The third step, i.e., data collection for S-LCA can be site-specific or generic and typically involves quantitative, qualitative, or semi-quantitative types of data. It involves conducting interviews, questionnaires, or examining available reports. The impact assessment is done by linking the inventory data to respective subcategories and quantifying social indicators by assigning them an indicator score (refer to Fig. 3). By collecting data from different stakeholders involved, S-LCA will enable the evaluation of social impacts such as job creation, rate of WAAM-related accidents, customer satisfaction, public trust, and transparency. A mathematical aggregation model is developed in which individual weights

are assigned to each social indicator. Each indicator is given a score based on specific evaluation criteria. These scores are then normalized and aggregated to produce a final score at both the stakeholder level and the life cycle level. These aggregated scores are compared to the cut-off criteria and based on their comparison relative to the cut-off criteria the social performance is assessed as positive, neutral, or negative. This assessment helps decision-makers consider social impacts in addition to environmental impacts and product costs when choosing a sustainable manufacturing approach.

3 Web tool architecture and development

This study proposes a web tool that combines LCA, LCC, and S-LCA to perform a comprehensive LCSA of WAAM products. The main aim of the tool is to provide interested parties with a better decision-making process when selecting the most appropriate manufacturing process, process parameters, or scenarios. This tool will reduce the time and effort required to conduct LCA, LCC, and S-LCA procedures, and can potentially become a reference point for all lifecycle-based activities related to WAAM. It will allow practitioners, policymakers, and stakeholders to interact and exchange data [27], ultimately resulting in more sustainable manufacturing practices.

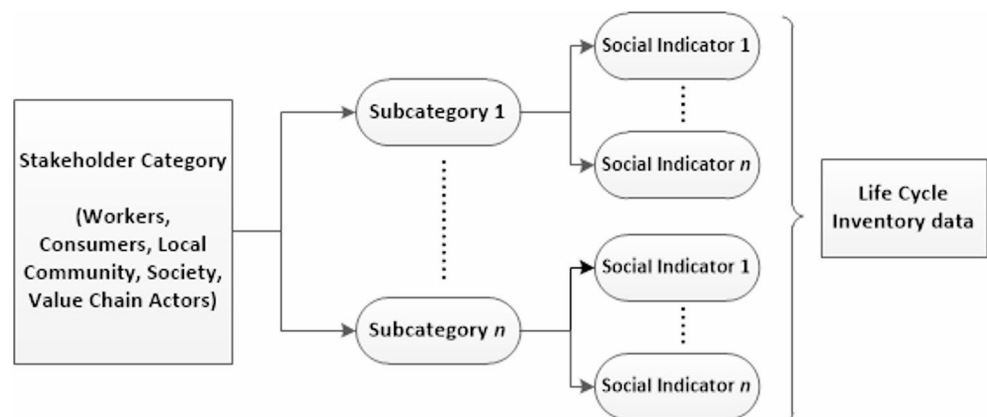
3.1 Framework of the web tool

The overview of the web tool is illustrated in Fig. 4. The webtool is organized into four main layers: Input Layer, Database Layer, Processing Layer and Output Layer as follows:

3.1.1 Input layer

Using the tool's graphical user interface (GUI), users can enter product- and process-specific data such as product volume, surface area, height, and process parameters for WAAM and post-processing finish machining. This layer

Fig. 3 Relation between stakeholder categories, subcategories, social indicators, and social inventory data [55]



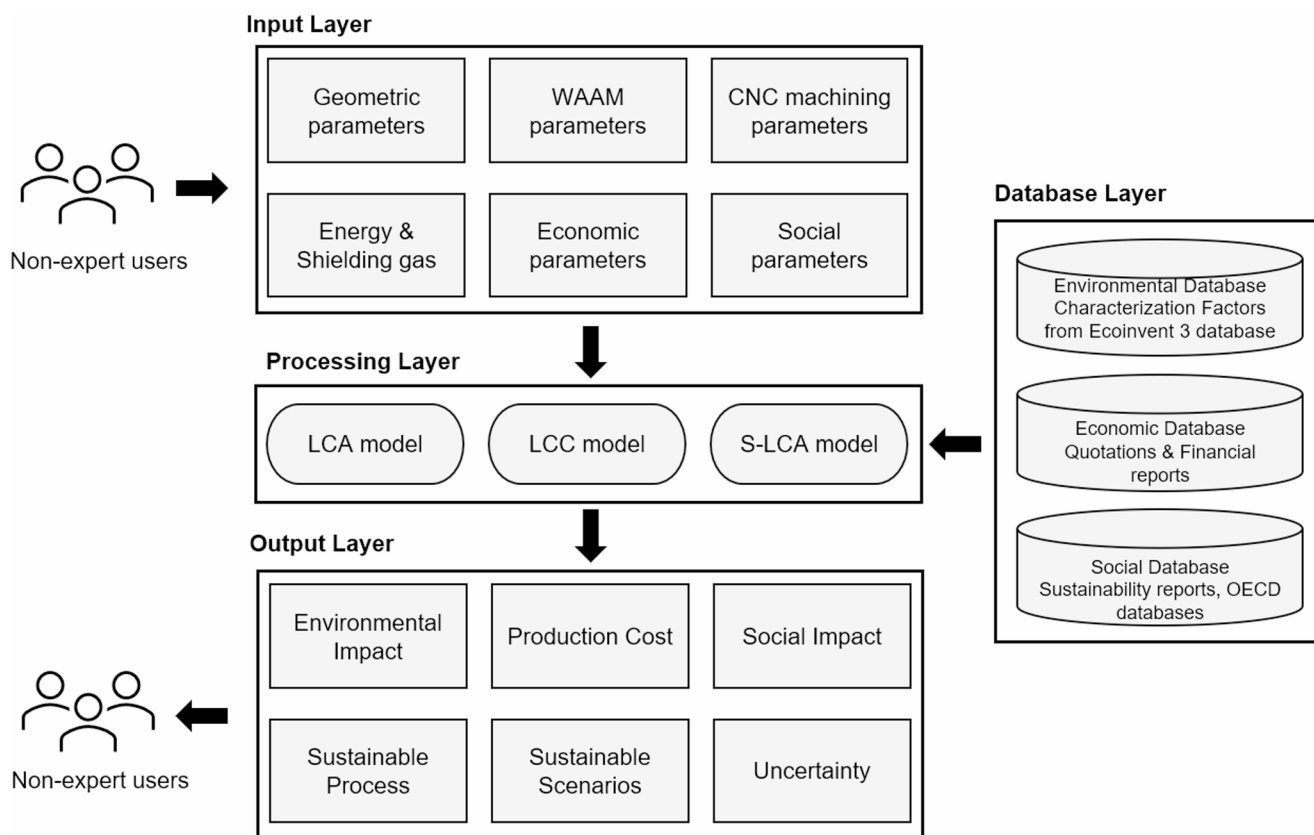


Fig. 4 Overview of the LCSA web tool architecture

serves as the main interaction point for users, providing the necessary parameters that drive the impact computations.

3.1.2 Database layer

The database layer compiles and organizes the background data required for the environmental, economic, and social assessments. Three key databases: environmental, economic, and social, are integrated into the web tool to ensure comprehensive LCSA.

The environmental database contains characterization factors for different inventory flows such as raw materials, energy, and other process consumables taken from Ecoinvent 3 database. The economic database includes data related to the costs of various resources such as machines, materials, energy, and labour, collected from vendor quotations and the company's financial records. The social database comprises data relevant to social indicators, gathered from the company's sustainability reports and public databases of international institutions such as the Organization for Economic Cooperation and Development (OECD), International Labour Organization (ILO), and European Union (EU-27), among others, as recommended in the methodological sheets for S-LCA by UNEP/SETAC [56]. This layer ensures that all models have access to the

necessary background data to compute environmental, economic, and social impacts consistently and accurately.

3.1.3 Processing layer

This layer contains LCA, LCC, and S-LCA models. These models are parametric models based on product and process parameters. Based on the user inputs from the input layer and background data from the database layer, the tool automatically calculates and compares the environmental, economic, and social impacts of WAAM with those of traditional CNC machining.

3.1.4 Output layer

The output layer visualizes the results through the GUI. The tool displays LCSA results across environmental, economic, and social dimensions and highlights hotspots, helping users identify the factors that most significantly influence sustainability performance. The effect of input data uncertainty on the results can also be visualized here. By revealing these results, the tool enables designers to make informed decisions to reduce impacts early in the product design stage, thereby integrating "Life Cycle Thinking" into product development and promoting sustainable design practices.

3.2 LCSA modelling

3.2.1 Goal and scope definition

The goal of LCSA in this study is to assess the environmental impacts, manufacturing costs, and social effects associated with producing a part using WAAM and compare its environmental and economic performance with conventional CNC milling. The functional unit here is the unit part that needs to be analyzed by the LCSA web tool user. The system boundaries of this LCSA are cradle-to-gate i.e., they encompass raw materials and manufacturing of the part, as illustrated in Fig. 5. Furthermore, the scope of LCSA is limited to high strength low alloy (HSLA) steel parts. For WAAM, the feedstock material, a steel wire, is manufactured by hot rolling a billet and then drawing it into wire. The part is fabricated by depositing molten wire layer-by-layer, allowing each layer to cool with the electric arc turned off between layers. Finally, the part undergoes post-processing, specifically finish machining, to achieve the desired final dimensions and tolerances. In contrast, the traditional CNC machining approach begins with a stock material—a steel bar—created by hot rolling a steel billet. The billet is then shaped into the desired part geometry on a CNC machine, where material is selectively removed using a rotating cutting tool.

3.3 Life cycle inventory calculations

3.3.1 Process time calculations

There are two main production modes in WAAM: deposition time ($t_{deposition}$) and cooling time ($t_{cooling}$). During the deposition mode, material is added to the print surface while the machine remains idle during the cooling period, allowing the printed layer to cool. The build rate (BR) of WAAM is computed as seen in Eq. (1).

$$BR = (\pi\phi^2/4) \times WFS \tag{1}$$

where ϕ is the wire diameter and WFS is the wire feed speed in WAAM.

The deposition time ($t_{deposition}$) is computed by dividing the part volume (V_{part}) by the build rate (refer to Eq. (2)).

$$t_{deposition} = V_{part}/BR \tag{2}$$

By multiplying the interlayer cooling time ($t_{cooling_layer}$) with the total number of layers, the cooling time ($t_{cooling}$) is calculated. Part height (h_{part}) and layer height (h_{layer}) are divided to calculate the total number of layers, as seen in Eq. (3).

$$t_{cooling} = t_{cooling_layer} \times (h_{part}/h_{layer}) \tag{3}$$

Hence, the total time for the WAAM process (t_{WAAM}) is the summation of deposition, cooling as well as set-up times (see Eq. (4)).

$$t_{WAAM} = t_{set-up} + t_{deposition} + t_{cooling} \tag{4}$$

3.3.2 Material calculation

The mass of wire required is the total mass of the final part (m_{part}) and the mass of material removed in post-processing (m_{scrap}), as seen in Eq. (5).

$$m_{wire} = m_{part} + m_{scrap} \tag{5}$$

In postprocessing, the material is removed to eliminate the surface waviness of WAAM parts. This material removed can be calculated as follows in Eq. (6):

$$m_{scrap} = a \times S \times \delta \tag{6}$$

where a is the uniform machining allowance, i.e., the depth up to which machining is required to eliminate surface waviness, S denotes the surface area of the part, and δ is the density of part material.

Therefore, the material efficiency of WAAM (ϵ_{WAAM}) is calculated as follows in Eq. (7):

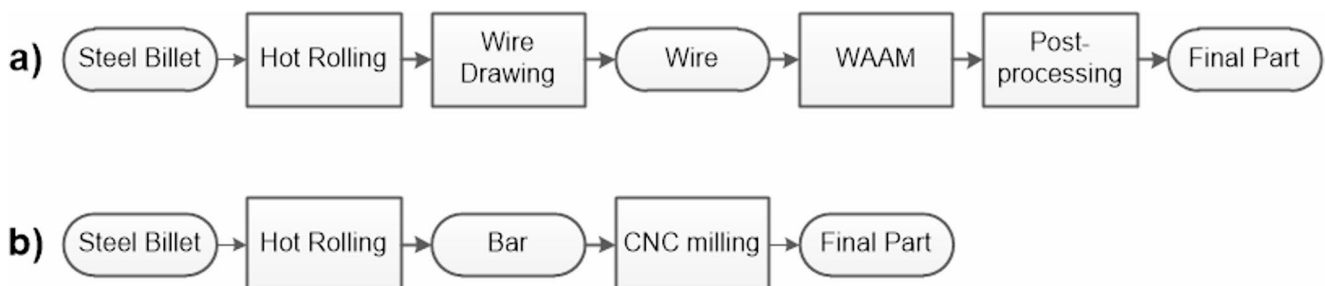


Fig. 5 Scope of LCSA (a) WAAM (b) CNC milling

$$\varepsilon_{WAAM} = \frac{m_{part}}{m_{wire}} \tag{7}$$

For post-processing CNC machining, the milling time ($t_{post-processing}$) is computed by dividing the mass of the material removed by the material removal rate (MRR) (see Eq. (8)).

$$t_{post-processing} = (1 - \varepsilon_{WAAM}) \times m_{part} / MRR \tag{8}$$

The MRR is calculated as follows in Eq. (9)

$$MRR = V_f \times a_e \times a_p \tag{9}$$

where V_f , a_e , a_p denote feed rate, width of cut and depth of cut used in CNC machining, respectively.

3.3.3 Electricity and shielding gas calculations

Electrical energy is used for creating an electric arc that melts the feed wire in WAAM and for finish machining. The shielding gas is used to protect the molten material pool from atmospheric interaction to avoid the formation of defects. The current and voltage during WAAM are monitored using sensors and a NI USB 6008 data acquisition device in Lab-View software. Then, the power consumption is computed and plotted against times, as illustrated in Fig. 6.

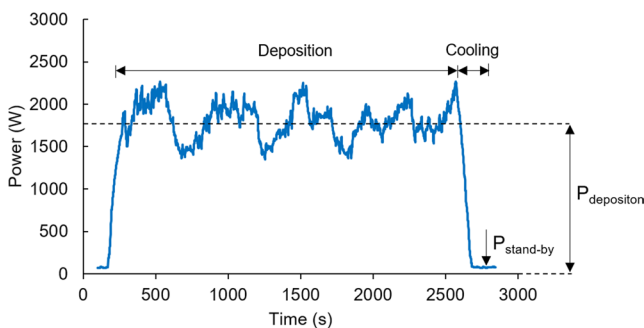
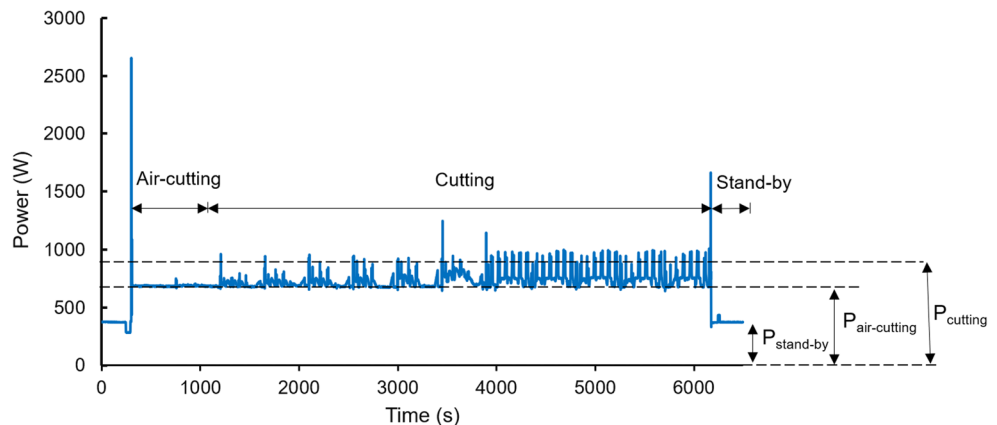


Fig. 6 Electricity consumed during WAAM [57]

Fig. 7 Electricity consumed during post-processing CNC machining [57]



The electricity consumed WAAM (E_{WAAM}) is calculated by multiplying the power of the machine and printing time as follows in Eq. (10):

$$E_{WAAM} = P_{stand-by} \times (t_{set-up} + t_{cooling}) + P_{deposition} \times t_{deposition} \tag{10}$$

Similarly, the power consumed during post-processing CNC machining is also monitored (refer to Fig. 7) and the energy consumption for post-processing CNC milling is calculated as follows (refer to Eq. (11)):

$$E_{CNC-milling} = P_{stand-by} \times t_{set-up} + P_{air-cutting} \times t_{air-cutting} + P_{cutting} \times t_{cutting} \tag{11}$$

Shielding gas is utilized during the process to prevent the molten metal from reacting with atmospheric gases. The shielding gas composition used in this study is 82% Argon and 18% CO₂. The volume of shielding gas used in WAAM (g_{part}) is calculated by multiplying the gas flow rate (f_{gas}) by the deposition time ($t_{deposition}$), as shown in Eq. (12).

$$g_{part} = f_{gas} \times t_{deposition} \tag{12}$$

3.3.4 Life cycle assessment model

In the LCA model, the environmental impact of all resources used in a manufacturing process is assessed and combined to determine the product’s total environmental impact. In this study, ReCiPe 2016 (Hierarchist) methodology is used to compute environmental impacts [58]. In ReCiPe 2016 (Hierarchist) method, the environmental impact is expressed in 18 different environmental impact categories, often known as midpoint indicators, as illustrated in Fig. 8. For each midpoint indicator, ReCiPe provides characterization factors, which are coefficients used to convert LCI inputs,

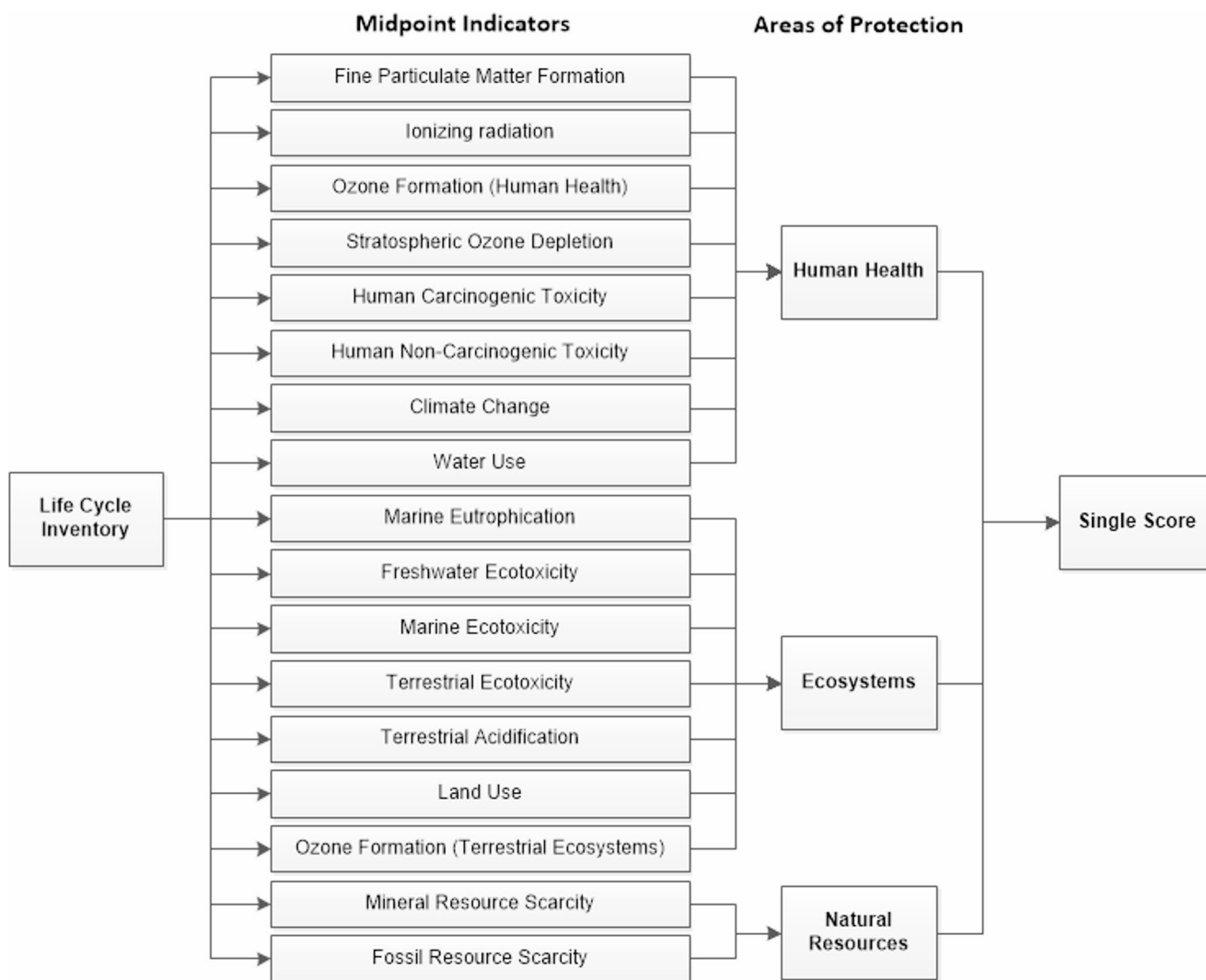


Fig. 8 Correlation between life cycle inventories, ReCiPe 2016 (Hierarchist) midpoint indicators and endpoint indicator expressed as a single score in Eco-points (Pts) [58]

into measurable environmental impacts [58]. For instance, the characterization factor of methane is 25 kg CO₂ eq./kg in the environmental impact category of Global Warming Potential (GWP100) [23]. Therefore, by multiplying the quantity of each LCI input by the appropriate characterization factor for the impact category, multiple LCI inputs are converted into a single numerical value for each midpoint indicator as follows [23] in Eq. (13):

$$EI_c = \sum_i Q_i \times F_{i,c} \tag{13}$$

where EI_c is the environmental impact for midpoint indicator c , Q_i is the quantity of LCI input i and $F_{i,c}$ is the characterization factor for LCI input i in midpoint indicator c . The environmental impact values for 18 midpoint indicators are aggregated into a single score by multiplying environmental

impact of each midpoint indicator with a weighing factor assigned to the corresponding midpoint indicator, as follows in Eq. (14):

$$S_{EI} = \sum_c W_c \times EI_c \tag{14}$$

where S_{EI} is the single score environmental impact expressed in Eco points (Pts) and W_c is the weighing factor assigned for midpoint indicator c .

The environmental impact of the wire in midpoint indicator c ($EI_{wire,c}$) is calculated by multiplying the mass of the wire consumed by the characterization factor for wire in midpoint indicator c ($F_{wire,c}$), and this is expressed in Eco-points (Pts) (refer to Eq. (15)).

$$EI_{wire,c} = m_{wire} \times F_{wire,c} \tag{15}$$

The environmental impact of the electricity consumed in midpoint indicator c ($EI_{\text{electricity},c}$) is determined by multiplying e_{part} by the characterization factor for electricity ($F_{\text{electricity},c}$), as shown below in Eq. (16):

$$EI_{\text{electricity},c} = e_{\text{part}} \times F_{\text{electricity},c} \quad (16)$$

The midpoint environmental impact of shielding gas ($EI_{\text{gas},c}$) is calculated by multiplying g_{part} by the respective characterization factor for shielding gas ($F_{\text{gas},c}$) (see Eq. (17)).

$$EI_{\text{gas},c} = g_{\text{part}} \times F_{\text{gas},c} \quad (17)$$

Likewise, the midpoint environmental impact of post-processing finish machining by CNC milling ($EI_{\text{post-processing},c}$) is calculated by multiplying the quantity of energy consumed during finish machining ($E_{\text{finishing}}$) by the corresponding characterization factor for electricity ($F_{\text{electricity},c}$), as seen in Eq. (18).

$$EI_{\text{post-processing},c} = E_{\text{finishing}} \times F_{\text{electricity},c} \quad (18)$$

The midpoint environmental impact of manufacturing a part by WAAM in an environmental category ($EI_{\text{WAAM},c}$) is derived from aggregating the environmental

impacts associated with raw materials, electricity consumption, shielding gas usage, and post-processing activities (see Eq. (19)).

$$EI_{\text{WAAM},c} = EI_{\text{wire},c} + EI_{\text{electricity},c} + EI_{\text{gas},c} + EI_{\text{post-processing},c} \quad (19)$$

Similarly, the midpoint environmental impact of manufacturing a part by traditional CNC milling is expressed as the total of environmental impacts caused by bar and energy consumed during the entire process, as seen in Eq. (20)

$$EI_{\text{CNC_milling},c} = \underbrace{m_{\text{bar}} \times F_{\text{bar},c}}_{EI_{\text{bar},c}} + \underbrace{E_{\text{CNC_milling}} \times F_{\text{electricity},c}}_{EI_{\text{electricity},c}} \quad (20)$$

Table 2 lists the characterization factors ($F_{i,c}$) obtained from the Ecoinvent 3 database for individual inventory flows. For calculating these characterization factors, individual LCAs of steel wire, bar, and shielding gas production were conducted in SimaPro 9.2.0.2 using ReCiPe 2016 (H). The characterization factors for unit electricity production depends on the country-wise electricity mix. The country-wise characterization factors for electricity are listed in Appendix (refer to Table 8).

Table 2 Characterization factors of various inventories based on ecoinvent 3 database [59]

Impact category (c)	Unit	Characterization Factors ($F_{i,c}$)			
		Steel Wire/kg	Steel Bar/kg	Shielding Gas/L	Electricity (Belgian mix)/kWh
Global warming	kg CO2 eq	2.74E+00	2.37E+00	1.93E+00	2.42E-01
Stratospheric ozone depletion	kg CFC11 eq	6.72E-07	5.54E-07	8.50E-07	1.61E-07
Ionizing radiation	kBq Co-60 eq	1.49E-01	1.09E-01	8.94E-01	3.72E-01
Ozone formation, Human health	kg NOx eq	6.28E-03	5.79E-03	3.29E-03	2.85E-04
Fine particulate matter formation	kg PM2.5 eq	4.45E-03	4.08E-03	2.68E-03	9.54E-05
Ozone formation, Terrestrial ecosystems	kg NOx eq	6.74E-03	6.22E-03	3.32E-03	2.91E-04
Terrestrial acidification	kg SO2 eq	7.33E-03	6.55E-03	6.65E-03	2.58E-04
Freshwater eutrophication	kg P eq	1.37E-03	1.17E-03	1.74E-03	4.15E-05
Marine eutrophication	kg N eq	1.12E-04	8.45E-05	1.33E-04	9.43E-06
Terrestrial ecotoxicity	kg 1,4-DCB	1.46E+01	1.38E+01	2.43E+00	2.04E-01
Freshwater ecotoxicity	kg 1,4-DCB	2.27E-01	2.05E-01	8.30E-02	7.78E-03
Marine ecotoxicity	kg 1,4-DCB	3.14E-01	2.83E-01	1.10E-01	9.99E-03
Human carcinogenic toxicity	kg 1,4-DCB	2.22E+00	1.88E+00	1.38E-01	9.11E-03
Human non-carcinogenic toxicity	kg 1,4-DCB	3.06E+00	2.67E+00	2.34E+00	1.36E-01
Land use	m2a crop eq	8.04E-02	6.55E-02	4.42E-02	1.41E-02
Mineral resource scarcity	kg Cu eq	1.52E-01	1.46E-01	2.73E-03	5.65E-04
Fossil resource scarcity	kg oil eq	6.03E-01	5.43E-01	5.02E-01	6.35E-02
Water consumption	m3	3.81E-02	2.04E-02	9.07E-02	2.75E-03
Single Score (S_{EI})	Eco-points (Pts)	2.29E-01	1.98E-01	8.06E-02	

3.3.5 Life cycle costing model

The cost model used in this study encompasses the machine, material, consumables, post-processing and labour costs. The cost of the machine tool ($C_{machine}$) includes the cost of purchasing the machine, its maintenance, repair, and tooling over its expected life span. The machine cost is expressed as follows in Eq. (21):

$$C_{machine} = \left(\frac{C_{mct} + C_{mt} + C_{tooling}}{t_{available}} \right) \times t_{machine} \quad (21)$$

The material cost ($C_{material}$) is cost of the feedstock materials such as wires or bars needed for production and is typically calculated as unit material cost (MC_{1kg}) multiplied by the amount of material consumed (m_{wire} in case of WAAM and m_{bar} in case of CNC milling) during production (refer to Eq. (22)).

$$C_{material} = m_{wire} \times MC_{1kg} \quad (22)$$

Table 3 List of social indicators and cut-off criteria for their assessment [56]

Social Indicator	Cut-off criterion
Gross Value Added per employee per annum (€)	Country average [62]
Corruption Index	EU average [63]
Collective Bargaining coverage of employees (%)	EU average [64]
Annual expenditure in social security (% GDP)	EU average [65]
Minimum monthly salary of employees (€)	Country average [66]
Presence of annual sustainability report	Yes
Gender ratio (%)	50 %
Gender pay gap (%)	EU average [67]
Lost Time Injury Frequency Rate	Global Sector average [68]
Presence of fair competition policy	Yes
Presence of policy to prevent IPR infringement	Yes
Integration of sustainability criteria in selecting suppliers	Yes
Organizational support for community-level engagement	Yes
Electricity used from renewable energy sources (%)	EU average [69]
Air quality (Annual average PM2.5 concentration)	5 µg/m ³
Presence of Management measures to assess consumer health and safety	Yes
Presence of a mechanism for customers to provide feedback	Yes
Presence of internal management system to protect consumer privacy	Yes

The consumables cost ($C_{consumables}$) includes the cost of consumables such as energy, cutting fluids, lubricants, or shielding gases consumed during the production process and is calculated similarly to material costs, as follows in Eq. (23):

$$C_{consumables} = e_{part} \times EC_{1kWh} + g_{part} \times GC_{1m3} \quad (23)$$

The cost of post-processing operations ($C_{post-processing}$) such as finish machining is computed as the hourly rate of using post-processing machines (PPC_{1h}) multiplied by the total time required for post-processing operations ($t_{post-processing}$), as shown in Eq. (24).

$$C_{post-processing} = PPC_{1h} \times t_{post-processing} \quad (24)$$

The cost of human labour (C_{labour}) directly required for execution, supervision, and management of the part production is calculated as an hourly rate (LC_{1h}) multiplied by the time spent by the operator on production (t_{labour}) (refer to Eq. (25)).

$$C_{labour} = LC_{1h} \times t_{labour} \quad (25)$$

3.3.6 Social life cycle assessment model

The social Life Cycle Assessment model is developed to assess the social impacts of WAAM products based on UNEP/SETAC guidelines [55]. The model consists of the following steps:

Selection of Social Indicators The social indicators, their scoring scale and cut-off criteria, are selected based on UNEP/SETAC methodological sheets [56] and are listed in Table 3. In this study, a binary scoring scale (0 or 1/Yes or No) is used, and regional/national averages are considered as cut-off criteria wherever company-specific data is unavailable, to facilitate easy integration of S-LCA in the early design stages. While the social indicators should be aligned with UNEP/SETAC guidelines [55], their cut-off criteria, and scoring scales can be customized for a company based on data availability and the level of detail in the social inventory. For instance, if more company-specific social data is available, the scoring system can be expanded from a binary scale (0 or 1) to a multi-level scale, such as 1 to 5 (where 1 represents highly negative performance and 5 represents highly positive performance), or company averages can be used instead of regional or national averages, as cut-off criteria.

Weighing of Social Indicators Next, the weightage for each social indicator for determining the total social impact is

calculated. In this study, all social indicators are equally weighed. Hence, the weightage for each indicator is calculated as follows (see Eq. (26)):

$$w = \frac{1}{n} \quad (26)$$

Scoring & Aggregation Next, the social indicators are evaluated based on the social inventory data collected. Based on the performance (P_i) relative to the cut-off criterion, the social indicators are assigned a score [60, 61]. If the social indicator performs better than the cut-off criteria, a score of 1 is assigned or else a score of 0 is assigned, as depicted in Eq. (27).

$$S_i = \begin{cases} 1 & \text{if } P_i > \text{cut-off criterion} \\ 0 & \text{if } P_i < \text{cut-off criterion} \end{cases} \quad (27)$$

This binary scoring scale simplifies normalization of all social indicators considered, especially in early design stages where social inventory data may not be readily available. Then the total aggregated score (S_{SI}) is quantified by calculating a weighted average of individual indicator scores (S_i) (refer to Eq. (28)).

$$S_{SI} = \sum_{i=1}^n w \cdot S_i \quad (28)$$

Decision rule The overall cut-off score is the average of the maximum (1) and minimum (0) scores possible i.e. 0.5. If the total aggregated score (S_{SI}) equals or exceeds the overall cutoff score, the social impact is considered positive, or else it is considered negative, as shown in Eq. (29).

$$\text{Social Impact} = \begin{cases} \text{Positive}; & \text{if } S_{SI} \geq 0.5 \\ \text{Negative}; & \text{if } S_{SI} \leq 0.5 \end{cases} \quad (29)$$

3.3.7 Assumptions and limitations in LCSA modelling

While formulating LCA, LCC and S-LCA models used in this study, some important assumptions and considerations had to be made. These assumptions and considerations are stated explicitly as follows:

- The scope of the LCA, LCC and S-LCA models is cradle-to-gate, covering raw materials and manufacturing phases (refer to Fig. 5) as opposed to cradle-to-grave that covers use and end-of-life phases in addition to cradle-to-gate system boundaries.

- From a materials perspective, this LCSA web tool is modelled exclusively for high strength low alloy (HSLA) steels.
- The raw materials (steel wire and bar), shielding gas, and electricity are assumed to be completely produced in the European Union (EU-27) region. The country-wise electricity mixes are considered based on the inventory data provided by Ecoinvent 3.0 database.
- For WAAM, the feedstock wire is considered to be manufactured from a steel billet that undergoes hot rolling followed by wire drawing (refer to Fig. 5a). A material loss of 5% in hot rolling and 4% in wire drawing is assumed based on the Ecoinvent 3.0 database. The life cycle inventories analysis for modelling steel wire is listed in Table 5 in Appendix at the end of this paper.
- For CNC milling, the feedstock bar is considered to be manufactured by hot rolling of a steel billet (refer to Fig. 5b). A 5% material loss in the hot rolling stage is assumed based on the Ecoinvent 3.0 database. The life cycle inventories analysis for modelling steel bar is listed in Table 6 in Appendix at the end of this paper.
- The shielding gas considered in this study is composed of 82% argon and 18% CO₂. The life cycle inventories for modelling shielding gas are enlisted in Table 7 in Appendix at the end of this paper.
- For S-LCA, a country-wise social inventory data for EU-27 region is compiled to assess the social indicators, as previously explained in Table 3. The country-wise data for these indicators are provided in Appendix (refer to Table 9) at the end of this paper.
- The environmental and economic impacts of transportation of raw materials to production site are not considered in this study.
- The data uncertainty for each environmental and economic input is assumed to follow a normal distribution where the value entered by the user is assumed to be the mean and standard deviation can be expressed as a percentage of mean value.

4 Results and discussion

A web based LCSA tool that estimates the life cycle environmental impact, cost, and social impacts of additive WAAM and pure subtractive CNC machining. The tool can be accessed via the internet without the need to possess commercial LCA software to calculate environmental impacts. This tool is developed using GRID [70], where the LCA, LCC, and S-LCA models as described previously are integrated into this tool using electronic spreadsheets.

The user needs to enter the geometric parameters such as the volume, surface area, and height of the part to determine its environmental, economic, and social impacts. For WAAM, processing and post-processing parameters must be entered, including the wire feed speed, travel speed of the axes, wire diameter, layer height, and gas flow rate. Additionally, post-processing parameters include material allowance for finish machining and cutting parameters like feed rate, width, and depth of cut. Economic parameters include the costs associated with machine tools for the WAAM process and post-processing operations, including their depreciation time, availability, maintenance, tooling, and operator costs. The user interface for entering WAAM inputs is displayed in Fig. 9.

For pure CNC machining, the geometry of the initial workpiece (stock) must be entered, and it must be specified whether it is cylindrical or cuboidal, along with its respective dimensions, such as diameter and height for cylindrical stock, or length, breadth, and height for cuboidal stock. Cutting parameters like feed rate, width of cut, and depth of cut are crucial. Economic parameters include the CNC milling machine cost, depreciation time, availability, maintenance and tooling costs, material cost, operator cost, and consumables cost. The user interface for entering CNC machining inputs is presented in Fig. 10.

The social parameters essential for evaluating the social impacts of WAAM operations include several critical inputs. Firstly, the country or territory of operation is an essential input as it determines the legal provisions regarding labor rights, minimum wage, corruption, pollution levels, in general. Additionally, the publication of an annual sustainability report ensures transparency regarding the disclosure of emissions arising from the organization's activities. The economic contribution to the society is indicated by the gross value added per year due to WAAM-related business. The number of employees employed directly in WAAM-related business is also a key parameter. The social impact on workers such as fair wages, discrimination and equal opportunities, and occupational safety is assessed by considering the minimum salary paid to the employees, the gender ratio (proportion of female employees) and gender pay gap (difference between wages received by male and female employees), and the Lost Time Injury Frequency rate (LTIFR). LTIFR refers to the number of accidents resulting in at least one day of absence from work over a given time period and is calculated per million hours worked. Furthermore, the presence of adequate policies related to anti-corruption, intellectual property rights (IPR), community engagement, procurement, health and safety, and data privacy, as depicted in Fig. 11, is crucial for comprehensive social impact evaluation on stakeholders such as customers, local communities and suppliers.

Once the above parameters are entered, the web tool calculates the environmental impact, cost, and social impact based on the parameters entered in the above input fields. The tool presents the following results: an environmental impact comparison expressed as a single score by ReCiPe in eco-points (Pts) for WAAM and pure CNC milling approaches; a production cost comparison in Euros for both WAAM and pure CNC milling approaches; and a social impact comparison between the aggregated score calculated using the S-LCA model developed and the cut-off score. It also provides a breakdown analysis of the environmental impacts of WAAM and pure CNC milling, indicating the contribution of each inventory consumed, as well as a breakdown analysis of production costs incurred by WAAM and pure CNC milling, highlighting the major cost drivers for each approach. Additionally, the tool compares the social performance of the WAAM organization in different social indicators against the EU/national average as the baseline. Furthermore, the results of the LCSA and their detailed analyses can be exported as PDF files.

4.1 Validation

To validate the tool, environmental impacts and costs for WAAM and CNC machining reported in peer-reviewed LCA/LCC studies [46, 47, 51, 52] were used as reference datasets. These studies were selected because they provide detailed life cycle inventories and process parameters for WAAM and CNC machining and hence, were easy to validate. The same product dimensions, feedstock material, shielding gas, flow rates, and cost data were entered into the tool, along with averaged values for WAAM deposition rates and CNC machining parameters as reported in the above studies. The percentage error was calculated using Eq. (30):

$$\% \text{ Error} = \frac{\text{Predicted Value by webtool} - \text{Actual Value}}{\text{Actual Value}} \times 100 \quad (30)$$

The percentage error of the environmental impact and cost predicted by the tool compared to existing studies are listed in Table 4. It is seen that the tool predicts environmental impacts for pure CNC milling with an error of less than 10%, while cost predictions show an error of up to 12.5%. CNC milling of the parts reported in [47, 51, 52] involves multiple machining operations such as roughing, semi-finishing, and finishing, each with distinct cutting parameters like cutting speed, feed rate, and depth of cut. Consequently, cutting toolpaths and cutting times vary across operations. However, the web tool simplifies this complexity by considering only averaged cutting parameter values for CNC milling. This simplification leads to inaccuracies in cutting time calculations, which in turn affect energy consumption

Geometric Parameters

Volume (cc) ? height (cm)

Surface area (sq. cm)

WAAM Process Parameters

wire feed speed (m/min) travel speed (mm/min) layer height (mm)

wire diameter (mm) gas flow rate (l/min)

WAAM Post-processing Parameters

Machining allowance (mm) Width of cut (mm) Feed rate (mm/min)

Depth of cut (mm)

Economic Parameters

For WAAM

WAAM facility cost (€) Depreciation time (years) No. of working days/year

Duration of shift/day (hours) No. of shifts/day Availability of WAAM facility (%)

No. of shifts/day Maintenance Cost/year (% of WAAM facility cost)

Tooling cost/year (% of WAAM facility cost) WAAM operator cost (€/h)

For WAAM Post-processing

CNC milling machine cost (€) Depreciation time (years) No. of working days/year

Duration of shift/day (hours) No. of shifts/day Availability of WAAM facility (%)

Maintenance Cost/year (% of CNC milling machine cost)

Tooling Cost/year (% of CNC milling machine cost) CNC operator cost (€/h)

Fig. 9 Web tool interface for entering geometric parameters, process parameters, and economic parameters for WAAM

CNC machining parameters

Stock type Cylindrical Cuboidal

Dimensions of stock:

diameter height

Feed rate (mm/min) Width of cut (mm) Depth of cut (mm)

Economic Parameters

CNC milling machine cost (€) Depreciation time (years) No. of working days/year

Duration of shift/day (hours) No. of shifts/day Availability (%)

Maintenance Cost/year (% of CNC milling machine cost) Tooling Cost/year (% of CNC milling machine cost)

CNC operator cost (€/h) Material cost (€/kg)

Electricity cost (€/kWh)

Fig. 10 Web tool interface for entering stock dimensions, process parameters and economic parameters for CNC machining

estimates, resulting in errors in both environmental impact and cost predictions.

For WAAM, error margins of up to 15% are observed. WAAM deposition and post-processing times depend on tool-path complexity and cutting parameters used for post processing operations. However, the tool uses an average build rate for deposition and averaged cutting parameters for machining as inputs. This simplification ignores the effect of toolpath and specific cutting parameters, causing inaccuracies in estimating deposition and post-processing times. These errors then affect electricity and shielding gas calculations, which ultimately lead to errors in environmental impact and cost predictions. However, despite these error margins, sustainability trends predicted by the tool remain consistent with those reported in existing studies. Hence, the tool remains a valuable resource for estimating approximate environmental, economic, and social impacts efficiently in terms of time and cost.

4.2 Case study

To demonstrate the utility of this online platform, a case study comparing the environmental impact and production cost of WAAM and CNC machining for manufacturing an inner cone part of a cone clutch was performed (refer to Fig. 12). This part has a volume of 4085 cm³, a surface area of 3003 cm² and is 10 cm in height.

For WAAM, the following process parameters were considered: wire feed speed (WFS)=6 m/min; layer height=1.5 mm; gas flow rate: 15 L/min. Additionally, a material allowance of 2 mm throughout the part surface was considered for the finish machining of the part. For finish machining the following cutting parameters are considered; feed rate=50 mm/min; width of cut=4 mm; and depth of cut=4 mm. For the CNC machining approach, a cylindrical workpiece of 33 cm in diameter and 11 cm in height and identical cutting parameters as mentioned previously, are considered. The costs of WAAM and CNC milling machine tools are 300,000 € and 150,000 €, respectively. Both the machine tools are assumed to have an availability of 80%, for 250 days/year and are used in 3 shifts of 8 h each per day. The operator cost is 13 €/hr while the wire and bar cost 13 €/kg and 5 €/kg, respectively. For social impact assessment, the data provided by a company based in Belgium that offers WAAM-based production and repair services was used in this case study. The above data were entered as input in the web tool. The results of LCSA are displayed in Fig. 13. WAAM was seen to be the most environmentally, economically, and socially friendly approach in this case. WAAM showed lower environmental emissions in 16 out of 18 midpoint indicators and reduced the single score environmental impact by 37%, compared to CNC milling. Additionally, WAAM costed 18% lower and its

Social Parameters

Country/Territory Your Company

Presence of annual sustainability report Yes No

Gross Value Added per annum (€)

No. of employees Minimum monthly salary of employees (€)

Gender ratio (%) Gender paygap (%) Lost Time

Injury Frequency Rate

Presence of fair competition policy Yes No

Presence of policy to prevent IPR infringement Yes No

Integration of sustainability criteria in selecting suppliers Yes No

Organization support for community level engagement Yes No

Presence of Management measures to assess consumer health and safety Yes No

Presence of internal management system to protect consumer privacy Yes No

Fig. 11 Interface for entering social parameters

Table 4 List of studies used for validating the LCSA models

Study	Product analyzed	Environmental Impact/ Cost	Process	Actual value	Value predicted by webtool	% Error
Bekker & Verlin-den [46]	1 kg of Stainless Steel 308L	Eco-points (mPts)	WAAM	1832.0	1797.0	-1.9
Campatelli et al.[47]	EN S235JR steel blade	Cumulative Energy Demand (MJ)	WAAM	128.9	113.8	-11.7
			Pure CNC machining	171.8	163.2	-5.0
Kokare et al.[51]	ER70S steel wall	Eco-points (mPts)	WAAM	96.7	98.3	1.6
			Pure CNC machining	43.6	39.4	-9.6
		Cost	WAAM	60.0	57.8	-3.6
			Pure CNC machining	19.7	18.1	-8.1
Kokare et al.[52]	ER70S marine propeller	Eco-points (mPts)	WAAM	197.0	178.0	-9.6
			Pure CNC machining	496.0	499.0	0.6
		Cost	WAAM	133.0	125.0	-6.0
			Pure CNC machining	144.0	126.0	-12.5

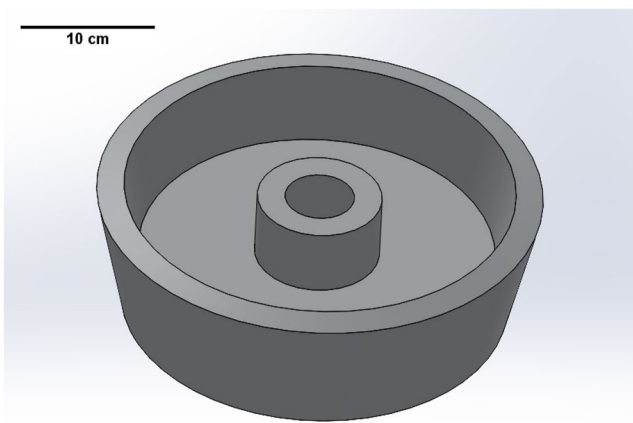


Fig. 12 Part model of the inner cone of a cone clutch [71]

implementation showed a positive social impact, exceeding the cutoff score.

Additionally, the web tool also displays a detailed analysis of results, indicating the environmental, economic, and social hotspots (refer to Fig. 14). In WAAM, the raw material consumed i.e. steel wire was the major contributor to environmental impact and production cost. The steel wire accounted for 85% of the environmental impact and 39% of the production cost. Other significant contributors to the production cost of WAAM were labor (20%), machine (19%), and post-processing (18%) costs. For CNC machining, raw material consumed was the environmental hotspot responsible for 93% of the total environmental impact. Labor cost was the major factor driving the production cost which accounted for 57% of the total production cost. Other

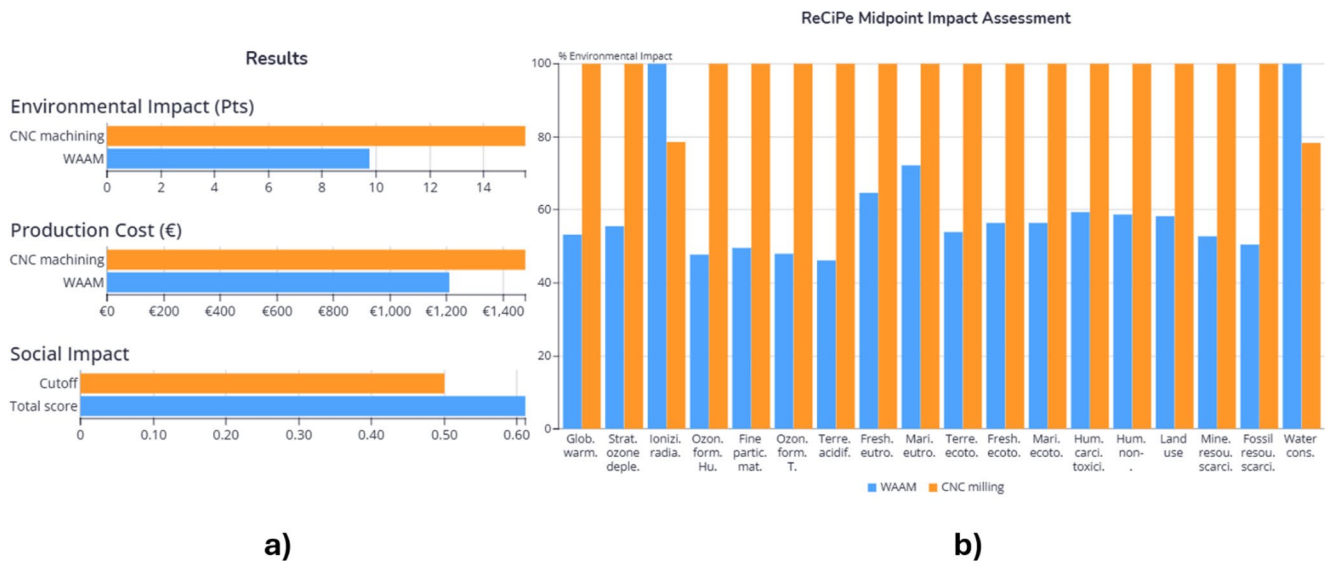
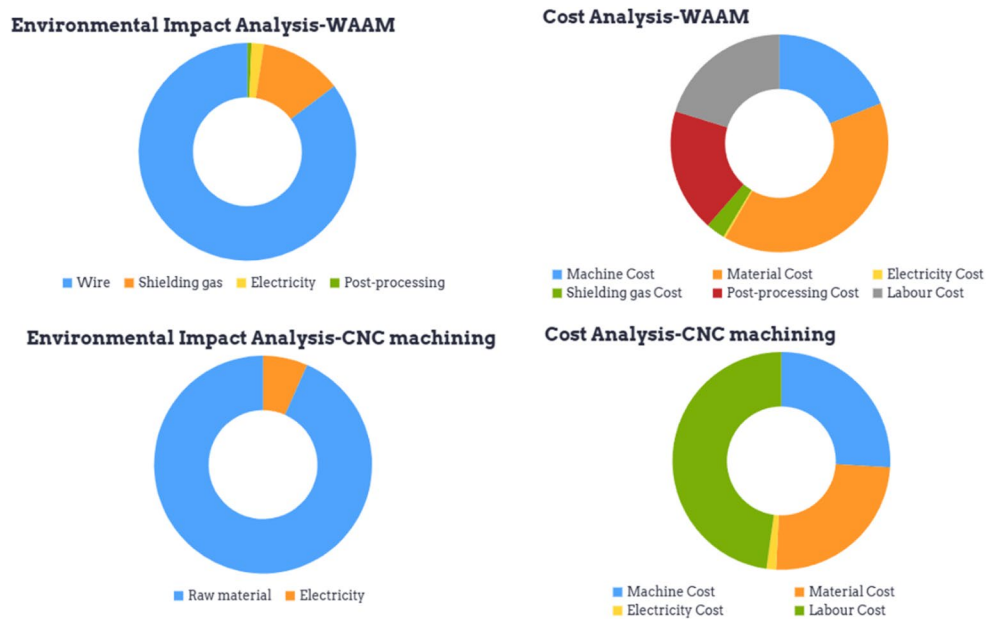


Fig. 13 Output interface of the web tool showing **a)** Environmental Impact, production cost, and social impact; **b)** A comparative environmental performance in other midpoint environmental indicators

Fig. 14 Output interface showing a detailed analysis of environmental impact and production cost for WAAM and CNC machining



significant costs were machine (27%) and material (15%) costs.

In addition to environmental and economic impacts, social impacts were also analyzed in detail in the web tool (refer to Fig. 15). In general, a positive social impact due to WAAM production and repair service was seen in its stakeholders. The company publishes its annual sustainability report disclosing its environmental emissions a positive social performance was seen in indicators like gross value added per employee, corruption perception index, annual

social security spending, and minimum wage. However, performances below the cutoff criteria were seen in indicators like the air quality index (PM 2.5 concentration in $\mu\text{g}/\text{m}^3$), lost time injury frequency rate, and electricity from renewable sources (%). Poor air quality with PM 2.5 concentration above the recommendation of $5 \mu\text{g}/\text{m}^3$ was reported in the location of the company mainly due to the dust emissions arising from steel production. This negatively affects the health and safety of the local communities. Additionally, the lost time injury frequency rate of 0.9 was found for the

Social Indicators

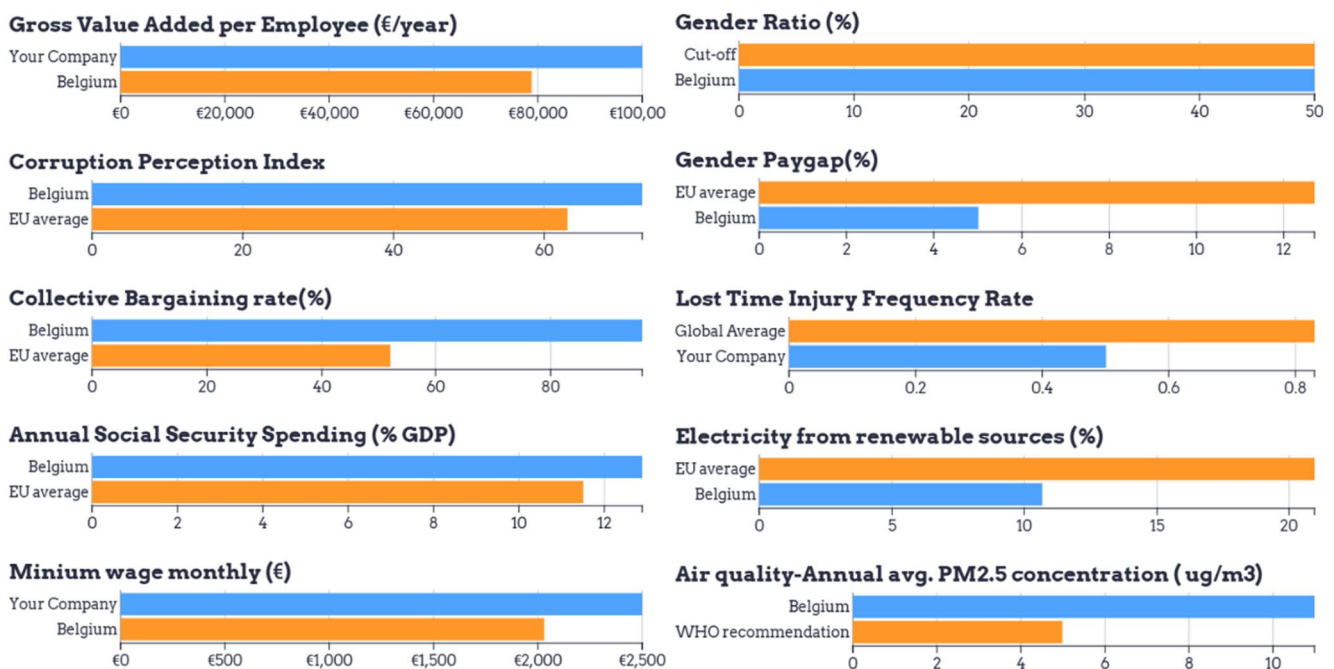


Fig. 15 Output interface showing social indicator-wise performance against the cut-off criterion

production site due to work-related accidents, exceeding the global average of 0.83 for the steel industry. About 11% of the electricity in Belgium is generated from renewable sources, well below the EU average of 23%. This puts pressure on the non-renewable natural resources in the region, limiting their access to the local communities. Hence, future efforts should focus on reducing PM 2.5 emissions, preventing work-related accidents, and generating more electricity from non-renewable energy sources.

With quick simulations enabled by this web tool, effect of multiple production variables environmental and economic impacts can be simulated to find optimum scenarios for environmentally and cost friendly part production. For example, Fig. 16 shows surface plots constructed using quick simulations performed by the web tool that study effect of variation in machining allowance: a post-processing parameter that determines the extra material left on the part for subsequent finish machining to eliminate surface waviness of WAAM (a) and Wire Feed Speed (WFS) of WAAM on its environmental and economic friendliness, as characterized by λ_e and λ_c . λ_e and λ_c are ratios of environmental impacts and production costs of WAAM and CNC milling, respectively. Hence, WAAM is environmentally and cost effective in regions with λ ratios less than one.

This case study was conducted within the Belgian context. However, using this web tool, the environmental, economic, and social impacts can be assessed for different countries in the European Union (EU) region. This tool was utilized to examine how geographical variations affect the environmental impact and cost-saving opportunities presented by WAAM. The web tool was used to calculate the environmental impact and production cost for manufacturing the specified part in various EU member countries, taking into

account their electricity mixes and average labour costs. Subsequently, the cost and environmental impact savings achieved by WAAM compared to CNC machining, and changes in social impact compared to Belgian scenario, were determined for each country, as illustrated in Fig. 17.

The results showed that WAAM resulted in greater cost savings in higher-income countries, where labour is expensive (Northern and Western Europe), compared to countries with relatively cheaper labour (Eastern and Southeastern Europe). Similarly, the country-wise variation in environmental impact due to variation in energy mix was also studied using this tool (refer to Fig. 18). Overall, WAAM showed lower environmental impact in all EU countries. Interestingly, WAAM demonstrated higher environmental savings in lower-income Southeast European countries that have a lower share of renewable energy in their electricity mixes compared to more prosperous Northern and Western European countries with electricity mixes rich in renewable sources.

Therefore, WAAM can enable decentralized manufacturing and repair of components in both higher- and lower-income countries by situating WAAM facilities close to customers, fulfilling customer requirements in an environmentally friendly and cost-effective manner. In higher-income countries, adopting WAAM can retain local manufacturing jobs and prevent the adverse social impacts on local communities and workers caused by outsourcing manufacturing jobs to lower-income countries with cheaper labour costs. For lower-income countries, adopting WAAM can create new manufacturing jobs, improve the standard of living, and can significantly reduce the environmental footprint in the manufacturing sector compared to conventional manufacturing technologies.

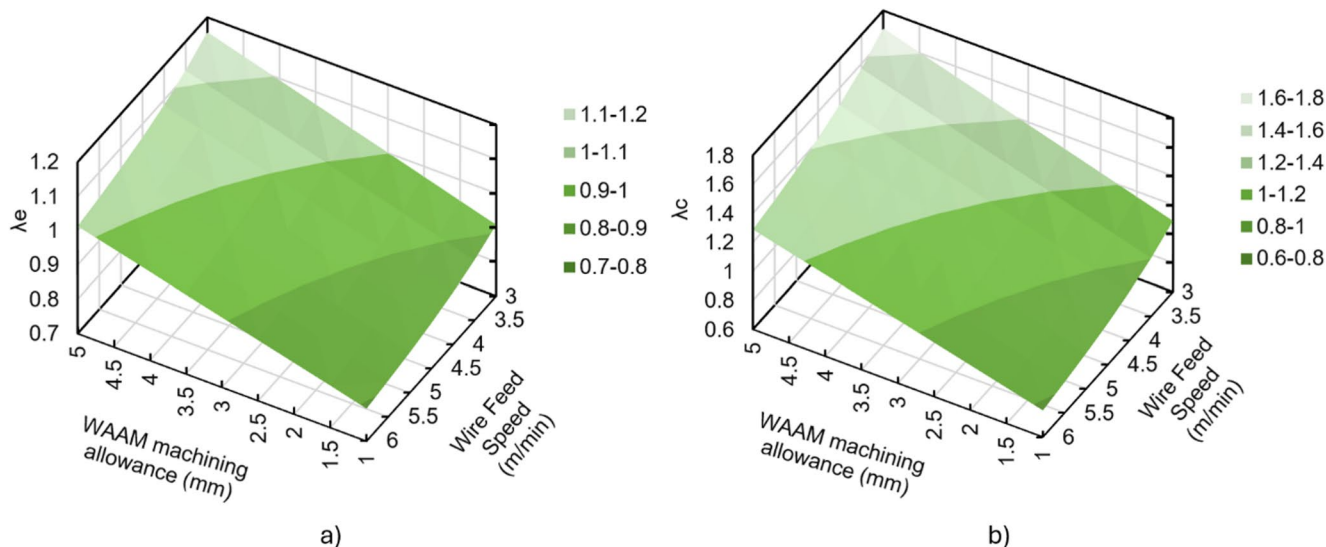


Fig. 16 Effect of WAAM machining allowance and wire feed speed on (a) Environmental impact and (b) Production Cost of WAAM. Regions with λ_e and $\lambda_c < 1$ indicate environmentally and economically friendlier WAAM, respectively

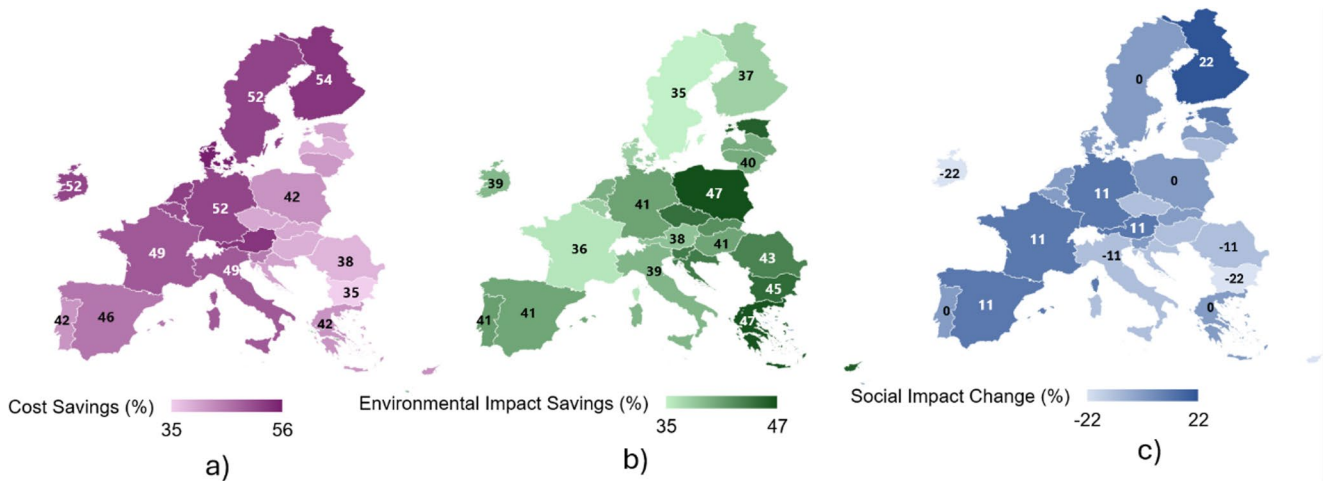


Fig. 17 (a) Country-wise cost savings; (b) Country-wise environmental impact savings achieved by WAAM in comparison with pure CNC machining; (c) Country-wise change in social impact in comparison with Belgium

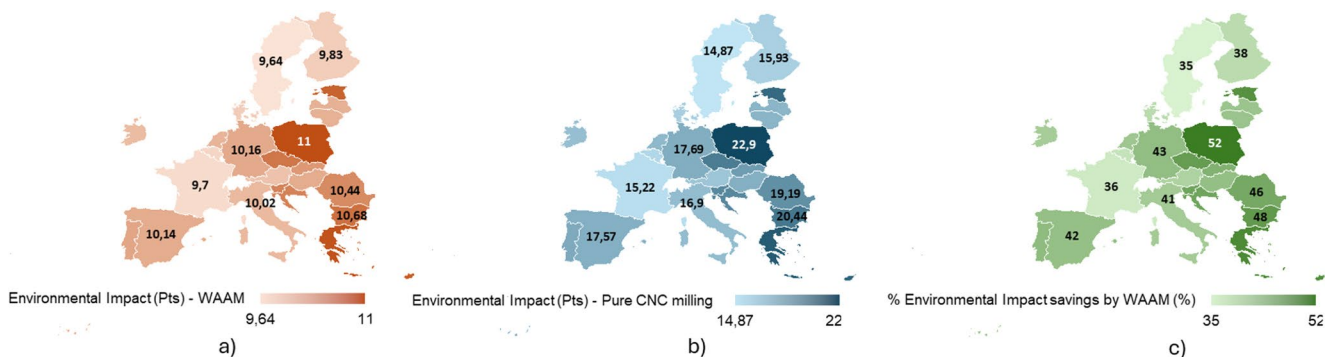


Fig. 18 Effect of country-wise energy mix on (a) Environmental impact of WAAM; (b) Environmental impact of pure CNC machining; (c) County-wise environmental impact savings achieved by WAAM in comparison with pure CNC machining

The digital tool can also conduct uncertainty analysis through Monte Carlo simulations [72]. In this approach, uncertainties in input data are assumed to follow a normal distribution, with the standard deviation defined as a percentage of the mean, which is the value provided by the user. Monte Carlo simulations are then run for 10,000 iterations [73]. During each iteration, values for each inventory item are randomly selected within their uncertainty range, and the environmental impact and production cost are calculated accordingly. The results of these environmental impacts and production costs are then plotted along with their probabilities of occurrence. Additionally, the mean, standard deviation, and the 95% confidence intervals (upper and lower limits) are computed (refer to Fig. 19).

Beyond the presented analysis of wire feed speed, machining allowance, country of operation, and energy mix, the tool can also be applied to other parameters. These insights help manufacturers pinpoint optimal ranges for sustainable performance and evaluate trade-offs between cost, environmental impact, and social performance. By using

these capabilities, decision-makers can align their strategies with sustainability goals while reducing operational risks.

4.3 Advantages of the web tool

The web tool presented in this paper offers better accessibility to perform LCSA for WAAM practitioners, especially SMEs involved in WAAM fabrication and repair businesses, as it can be accessed via the internet. This also allows them to perform sustainability assessments for their products and transparently declare their impacts. The tool is time and cost-effective, enabling rapid sustainability assessments without the need for software installation, expert hiring, or extensive data collection, thus reducing the time, effort, and costs involved. Its user-friendly interface features interactive graphics, such as sliders to alter parameter values, bar graphs, and pie charts, facilitating easy use for non-expert users. Additionally, the tool supports scenario analysis, allowing users to create and save different parameter scenarios, compare the environmental, economic, and

Uncertainty Analysis (Monte Carlo Simulations)

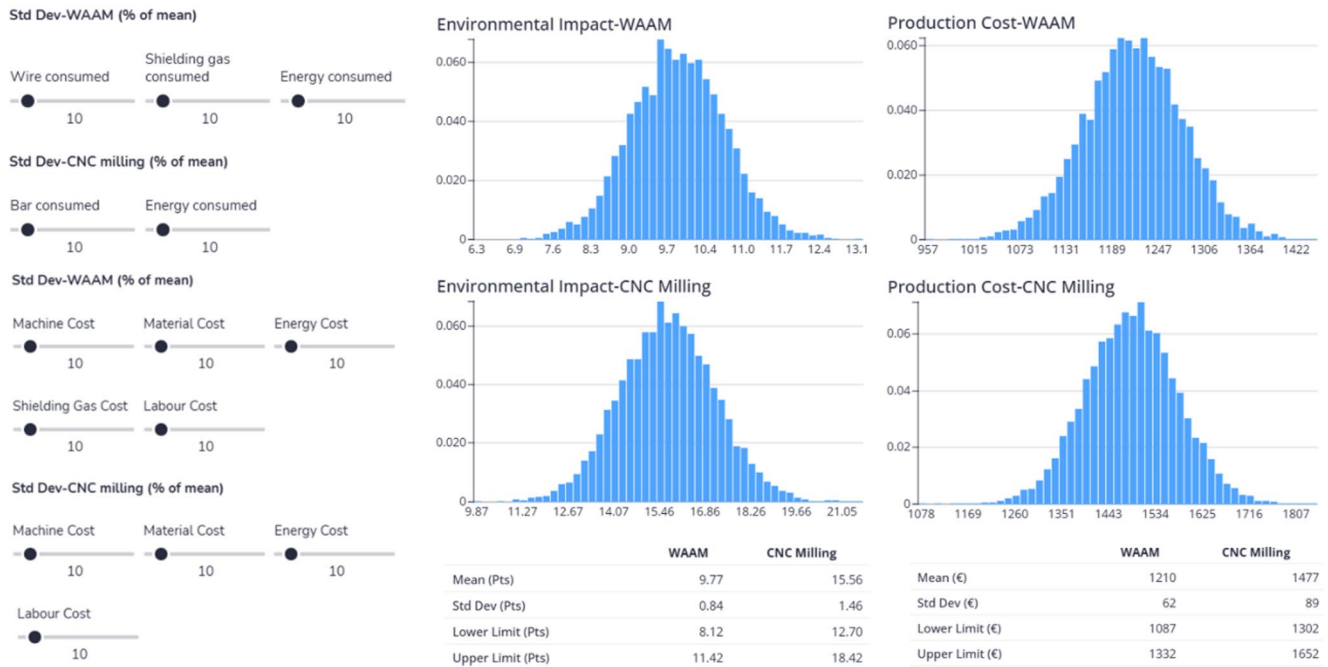


Fig. 19 Uncertainty assessment interface of the web tool

social impacts, and select the most sustainable option for WAAM and CNC milling. The web tool also promotes life cycle thinking by simulating the impacts of a WAAM component from its conceptualization and design stages. This enables the identification of sustainability hotspots early in the process, allowing manufacturers to implement mitigation measures, such as changes in materials, design, or processing parameters, thus integrating life cycle sustainability into product design and development.

4.4 Limitations and future research directions

The web tool currently has several limitations. It has been modelled and validated only for low alloy steel parts, requiring the collection of environmental, economic, and social inventory data for different materials and updating the LCSA models with new material inventories. Its geographical coverage is restricted to EU member states, necessitating efforts to expand its applicability to other regions. The tool employs simplified models that do not capture all real-world manufacturing complexities, such as supply chain logistics, maintenance, and end-of-life strategies, indicating a need for future research to incorporate these aspects into life cycle models. Additionally, the data in the tool, including electricity, electricity mixes, labour costs, and social data for different countries, are static and must be regularly updated to reflect inflation, economic conditions, and policy changes.

5 Conclusions

In this study, an online LCSA tool that performs environmental, economic, and social sustainability assessment of WAAM products using LCA, LCC, and S-LCA approaches respectively. The LCA, LCC, S-LCA models, and pertinent databases tailored for WAAM are developed and integrated into the online LCSA tool. By entering product and process parameters, even a non-expert user can perform a sustainability assessment of adopting WAAM technology, create and compare different scenarios, and contrast the environmental, economic, and social impacts of WAAM with traditional subtractive machining. The tool was also validated with data from existing LCA studies, and it predicted environmental and economic impacts with a maximum error margin of 12.5%. Furthermore, the online tool also presents a detailed analysis of factors driving environmental, economic, and social impacts acting as a basis for eco-design activities, product and process optimization, and informed decision-making aligned with sustainability goals. Additionally, a case study demonstrating the utility of the web tool was presented where environmental, economic, and social impacts of WAAM and CNC milling were compared in the manufacturing of a mechanical component. Utilizing this tool for sustainability assessments has several advantages, especially for SMEs that lack the financial and human expertise to conduct LCSA assessments. Firstly, the accessibility of this online tool through internet

democratizes LCSAs and promotes transparency across the value chain as interested stakeholders can rapidly perform environmental, economic, and social assessments of the products involved. The user-friendly interface of this tool assists in conducting sustainability assessments without any need for special knowledge of LCSA methodologies and their software. This facilitates widespread adoption of LCSA right from the initial stages of product development, ensuring a comprehensive sustainability analysis and improving the sustainability practices throughout WAAM products' lifecycles. Beyond WAAM, this framework can easily be adapted to other additive and subtractive manufacturing processes, and geographical locations outside the

EU by updating material, cost, and social datasets. This flexibility makes the tool a practical resource for companies, especially SMEs aiming to meet sustainability goals and comply with evolving environmental regulations. Hence, further efforts are required in expanding the coverage of databases incorporating more materials, manufacturing processes, countries of operation, cost data, and social indicators. In conclusion, online LCSA tools and WAAM hold great promise for driving sustainability in manufacturing. By leveraging synergies between AM and the life cycle thinking approach, a paradigm shift towards more environmentally cleaner, economically viable, and socially friendly manufacturing can be realized.

Appendix

Table 5 Life cycle inventories for manufacturing 1 kg steel wire

Materials/assemblies	Quantity	Comments
Steel, low-alloyed {RER} steel production, converter, low-alloyed Cut-off, U	1.096 kg	Steel billet
Processes		
Wire drawing {RER} processing Cut-off, U	1.041 kg	4% material loss in Wire Drawing
hot rolling, {Europe without Austria} hot rolling Cut-off, U	1.096 kg	5 % material loss in Hot Rolling

Table 6 Life cycle inventories for manufacturing 1 kg steel bar

Materials/assemblies	Quantity	Comments
Steel, low-alloyed {RER} steel production, converter, low-alloyed Cut-off, U	1.053 kg	Steel billet
Processes		
hot rolling, {Europe without Austria} hot rolling Cut-off, U	1.053 kg	5 % material loss in Hot Rolling

Table 7 Life cycle inventories for producing 1 L shielding gas (Ar 82% + CO₂ 18%)

Materials/assemblies	Unit
Argon, liquid {RER} production Cut-off, U	1.173 kg
Carbon dioxide, liquid {RER} production Cut-off, U	0.257 kg

Table 8 Country-wise characterization factors for midpoint and endpoint indicators and 1kWh electricity production as calculated in SimaPro 9.2. software using Ecoinvent 3.0 database [59]

Country	Characterization Factor (F _{i,c})													Single Score						
	Global warming	Stratospheric ozone depletion	Ionizing radiation	Ozone human health	Ozone formation	Fine particulate matter formation	Ozone formation, terrestrial ecosystems	Terrestrial acidification	Freshwater eutrophication	Marine eutrophication	Terrestrial ecotoxicity	Freshwater ecotoxicity	Marine ecotoxicity		Human carcinogenic toxicity	Human non-carcinogenic toxicity	Land use	Mineral resource scarcity	Fossil resource scarcity	Water consumption
	kg CO ₂ eq	kg CFC11 eq	kBq Co-60 eq	kg NOx eq	kg NOx eq	kg PM _{2.5} eq	kg SO ₂ eq	kg P eq	kg N eq	kg eq	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	kg 1,4-DCB	m ² a crop eq	kg Cu eq	kg oil eq	m ³	Pts
Austria	3.53E-01	2.11E-07	5.94E-02	4.72E-04	2.31E-04	4.79E-04	6.87E-04	4.04E-04	2.61E-05	1.37E-01	1.69E-02	2.22E-02	2.86E-02	4.61E-01	1.05E-02	3.30E-04	9.01E-02	7.46E-03	1.18E-02	
Belgium	2.42E-01	1.61E-07	3.72E-01	2.85E-04	9.54E-05	2.91E-04	2.58E-04	4.15E-05	9.43E-06	2.04E-01	7.78E-03	9.99E-03	9.11E-03	1.36E-01	1.41E-02	5.65E-04	6.35E-02	2.75E-03	6.31E-03	
Bulgaria	6.61E-01	1.34E-07	2.79E-01	9.57E-04	1.40E-03	9.60E-04	3.36E-03	1.51E-03	9.71E-05	7.43E-01	4.33E-02	5.88E-02	7.79E-02	1.53E+00	2.13E-03	4.92E-04	1.69E-01	4.04E-03	3.63E-02	
Croatia	5.00E-01	2.19E-07	1.20E-01	1.03E-03	1.61E-03	1.04E-03	4.18E-03	6.59E-04	4.24E-05	3.36E-01	2.33E-02	3.14E-02	4.21E-02	7.72E-01	9.97E-03	3.75E-04	1.29E-01	1.17E-02	3.10E-02	
Cyprus	1.03E+00	7.83E-07	8.34E-03	3.51E-03	2.17E-03	3.54E-03	6.89E-03	1.44E-05	1.40E-06	3.83E+00	7.57E-03	1.23E-02	1.39E-02	1.04E-01	1.88E-03	3.43E-04	2.94E-01	1.28E-03	4.21E-02	
Czechia	9.08E-01	1.82E-07	2.54E-01	1.48E-03	8.61E-04	1.49E-03	2.62E-03	1.44E-03	9.29E-05	2.59E-01	4.21E-02	5.70E-02	7.82E-02	1.54E+00	1.02E-02	4.90E-04	1.87E-01	2.14E-02	3.47E-02	
Denmark	2.47E-01	2.35E-07	5.60E-02	4.78E-04	2.01E-04	4.84E-04	6.03E-04	1.68E-04	1.18E-05	2.88E-01	1.40E-02	1.80E-02	2.19E-02	2.98E-01	4.73E-02	4.26E-04	6.11E-02	1.07E-02	8.86E-03	
Estonia	9.55E-01	7.43E-07	4.91E-02	3.36E-03	2.07E-03	3.44E-03	6.07E-03	8.34E-05	6.52E-06	3.29E+00	1.05E-02	1.58E-02	1.96E-02	2.20E-01	3.46E-02	4.15E-04	2.84E-01	3.13E-03	4.07E-02	
Finland	2.31E-01	2.18E-07	2.87E-01	4.07E-04	2.95E-04	4.15E-04	6.19E-04	7.76E-05	9.91E-06	2.65E-01	1.02E-02	1.30E-02	1.24E-02	1.92E-01	2.32E-02	5.02E-04	5.66E-02	7.34E-03	8.62E-03	
France	1.11E-01	1.04E-07	5.66E-01	2.30E-04	1.29E-04	2.33E-04	3.40E-04	2.77E-05	1.20E-05	2.71E-01	6.98E-03	8.88E-03	7.79E-03	1.31E-01	3.06E-03	7.14E-04	3.11E-02	3.34E-03	4.28E-03	
Germany	8.29E-01	3.05E-07	1.03E-01	6.06E-04	2.88E-04	6.13E-04	8.46E-04	8.64E-04	5.53E-05	1.80E-01	2.94E-02	3.92E-02	5.19E-02	9.21E-01	8.40E-03	4.46E-04	1.44E-01	3.68E-03	1.94E-02	
Greece	4.67E-01	3.38E-07	1.91E-02	1.01E-03	1.76E-03	1.03E-03	3.62E-03	1.76E-03	1.07E-04	1.01E+00	5.09E-02	6.95E-02	9.59E-02	1.84E+00	2.11E-03	2.99E-04	2.70E-01	4.48E-03	4.52E-02	
Hungary	4.67E-01	2.23E-07	3.53E-01	8.12E-04	5.48E-04	8.23E-04	1.52E-03	5.79E-04	4.17E-05	4.16E-01	2.14E-02	2.87E-02	3.79E-02	7.19E-01	1.68E-02	5.71E-04	1.24E-01	6.10E-03	1.88E-02	
Ireland	4.67E-01	1.86E-07	1.26E-02	6.99E-04	3.92E-04	7.04E-04	1.14E-03	8.26E-05	5.83E-06	1.56E-01	1.04E-02	1.44E-02	1.73E-02	2.04E-01	8.23E-03	2.93E-04	1.60E-01	9.21E-04	1.39E-02	
Italy	4.61E-01	2.88E-07	5.01E-02	7.67E-04	4.61E-04	7.81E-04	1.38E-03	1.01E-04	7.57E-06	2.68E-01	9.67E-03	1.26E-02	1.54E-02	1.94E-01	8.99E-03	3.48E-04	1.41E-01	6.34E-03	1.46E-02	
Latvia	4.35E-01	4.01E-07	3.51E-02	1.14E-03	7.53E-04	1.17E-03	1.83E-03	7.10E-05	5.23E-06	8.81E-01	8.48E-03	1.15E-02	1.30E-02	1.50E-01	2.66E-02	3.01E-04	1.39E-01	2.45E-03	1.69E-02	
Lithuania	4.18E-01	4.10E-07	1.21E-01	8.36E-04	7.35E-04	8.53E-04	1.37E-03	1.62E-04	1.24E-05	4.19E-01	1.18E-02	1.54E-02	1.95E-02	2.57E-01	2.03E-02	4.24E-04	1.31E-01	5.95E-03	1.71E-02	
Malta	5.35E-01	3.37E-07	1.80E-01	5.66E-04	2.63E-04	5.73E-04	7.64E-04	7.08E-04	4.71E-05	2.11E-01	2.56E-02	3.41E-02	4.53E-02	7.79E-01	1.10E-02	5.34E-04	1.30E-01	3.68E-03	1.73E-02	
Netherlands	5.26E-01	3.38E-07	2.26E-02	8.52E-04	4.57E-04	8.67E-04	1.40E-03	4.72E-05	3.68E-06	5.18E-01	7.66E-03	1.04E-02	1.07E-02	1.09E-01	4.22E-03	2.91E-04	1.80E-01	3.22E-03	1.50E-02	
Poland	6.07E-01	2.97E-07	4.57E-02	7.44E-04	2.59E-04	7.54E-04	7.61E-04	2.73E-04	1.85E-05	1.42E-01	1.49E-02	1.98E-02	2.48E-02	4.12E-01	8.58E-03	3.54E-04	1.69E-01	5.11E-03	1.60E-02	
Portugal	1.02E+00	1.97E-07	2.17E-02	2.01E-03	1.78E-03	2.02E-03	5.19E-03	1.31E-03	8.10E-05	6.80E-01	4.11E-02	5.59E-02	8.49E-02	1.60E+00	1.60E-02	3.55E-04	2.53E-01	3.03E-02	4.70E-02	
Romania	5.15E-01	1.85E-07	2.64E-02	1.34E-03	8.67E-04	1.35E-03	2.65E-03	1.81E-04	1.20E-05	3.46E-01	1.28E-02	1.70E-02	2.42E-02	3.40E-01	9.88E-03	3.47E-04	1.44E-01	2.52E-03	2.06E-02	
Slovakia	4.87E-01	1.38E-07	2.31E-01	7.93E-04	1.26E-03	7.97E-04	2.35E-03	9.44E-04	6.17E-05	4.61E-01	3.25E-02	4.35E-02	5.56E-02	1.00E+00	3.64E-03	5.49E-04	1.28E-01	1.03E-02	2.86E-02	
Slovenia	5.28E-01	1.83E-07	3.48E-01	9.95E-04	9.22E-04	1.00E-03	2.48E-03	7.32E-04	5.11E-05	8.71E-01	2.46E-02	3.35E-02	4.46E-02	8.67E-01	8.47E-03	5.50E-04	1.19E-01	1.57E-02	2.46E-02	
Spain	4.22E-01	1.70E-07	2.18E-01	8.91E-04	1.71E-03	8.95E-04	5.30E-03	7.30E-04	4.83E-05	2.16E-01	2.44E-02	3.27E-02	4.27E-02	3.11E-01	8.86E-03	4.20E-04	9.71E-02	8.56E-03	3.08E-02	
Sweden	3.93E-01	1.75E-07	2.17E-01	1.25E-03	8.92E-04	1.25E-03	2.29E-03	1.50E-04	1.34E-05	3.36E-01	1.20E-02	1.57E-02	2.28E-02	3.18E-01	8.02E-03	5.22E-04	1.05E-01	2.58E-03	1.87E-02	

Table 9 Country-wise social indicators, their data sources and values used in S-LCA

Country	Corruption Perception Index [63]	Collective Bargaining coverage (%) [64]	Annual social security expenditure (% of GDP in 2022) [65]	Minimum wage monthly in 2024 (€) [66]	PM 2.5 concentration ($\mu\text{g}/\text{m}^3$) [74]	Energy from renewable sources (%) [69]	GVA/employee in 2022 (€) [62]	Gender pay gap (%) [67]
Austria	71	98.0	20.6	Not applicable	11	36.6	71320	18.4
Belgium	73	96.0	20.3	2029.88	11	10.7	78794	5
Bulgaria	45	27.8	13.3	477	19	12.6	No data	13
Croatia	50	52.7	12.9	840	15	26.9	No data	12.5
Cyprus	53	43.3	11.8	1000	13	No data	No data	10.2
Czechia	57	34.7	13.7	771.15	15	7.4	No data	17.9
Denmark	90	82.0	18.9	Not applicable	8	43.0	70957	13.9
Estonia	76	6.1	12.7	820	5	15.3	50189	21.3
Finland	87	88.8	23.6	Not applicable	5	38.5	66356	15.5
France	71	98.0	23.8	1766.92	9	14.6	69104	13.9
Germany	78	54.0	20.4	2151	10	21.3	65283	17.7
Greece	49	14.2	19	968	15	19.9	42132	17.7
Hungary	42	21.8	13.1	710	15	9.1	43516	10.4
Ireland	77	34.0	7.5	2146.3	8	20.1	147418	9.3
Italy	56	100.0	21.9	Not applicable	13	16.6	62904	4.3
Latvia	60	27.1	13.2	700	14	26.9	44220	17.1
Lithuania	61	7.9	13.5	924	10	12.5	52278	12
Luxembourg	78	56.9	19.1	3085.11	9	11.8	No data	-0.7
Malta	51	50.1	10.1	854.16	12	No data	No data	10.2
Netherlands	79	75.6	15.5	2300	10	14.4	68598	13
Poland	54	13.4	16.9	971	19	9.4	52503	7.8
Portugal	61	73.6	17.5	956.66	7	29.0	45740	12.5
Romania	46	15.0	13.3	663.49	15	18.1	42693	4.5
Slovakia	54	24.4	15.6	750	16	10.3	53401	17.7
Slovenia	56	78.6	17.6	1253.36	12	15.6	50279	8.7
Spain	60	49.0	18.8	1323	9	21.0	60412	8.7
Sweden	82	88.0	17.5	Not applicable	6	53.3	73914	11.1

Author contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Samruddha Kokare, João Pedro Oliveira and Radu Godina. The first draft of the manuscript was written by Samruddha Kokare and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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Data availability The data that support the findings of this study are available from the corresponding author, upon reasonable request.

Declarations

Declaration of generative AI and AI-assisted technologies In the preparation of this article, the authors used a generative AI-based tool ChatGPT-4 to assist with language refinement and grammar checks. The authors reviewed and verified all AI-generated content to ensure its accuracy and integrity and take full responsibility for the final manuscript.

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