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SOCIETAL LCA

Social organizational life cycle assessment of wire arc additive manufacturing: a case study of a Belgian company

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Abstract

Purpose Additive manufacturing (AM) is gaining attention in industry due to its benefits like the ability to fabricate complex geometries, reduced material wastage, minimal tooling, and shorter lead times. From a sustainability perspective, the environmental and economic dimensions of AM have been studied in the literature, but its social dimensions remain relatively unexplored. This study presents a social organizational life cycle assessment (SO-LCA) of a wire arc additive manufacturing (WAAM) technology-based company that offers production and fabrication services in Belgium.

Method The scope of this investigation includes phases like production of primary material, i.e., steelmaking, production of feedstock wires from steel, WAAM production, and post-processing to fabricate/repair components. The relevant social indicators, social impact subcategories, and stakeholders are identified based on the S-LCA guidelines and methodological sheets provided by the United Nations Environment Programme/Society of Environmental Toxicology and Chemistry (UNEP/SETAC). The social inventory data are collected from interviews with top management, company reports, as well as national and international databases. Based on the data obtained, social indicators are evaluated using the reference scale method on a scale of 1–5 (with 1 = highly negative social impact and 5 = highly positive social impact). An aggregation model was also developed to average individual social indicator scores at both the stakeholder level and across the entire life cycle.

Results Overall, a positive impact on the stakeholder groups such as workers, society, and suppliers while the impact on customers is neutral. However, a negative impact is seen on the stakeholder group local community due to unhealthy air quality caused by higher concentrations of fine dust (particulate matter 2.5) and nitrous oxide (NO_x) emissions, especially from the steel-making phase.

Conclusions The issues of social concern are identified for each stakeholder and suggestions for improvement of their social performance are discussed. Limitations of the study include the sensitivity of results to geographical and legislative context, exclusion of mining activities in steel production, and lack of site-specific data for certain indicators. Hence, future research should focus on the integration of mining activities, obtaining more site-specific data, and studying the influence of different geographical and legislative contexts on the company's social performance.

Keywords Social organizational life cycle assessment (SO-LCA) · Social indicators · Wire arc additive manufacturing (WAAM) · Social sustainability · Additive manufacturing (AM)

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1 Introduction

Industrialization is one of the causes that has led to the depletion of natural resources as well as adverse environmental and social impacts having repercussions on both current and future generations. Realizing these consequences, the concept of sustainable development balancing economic activities and environmental quality was defined as the "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" was outlined by the Brundtland Report in 1987

(United Nations General Assembly 1987). Furthermore, Elkington coined the term "Triple Bottom Line," driving companies to measure their sustainability performance against three bottom lines: economic, environmental, and social to achieve better economic prosperity, environmental quality, and social justice (Elkington 1997). Hence, the impact of manufacturing that extends beyond the traditional economic bottom line, to environmental and social implications such as environmental emissions, child and exploitative labor, unfair wages, and discrimination at the workplace, among others (Uttam et al. 2024) needs to be taken into account for its sustainable development.

In recent years, the emergence of digital manufacturing technologies like Additive Manufacturing (AM) technologies has been seen as disruptive to existing business and supply chains, where various stakeholders such as raw material producers, logistics providers, suppliers, manufacturers, and customers may face uncertainty and struggles to survive under new circumstances (Öberg 2019). One such additive technology is wire arc additive manufacturing (WAAM), where metal parts are built in a relatively shorter time by melting metal wire using an electric arc and layer-by-layer deposition of the molten material to build the required part (Williams et al. 2016; Xia et al. 2020; Taşdemir and Nohut 2021). WAAM also has demonstrated its utility in the repair of broken or worn parts, extending the part life cycle and eliminating the need to produce new parts resulting in substantial material and energy savings (Priarone et al. 2021; Pagone et al. 2022). The applications of WAAM in various sectors, like shipbuilding, aerospace, construction, and structural engineering, are depicted in Fig. 1.

The majority of studies on the sustainability of AM technologies focus on their environmental and economic dimensions, neglecting their social dimension (Kokare et al. 2023a). The studies assessing the sustainability of WAAM have solely focussed on its environmental and economic performances using environmental Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) approaches respectively while assessment of its social performance has received relatively lower attention (Bekker and Verlinden 2018; Priarone et al. 2020; Campatelli et al. 2020; Pagone et al. 2022; Kokare et al. 2023b). Campatelli et al. (2020) assessed the material and energy-saving potential of WAAM in manufacturing an airfoil, in comparison with the traditional machining process. Bekker and Verlinden (2018) performed a cradle-to-gate LCA for assessing the environmental impact of 1 kg stainless steel product deposited using WAAM. Priarone et al. (2020) conducted a comparative LCA and LCC for manufacturing three aerospace components of aluminum, titanium, and steel alloys using WAAM and traditional machining processes. Similarly, Kokare et al. (2023b) conducted LCA and LCC for manufacturing a steel marine propeller using WAAM and traditional machining approaches. Pagone et al. (2022) performed LCA that demonstrated cumulative energy and CO2 savings achieved by WAAM-enabled repair of a worn-out steel driver disk in comparison with the production of a new steel driver disk.

Few studies have attempted to conduct a Social Life Cycle Assessment (S-LCA) of AM technologies or a Social Organization Life Cycle Assessment (SO-LCA) of companies adopting AM (Cardeal et al. 2020; Naghshineh et al. 2020; Soares et al. 2021). Soares et al. (2021) conducted a comparative S-LCA for two orthopedic devices: prosthesis and orthosis manufactured by additive FDM and conventional manual fabrication approaches. A positive social impact due to the adoption of the FDM approach for

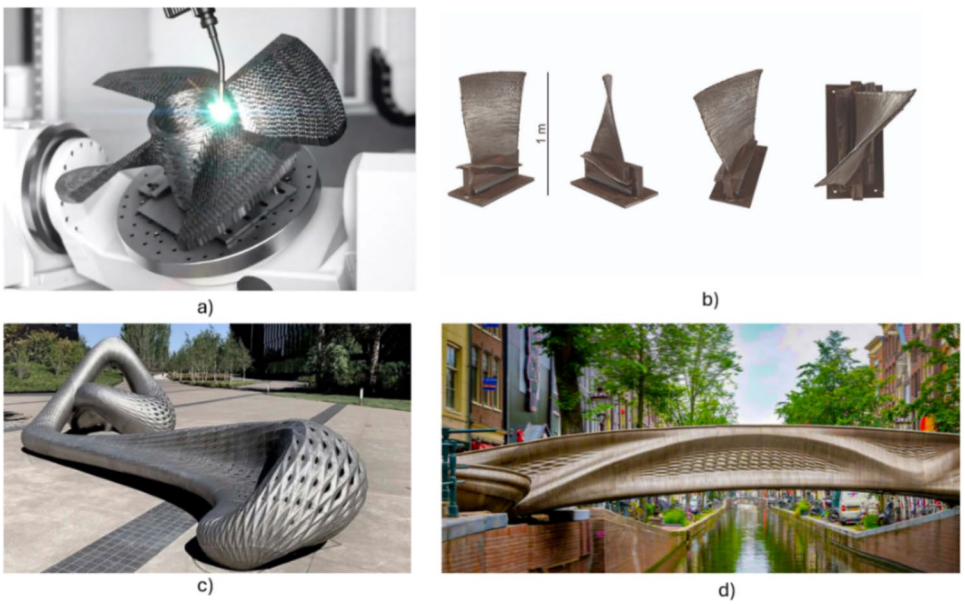

Fig. 1 Examples of products fabricated using WAAM **a** marine propeller (GEFERTECH Gmbh, n.d.); **b** turbine blades (WAAM3D, n.d.); **c** a bench in a park (MX3D, n.d.); **d** a pedestrian bridge (MX3D, n.d.)

stakeholders like the local community, society, and customers was observed resulting from the generation of local specialized jobs, technological and economic development, and the creation of personalized products, respectively. However, negative social impacts on workers were reported due to the loss of collective bargaining power arising from AM-enabled automated and delocalized production. Similarly, negative social impact was perceived on value chain actors due to risks of intellectual property infringement due to AM adoption due to ease of copying designs compared to manual fabrication method.

Naghshineh et al. (2020) conducted an SO-LCA study of a company specializing in manufacturing compact heat exchangers using LPBF in England. The study assessed the performance of 26 social indicators. In general, LPBF adoption had a positive social impact in the majority of the indicators (16 out of 26) studied with negative impacts seen in social two indicators namely working hours for full-time employees and the proportion of workers hired locally. In the remaining 8 indicators no positive or negative impact due to LPBF was reported. As LPBF is a relatively new technology, employees often worked beyond official working hours exceeding 40 h a week. Hence, a negative impact on working hours for employees was perceived. In addition to this, most of the company's AM-related employees came from different parts of England and Europe as the local labor pool did not meet the requirements of AM-related skills, resulting in a lower proportion of the workforce hired locally.

Cardeal et al. (2020) carried out an S-LCA of two business models for aircraft maintenance, one utilizing the traditional metal forging method with the other incorporating LPBF. The AM model shows a positive impact on the local community due to its ability to generate local employment resulting from decentralized production of spare parts from big factories to local facilities. Similarly, the society stakeholder was seen to benefit from the AM-based business model's economic contribution, technological development, and public commitment to sustainable aviation. Additionally, positive impacts such as better pay to workers due to enhanced skills and more customer-centric feedback mechanisms than traditional business models were seen in the AM-based business model. The negative impacts associated with AM based business model include worker health risks associated with metal powder inhalation, potential intellectual property violation risks, and changes in supplier relationships. Despite these considerations, the overall evaluation favored the adoption of the AM business model, with a higher utility value compared to the traditional model.

Based on the literature reviewed, the following gaps in research are realized. Firstly, assessing the social impacts of implementing AM technologies has received much less attention compared to the assessment of their environmental and economic impacts. Hence, more studies are needed to develop AM-specific social indicators, and stakeholders and subsequently perform S-LCA or SO-LCA to understand the positive and negative impacts on AM stakeholders. Secondly, the existing S-LCA and SO-LCA studies of AM focus on LPBF and FDM technologies. No S-LCA or SO-LCA studies in the context of WAAM have been found to date. Also, the existing studies focus solely on the additive manufacturing phase and ignore the social impacts during the raw material phase, i.e., production of feedstock material like powders, filaments, or wires for AM technologies and post-processing phases. Hence, the need to include AM raw material, production, and post-production phases is realized. Hence, the main aim of this study is to understand the social implications of WAAM production and repair on its different stakeholders using the guidelines prescribed by the United Nations Environment Programme/Society of Environmental Toxicology and Chemistry (UNEP/SETAC) (UNEP 2020). A SO-LCA study of WAAM production and repair services offering company located in the Flemish community of Belgium is presented in this paper. The purpose of conducting this study is twofold: firstly, to systematically analyze the social impacts encompassing the WAAM's different stakeholders: workers, suppliers, local community, society, and customers; and secondly, to identify social hotspots that can guide stakeholders, policymakers, and industry in decision-making within the field of WAAM production and repair.

The S-LCA is a standardized methodology for evaluating the positive and negative social impacts of products, services, and processes across various stakeholders, including workers, consumers, local communities, society, and value chain actors. SO-LCA extends this approach to assess social impacts at the organizational level, offering a broader perspective beyond individual products or services. Both S-LCA and SO-LCA follow UNEP/SETAC guidelines (UNEP 2020) and consist of four key steps:

1. **Goal and scope definition** – Establishing objectives, boundaries, functional or reporting unit, stakeholder groups, social indicators, and impact assessment method.
2. **Social life cycle inventory analysis** – Collecting qualitative and quantitative data related to the social indicators, through literature reviews, reports, audits, interviews, and surveys (refer to Fig. 2).
3. **Social life cycle impact assessment** – Evaluating social impacts using one of the two methods: (i) the reference scale (RS) method, which benchmarks social indicators against predefined performance scales, and (ii) the impact pathway (IP) method, which assesses cause-effect chains through midpoint and endpoint indicators.
4. **Interpretation** – Identifying key social concerns, drawing conclusions, and providing recommendations for

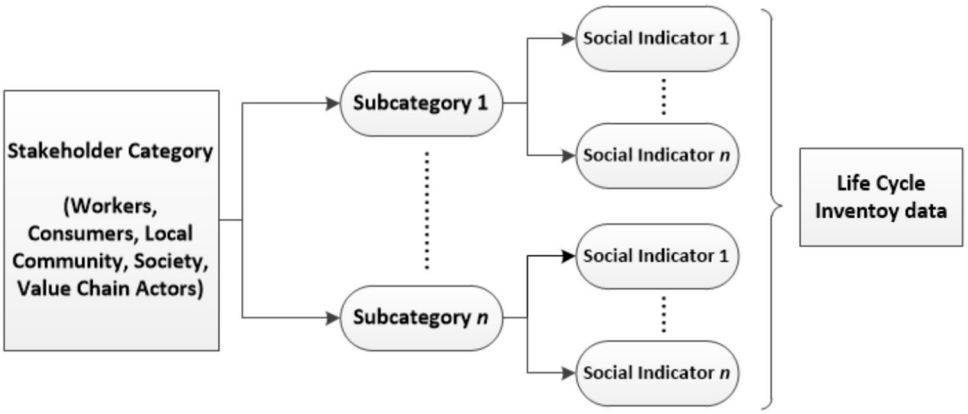

Fig. 2 Life cycle inventory analysis for different social indicators, subcategories, and stakeholders (UNEP 2020)

improving social performance at the product, process, or organizational level.

2 Methodology

2.1 Goal and scope definition

The primary goal of this study is to comprehensively evaluate the social impacts associated with WAAM production and repair based on UNEP/SETAC guidelines (UNEP 2020). This assessment aims to identify, understand, and quantify both positive and negative implications of WAAM adoption on five stakeholder groups namely workers, society, local community, suppliers, and customers involved in the value chain. The scope of this investigation is gate-to-gate and is limited to the production of steel, the production of wires, and WAAM production/repair of parts. The raw material extraction, i.e., mining of iron ore, coal, and other minerals are excluded from the scope of this study to focus more on WAAM-specific social impacts. All these activities take place at the site of a multinational steel company X located in the Flanders region of Belgium. The WAAM production and repair service is offered by company Y which is a spin-off of company X. Hence, Company X is the parent company of WAAM spin-off company Y. The employees of company X that specialize in WAAM are seconded to company Y and are on the payroll of its investors' shares. Company Y was created 5 years ago and does not have formal policies or procedures. Hence, it is subjected to the policies and procedures of its parent company X.

2.1.1 Reporting unit

In SO-LCA, a reporting unit serves as a reference to assess the social performance of an organization, which typically encompasses the whole organization or its relevant divisions (UNEP 2020). In this study, the reporting unit includes the WAAM production and repair services division of Company Y, along with the steelmaking and wire production divisions of Company X, assessed over the period July 2023 to June 2024.

2.1.2 System boundaries

The system boundaries of this study include raw materials production and WAAM production/repair phases. The raw materials production includes steel making and wire production. The mining of iron ore, coal, and other minerals involved in steel production is beyond the scope of this study. This was done due to complexities in tracing the mining phase details and challenges in data collection arising from the intricate global supply chains of these raw materials. Hence, this study focuses primarily on the downstream social impacts specific to WAAM rather than the upstream social impacts associated with mining activities. It starts with the melting of iron ore, coal, and scrap steel to make liquid iron in a blast. Next, steel billets are produced using continuous casting. Using hot rolling and wire drawing processes, the steel wires of the required diameters are produced (ArcelorMittal 2018). The steel wires act as feedstock material for WAAM. The next phase is the manufacturing phase where the WAAM production/repair and post-processing operations take place. The WAAM-fabricated parts have lower dimensional accuracy due to poor surface quality (Xia et al. 2022), while the presence of residual stresses is also common in WAAM parts (Ding et al. 2015). Hence, post-processing operations like finish machining to eliminate surface waviness (Chernovol et al. 2021) and heat treatment to relieve residual stresses are required (Laleh et al. 2023). The activities involved in the scope of this investigation are outlined in Fig. 3.

The WAAM spin-off company (Company Y) has developed a WAAM production line on its parent organization's site where heavy metal parts up to a weight of 20 tons can be repaired. WAAM process parameter database for 24 different materials including stainless steel, Inconel, titanium, aluminum, and bronze, among others has been

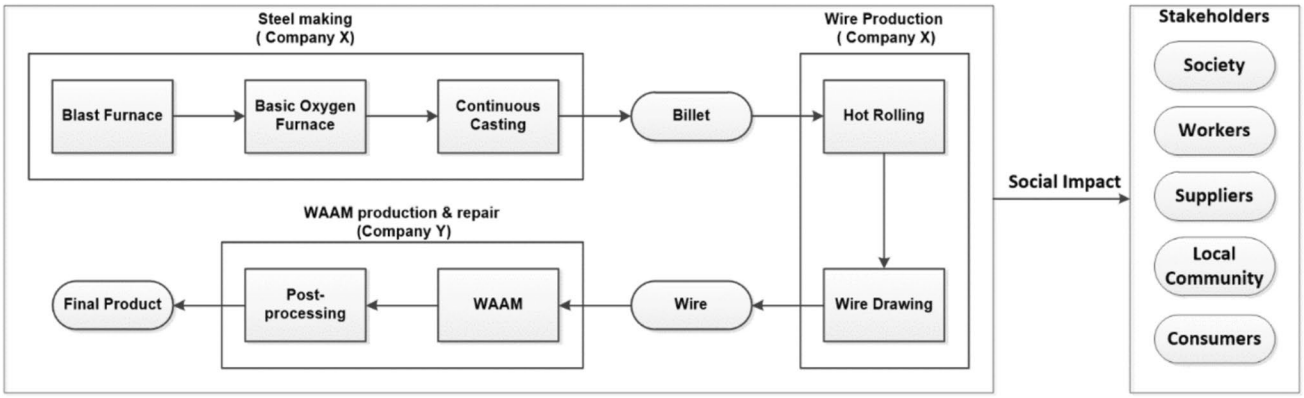

Fig. 3 System boundaries considered in this study

developed and is being expanded. Specialized software has been developed to automatically generate robot paths determine optimal material deposition strategy and simulate the WAAM process in advance, offering assurance at a micro-level.

2.1.3 Impact assessment method

The reference scale (RS) method is used as the impact assessment method in this study. An ascending reference scale that corresponds to a 5-point Likert scale with performance reference points 1,2,3,4, and 5 that imply highly negative, negative, neutral, positive, and highly positive social impacts, respectively. Likert scale is chosen as the reference scale it is a popular tool for data collection in domains that use both qualitative and quantitative data (Pescaroli et al. 2020), especially in assessing social impact (Singh and Gupta 2018; Martínez-Mendoza et al. 2020; Kirby et al. 2021). These reference points are assigned to a social indicator by evaluating its performance against a defined threshold level. The threshold may be based on compliance with a specific norm, industry practice, or sector average, depending on the context. The reference points are defined as follows:

1. – performance significantly below the threshold (highly negative impact).
2. – performance below the threshold (negative impact).
3. – performance comparable to the threshold (neutral).
4. – performance above the threshold (positive impact).
5. – performance significantly above the threshold (highly positive impact).

Further details about reference scales for each social indicator are given in Sect. 2.3.1 Scoring and Assessment Criteria.

2.1.4 Selection of stakeholder category groups, subcategories, and indicators

The stakeholder categories and subcategories are taken from the Methodological Sheets for Subcategories in Social Life Cycle Assessment, published by UNEP/SETAC (UNEP 2021). Five stakeholder groups namely Workers, Society, local community, Suppliers, and Customers were considered in this study. The stakeholder category of Workers (including women, children, local and migrant workers) was selected to assess the social impact of the WAAM adoption in terms of occupational health and safety risks, fair wages, working hours, and overall working conditions. The local community was included to evaluate the impacts on local residents, particularly regarding local employment opportunities, strain on local resources, and environmental concerns such as pollution created by WAAM production and repair activities. As WAAM production and repair rely on a supply chain involving raw material suppliers (e.g., metal wires and process consumables) and end users of WAAM-built or repaired components (such as the shipbuilding, aerospace, and automotive industries), the Suppliers and Customers stakeholder groups were also considered. From the suppliers' perspective, the assessment examines economic impacts on suppliers, adherence to fair competition practices, intellectual property rights protection, and the promotion of socially responsible procurement. For Customers, key aspects to assess include the safety and reliability of WAAM components, protection of customer privacy, feedback mechanisms, and sustainability reporting. Additionally, the society stakeholder group was involved in analyzing the broader national and regional impacts of WAAM production and repair. This includes WAAM's economic contribution, role in technological innovation, potential role in armed conflicts, risks related to corruption, and overall sustainability implications.

To evaluate the workers category, a questionnaire was conducted with five worker participants. For the remaining four stakeholder groups, a semi-structured interview with the company's General Manager was conducted. All five worker participants and the General Manager were male, Belgian nationals, and aged between 30 and 50. Additionally, company policies, annual reports, sustainability reports, financial statements, and national and international databases were consulted wherever applicable to complement the analysis and ensure a comprehensive assessment. Based on background information and data sources, social indicators that are relevant to this study were developed. The social indicators were divided into two groups: group 1 indicators are quantitative indicators assessed based on numerical data such as figures and percentages; and group 2 indicators are quantitative, evaluated based on qualitative data such as the extent to which a particular policy is being complied with existing rules and regulations. The stakeholder categories, subcategories, and their indicators are listed in Table 1.

2.2 Social life cycle inventory assessment

The social inventory data for this study was collected between July 2023 and June 2024. The social indicators were classified into two groups to reflect the nature of the data sources: Group 1 includes indicators assessed using quantitative data due to insufficient stakeholder input, while group 2 comprises indicators rated based on information obtained through stakeholder interviews. The indicators in Group 1 are assessed using the company's financial data, data from sustainability reports, and national-level data for Belgium from databases of the Belgian Statistical Office (STATBEL) and The Organization for Economic Cooperation and Development (OECD, n.d.) when company-specific data is unavailable. The data sources used for assessing the performance of each group 1 indicator are listed in depth in Table 2

For group 2 indicators, a semi-structured interviews of a single expert with professional experience over 25 years in the steel-making industry and five WAAM operators were conducted. This expert is currently the General Manager of the WAAM spin-off, overseeing the WAAM production and repair service for the past 5 years. Additionally, the expert has also about 20 years as a material processing research engineer and manager in the parent company X that produces steel wires for the WAAM spin-off company. Hence, the interviewee expert has in-depth knowledge of both steel production and WAAM processes. The use of single expert interview poses limitations to this study in terms of representativeness of stakeholder groups. To mitigate this issue, the insights gained from the single expert were complemented with information obtained from company policies, annual report, sustainability report, financial report, and national and international databases.

2.3 Social life cycle impact assessment

2.3.1 Scoring and assessment criteria

As previously stated, group 1 indicators are quantitative and scored against their threshold on a reference scale of 1 to 5 based on numerical performance, with the reference point of 3 corresponding to the threshold. For group 1 indicators, where the minimum value is 0 and the maximum is 100 (such as the Corruption Perception Index or Collective Bargaining Agreement coverage (%)), the threshold is set at the midpoint of 50. For other group 1 indicators, like gross value added per employee or the lost time injury frequency rate (LTIFR), where minimum and maximum values are unknown, the threshold values are determined based on the available averages from Belgian, EU, or OECD databases. Group 2 indicators are qualitative, assessing policy implementation and scored on a scale of 1 to 5 according to the extent of policy adoption within an organization. For group 2 indicators, the threshold is met when the organization shows moderate compliance with a specific policy. This indicates that the organization has implemented the policy, but significant improvements are still needed to ensure its effective implementation and enforcement throughout the organization. The assessment and scoring criteria for group 1 and group 2 indicators are listed in Tables 3 and 4, respectively.

2.3.2 Aggregation model

Using the reference scale approach, each social indicator is assigned a score. These individual scores need to be averaged into a single score at stakeholder and life cycle levels for a better understanding of underperforming stakeholders or life cycle stages. Hence, an aggregation model is developed in which each social indicator score is averaged into a single score at stakeholder and overall life cycle levels (Naghshineh et al. 2020). This model is based on the aggregation approach presented in an S-LCA study of the Indian steel sector (Singh and Gupta 2018). Hence, this aggregation approach is used due to the similarities in stakeholders and industrial processes involved. The aggregation approach consists of the following steps:

Step 1: Identifying the total number of stakeholders and social indicators

The first step involves identifying all the relevant stakeholders, their subcategories, and social indicators considered in the SO-LCA study. N_i denotes the number of social indicators used to assess a stakeholder i while n represents the total number of social indicators used in the SO-LCA study.

Table 1 List of stakeholders, subcategories, and their indicators based on (UNEP 2021)

Stakeholder	Subcategory	Indicator	Group
Society	Public commitment to sustainability issues	Presence of publicly available promises or agreements on sustainability issues	Group 2
	Prevention and mitigation of conflicts	Organization's involvement in escalation or de-escalation of conflicts	Group 2
	Contribution to economic development	Gross Value Added/Employee (€)	Group 1
	Corruption	Corruption Perception Index (CPI) in the country	Group 1
	Technology transfer	Involvement in technology transfer program or projects	Group 2
Workers	Freedom of association and collective bargaining	Collective Bargaining agreement coverage (%)	Group 1
		Trade union density (%)	Group 1
	Child labor	Prohibition of working children under the legal age or 15 years old	Group 2
	Social security	Social security expenditure per employee (€)	Group 1
	Fair salary	Difference between minimum wage and non-poverty wage (%)	Group 1
	Hours of work	Employees working more than 50 h per week (%)	Group 1
	Forced labor	Workers voluntarily agree upon employment terms. Employment contracts stipulate wage, working time, holidays and terms of resignation	Group 2
	Discrimination and equal opportunities	Proportion of women employees (%)	Group 1
		Gender pay gap (%)	Group 1
	Health and safety	Lost time injury frequency rate (LTIFR)	Group 1
Suppliers	Fair competition	Strength of policies to prevent engaging in or being complicit in anti-competitive behavior	Group 2
	Respect of intellectual property rights (IPR)	Strength of organization's policy and practice to prevent abuse of IPR	Group 2
	Supplier relationship	Expenditure on suppliers (%)	Group 1
	Promoting social responsibility	Integration of ethical, social, environmental and regarding gender equality criterions in purchasing	Group 2
Local community	Delocalization and migration	Employment Gap between migrant and native-born (%)	Group 1
	Local employment	Hiring preference for locals	Group 2
	Community engagement	Organizational support for on community engagement at local level	Group 2
	Cultural heritage	Relevant organizational information available to community members in their spoken language(s)	Group 2
	Access to resources	Water recycling rate (%)	Group 1
		Electricity used from renewable and recovered energy sources (%)	Group 1
	Safe and healthy living conditions	Air quality-average. PM2.5 concentration relative to WHO recommendation (5 ug/m3)	Group 1
Consumer	Health and safety	Presence of Management measures to assess consumer health and safety	Group 2
	Feedback mechanism	Presence of a mechanism for customers to provide feedback	Group 2
	Privacy	Strength of internal management system to protect consumer privacy	Group 2
	Transparency	Organization sustainability reports adhering to GRI (%)	Group 1

Step 2: Assigning a score to each social indicator

Based on the performance of each social indicator j for the stakeholder i, a score ($S_{i,j}$) on a reference scale of 1 to 5 is assigned to each social indicator as per the assessment criteria of social indicators.

$$S_{i,j} \in \{1, 2, 3, 4, 5\} \quad (1)$$

Table 2 Data sources for group 1 indicators

Stakeholder	Subcategory	Indicator	Source
Society	Contribution to economic development	Gross value added/employee (€)	Calculated based on the company's financial report
	Corruption	Corruption Perception Index	Transparency International (2023)
Workers	Freedom of association and collective bargaining	Collective bargaining agreement coverage (%)	Company sustainability report
		Trade union density (%)	OECD database (OECD, n.d.)
	Social security	Annual social security expenditure/employee (€)	Calculated based on the company's financial information
	Fair salary	Difference between minimum wage and non-poverty wage (%)	(STATBEL 2024; WageIndicator Foundation, 2024)
	Discrimination and equal opportunities	Proportion of women employees (%)	Company statistics
		Gender pay gap (%)	STATBEL database (STATBEL, n.d.)
	Hours of work	Employees working more than 50 h per week (%)	OECD database (OECD 2020a)
	Health and safety	Lost time injury frequency rate (LTIFR)	Company sustainability report
Suppliers	Supplier relationship	Expenditure on suppliers (%)	Calculated based on the company's financial data
Local community	Delocalization and migration	Employment gap between migrant and native-born (%)	OECD database (OECD 2023)
	Access to resources	Water recycling rate (%)	Company statistics report
		Electricity from renewable and recovered energy sources (%)	
	Safe and healthy living conditions	Air quality -average. PM2.5 concentration relative to WHO recommendation (5 ug/m3)	(Sciensano 2022)
Consumer	Transparency	Organization sustainability reports adhering to GRI (%)	Company sustainability report

Step 3: Calculating the average score at the stakeholder level

Next, the average stakeholder score (Ai) is calculated by summing up all the individual social scores and then dividing the sum by the total number of indicators for that stakeholder

$$A_i = \frac{\sum_{j=1}^{j=N_i} S_{i,j}}{N_i} \tag{2}$$

Step 4: Calculating the average score at life cycle level

Similarly, the overall average score at the life cycle level (A_{LC}) is calculated by adding all social indicator scores ($S_{i,j}$) and dividing it by the total number of social indicators considered.

$$A_{LC} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{N_i} S_{i,j}}{n} \tag{3}$$

Step 4: Defining the cut-off score at the stakeholder and life cycle level

The cut-off score for the stakeholder i (cut-off score$_i$) is defined as the average of minimum and maximum average stakeholder scores possible. Similarly, the cut-off score at the life cycle level (cut-off score$_{LC}$) is also defined. The minimum and maximum possible average scores are 1 and 5, respectively. Hence, the cut-off score at stakeholder and life cycle levels is 3.

$$Cut-off\,score_i = \frac{\left(Min.A_i + Max.A_i\right)}{2} \tag{4}$$

$$Cut-off\,score_{LC} = \frac{\left(Min.A_{LC} + Max.A_{LC}\right)}{2} \tag{5}$$

Table 5 summarizes the number of social indicators, their individual scores, and average stakeholder scores.

As an example, the stakeholder society has five social indicators ($N_{society} = 5$). The social indicators of the subcategory "public commitment to sustainability issues," "prevention and mitigation of conflicts," "contribution to economic development," "corruption," and "technology transfer" are assigned a score ($S_{i,j}$) of 3, 3, 4, 4, and 2, respectively. The

Table 3 Assessment criteria for group 1 indicators

Stakeholder	Subcategory	Indicator	Threshold	Reference Scale				
				1	2	3	4	5
Society	Contribution to Economic Development	Gross Value Added (GVA)/employee (€)	National Average (OECD 2022)	Very low productivity with GVA/employee below 70% the national average	Low productivity with GVA/employee between 70%–89% of the national average	Average productivity with GVA/employee between 90%–109% of the national average	High productivity with GVA/employee between 110%–129 % of the national average	Very high productivity with GVA/employee 130% or above of the national average
	Corruption	Corruption Perception Index (CPI)	50 (Transparency International 2023)	Very high corruption risk with CPI less than 20	High Corruption risk with CPI between 21–40	Moderate Corruption risk with CPI between 41–60	Low Corruption risk with CPI between 61–80	Very Low Corruption risk with CPI between 81–100
Workers	Freedom of Association & Collective Bargaining	Collective Bargaining Agreement (CBA) coverage (%)	50%	Very Low CBA coverage, less than 20%	Low CBA coverage, between 21%–40%	Moderate CBA coverage, between 41%–60%	High CBA coverage, between 61%–80%	Very High CBA coverage, between 81%–100%
		Trade Union Density (TUD) (%)	50%	Very Low TUD, less than 20%	Low TUD, between 21%–40%	Moderate TUD, between 41%–60%	High TUD, between 61%–80%	Very High TUD, between 81%–100%
	Social Security	Annual Social security expenditure/employee (€)	OECD Average (OECD)	Minimal employer social security contribution, below 2,500€ p.a.	Limited employer social security contribution, between 2,501€–5,000€ p.a.	Adequate employer social security contribution, between 5,001€–7,500€ p.a.	Strong employer social security contribution, between 7,501€–10,000€ p.a.	Exceptional employer social security contribution, above10,000€ p.a.
	Fair Salary	Difference between minimum wage to non-poverty wage	0 (STATBEL 2024)	Minimum wage significantly below the non-poverty wage, by 20% or more	Minimum wage below the non-poverty wage, ranging from 1% to 19% lower	Minimum wage equal to non-poverty wage	Minimum wage slightly above non-poverty wage, ranging from 1% to 19% higher	Minimum wage significantly above non-poverty, by 20% or more
	Discrimination and Equal Opportunities	Proportion of women employees (%)	EU average (Eurostat 2024)	Poor female representation, lower than 20% of the workforce	Below average female representation, ranging from 21%–30% of the workforce	Average female representation, ranging from 31%–40% of the workforce	Balanced female representation, ranging from 41%–50% of the workforce	Strong female representation, above 50%
		Gender pay gap (%)	EU average (STATBEL)	Women severely underpaid than men, by 20% or more	Women highly underpaid than men, ranging between 15%–19%	Women moderately underpaid than men, ranging between 10%–14%	Women slightly underpaid than men, ranging between 5%–9%	The gender pay gap is negligible, less than 5%
	Hours of Work	Employees working more than 50 hours per week (%)	OECD average (OECD 2020a)	Very high percentage of employees work more than 50 hours per week (≥ 20%)	High percentage of employees work more than 50 hours per week (15%–19.9%)	Moderate percentage of employees work more than 50 hours per week (10%–14.9%)	Low percentage of employees work more than 50 hours per week (5%–9.9%)	Very low percentage of employees work more than 50 hours per week (<5%)

Table 3 (continued)

Stakeholder	Subcategory	Indicator	Threshold	Reference Scale				
				1	2	3	4	5
	Health & safety	Lost Time Injury Frequency Rate (LTIFR)	Sectoral Average (World Steel Association 2023)	Very Low workplace safety, with LTIFR above 1	Low workplace safety, with LTIFR between 0.76–1.00	Moderate workplace safety, with LTIFR between 0.51–0.75	High workplace safety, with LTIFR between 0.25–0.5	Very high workplace safety, with LTIFR below 0.25
Suppliers	Supplier Relationship	Expenditure on suppliers (%)	50%	Lower supplier reliance, with expenditure on suppliers less than 20% of the budget	Limited supplier reliance, with expenditure on suppliers ranging 21%–40% of the budget	Balanced supplier reliance, with expenditure on suppliers ranging 41%–60% of the budget	High supplier reliance, with expenditure on suppliers ranging 61%–80% of the budget	Very High supplier reliance, with expenditure on suppliers above 80% of the budget
Local Community	Delocalization and Migration	Employment gap between migrant & native-born (%)	OECD Average (OECD 2023)	Migrant workers severely disadvantaged, with an unemployment gap of 5% or more	Migrant workers significantly disadvantaged, with an unemployment gap of 2.5%–5%	Migrant workers slightly disadvantaged, with an unemployment gap of 0%–2.5%	Migrant workers slightly advantaged, with an employment gap of 0%–2.5%	Migrant workers significantly advantaged, with an employment gap exceeding 2.5%
	Access to Resources	Water recycling rate (%)	50%	Minimal water recycling rate, below 20%	Limited water recycling rate between 21%–40%	Balanced water recycling rate between 41%–60%	Strong water recycling rate between 61%–80%	Exceptional water recycling rate exceeding 80%
		Electricity used from renewable and recovered energy sources (%)	50%	Minimal renewable energy use, with 20% or less of electricity from renewable and recovered sources	Limited renewable energy use, with 21%–40% of electricity from renewable and recovered sources	Balanced energy mix, with 41%–60% of electricity from renewable and recovered sources	Strong renewable energy use, with 61% to 80% of electricity from renewable and recovered sources	Exceptional renewable energy use, with more than 80% of electricity from renewable and recovered sources
	Safe & Healthy Living Conditions	Air quality - average. PM2.5 concentration relative to WHO recommendation (5 $\mu g/m^3$)	5 $\mu g/m^3$ (Sciensano 2022)	Extremely poor air quality with PM 2.5 level exceeding 10 $\mu g/m^3$)	Poor air quality with PM2.5 level between 7.5–9.9 $\mu g/m^3$)	Acceptable air quality with PM2.5 level between 5–7.4 $\mu g/m^3$	Good air quality with PM2.5 level between 2.5–4.99 $\mu g/m^3$	Excellent air quality with PM2.5 level below 2.5 $\mu g/m^3$)
Consumers	Transparency	Organization sustainability reports adhering to GRI (%)	50%	Low transparency with less than 20% of sustainability reports adhering to GRI	Limited transparency with 21%–40% of sustainability reports adhering to GRI	Partial transparency with 41%–60% of sustainability reports adhering to GRI	Good transparency with 61%–80% of sustainability reports adhering to GRI	Excellent transparency with above 80% sustainability reports adhering to GRI

Table 4 Assessment criteria for group 2 indicators

Stakeholder	Subcategory	Indicator	Reference Scale				
			1	2	3	4	5
Society	Public Commitment to Sustainability Issues	Presence of publicly available promises or agreements on sustainability issues	Absence of sustainability commitments	Some public sustainability commitments exist, but lack enforcement and monitoring	Public sustainability commitments exist with inconsistent enforcement and monitoring	Well-defined sustainability commitments, with minor inconsistencies in enforcement and monitoring	Fully defined sustainability commitments, with strict enforcement and monitoring
	Prevention and Mitigation of Conflicts	Organization's involvement in escalation or de-escalation of conflicts	Directly escalates conflicts and does nothing to mitigate them	Indirectly escalates conflicts and does nothing to mitigate them	No direct/indirect escalation but does nothing to mitigate them	De-escalates conflict effectively with minor gaps in implementation	Proactively prevents and resolves conflicts with effective approach
	Technology Transfer	Involvement in technology transfer program or projects	No initiatives and engagements in technology transfer	Some technology transfer initiatives exist with minimal involvement but no structured programs and monitoring	Occasional participation in technology transfer initiatives but lacks well-structured programs and monitoring	Active participation in technology transfer initiatives with well-structured program & regular monitoring	Proactive leadership in technology transfer initiatives with comprehensive programs, active collaboration, & continuous monitoring
Workers	Child Labour	Prohibition of working children under the legal age or 15 years old	Lack of child labour prohibition policy and employs children under legal age or 15 years old	Child labour prohibition policy exists but lacks enforcement and monitoring	Child labour prohibition policy exists with inconsistent enforcement and monitoring	Child labour prohibition policy exists with minor gaps in enforcement and monitoring	Child labour prohibition policy exists with strict enforcement and regular monitoring
	Forced Labour	Workers voluntarily accept employment terms, which specify wages, working hours, holidays, and resignation conditions	No formal policy against forced labour; Workers are coerced or forced into accepting terms	The formal policy exists with poor communication, leaving workers with no understanding or choice	The formal policy exists with clear communication but lacks proper enforcement and monitoring	The formal policy exists, clearly communicated and understood, with minor inconsistencies in enforcement and monitoring	The formal policy exists, well communicated and understood, with strict enforcement and regular monitoring
Suppliers	Fair Competition	Strength of policies to prevent engaging in or being complicit in anti-competitive behaviour	Absence of formal policy to prevent anti-competitive behaviour	The formal policy exists but lacks enforcement & monitoring	The formal policy exists with inconsistent enforcement & monitoring	The formal policy exists with minor inconsistencies in enforcement & monitoring	The formal policy exists with strict enforcement & regular monitoring
	Respect of Intellectual Property Rights (IPR)	Strength of organization´s policy and practice to prevent abuse of IPR	Absence of a formal policy to prevent IPR violations	IPR policy exists but lacks enforcement and monitoring, vulnerable to IPR violations	Basic IPR protection policy exists but with inconsistent enforcement and monitoring	Strong IPR protection policy with minor inconsistencies in enforcement & monitoring	Fully protective IPR policy with strict enforcement and regular monitoring
	Promoting social responsibility	Integration of ethical, social, environmental and regarding gender equality criteria in purchasing	No formal policy exists for integration of ethical, social, environmental and gender equality criteria in purchasing	The formal policy exists but lacks enforcement & monitoring, with minimal impact on purchasing decisions	The formal policy exists with inconsistent enforcement and monitoring; Some purchasing decisions may consider these criteria	The formal policy exists with minor inconsistencies in enforcement and monitoring; Most purchasing decisions follow these criteria	The formal policy is strictly enforced and regularly monitored, ensuring all purchasing decisions align these criteria

Table 4 (continued)

Stakeholder	Subcategory	Indicator	Reference Scale				
			1	2	3	4	5
Local Community	Local Employment	Hiring preference for locals	The local candidates are not considered in hiring decisions	The local candidates are rarely considered in hiring decisions	The local and non-local candidates are equally considered in hiring decisions	The local candidates are preferred when they are better qualified than non-locals, but this preference is not systemic	The local candidates are systemically prioritized when they are better qualified than non-locals, while maintaining non-discriminatory hiring practices
	Community Engagement	Organizational support for community engagement at local level	No support or engagement initiatives for local community exist	The organization engages rarely with local community with minimal support but no structured program or dedicated resources	The organization occasionally engages with local community but lacks well-structured program or dedicated resources	The organization actively regular engages with local community through well-structured program and dedicated resources	The organization embeds local community engagement into its core policies and missions, ensuring strong institutional support
	Cultural heritage	Relevant Organizational Information Available to Community Members in their Spoken Language(s)	No organizational information is available in local languages	Limited organizational information is available in local languages	Adequate organizational information is available, but not necessarily in all local languages	Most of the organizational information is available in local languages, with minor gaps	All organizational information is fully available in all local languages
Consumers	Health and Safety	Presence of Management measures to assess consumer health and safety	No formal measures exist to assess consumer health and safety	Some measures exist, but they are reactive and not systemic	Established measures exist, but they are implemented inconsistently	Well-established measures exist with minor inconsistencies in implementation	Fully established measures exist with rigorous implementation and continuous improvement mechanisms
	Feedback Mechanism	Presence of a mechanism for customers to provide feedback	No formal mechanism to provide feedback exists	Customers can submit feedback informally; no structured mechanism exists	A basic feedback mechanism exists but feedback is addressed inconsistently	A structured feedback mechanism exists, and feedback is addressed regularly	A well-structured feedback mechanism exists, feedback is addressed regularly and used to improve the quality of products and services
	Privacy	Strength of internal management system to protect consumer privacy	No formal measures exist to protect consumer privacy	Some measures exist, but they are enforced inconsistently	Some measures exist, but lack proper enforcement and monitoring	Well-defined measures exist, with minor inconsistencies in enforcement and monitoring	Fully established measures exist with rigorous enforcement and monitoring

average stakeholder score for society ($A_{Society}$) is calculated using Eq. 2 as follows.

$$A_{Society} = \frac{3+3+4+2}{5} = 3.2 \quad (6)$$

Similarly, the average stakeholder scores for workers ($A_{Workers}$), suppliers ($A_{Suppliers}$), local community ($A_{LocalCommunity}$), and consumers ($A_{Consumers}$) are calculated as 3.9, 3.75, 2.71, and 3, respectively. Likewise, the average score at life cycle level (A_{LC}) is calculated using Eq. 3 as follows:

$$A_{LC} = \frac{\sum_{j=1}^{5} S_{Society,j} + \sum_{j=1}^{10} S_{Workers} + \sum_{j=1}^{4} S_{Suppliers,j} + \sum_{j=1}^{7} S_{LocalCommunity,j} + \sum_{j=1}^{4} S_{Consumers,j}}{n} = \frac{101}{30} = 3.37 \quad (7)$$

Since the average score at the life cycle level ($A_{LC} = 3.37$) exceeds the cut-off score of 3, a positive social impact is inferred. Similarly, a positive impact is observed on society, workers, and suppliers, as their average stakeholder scores also surpass the cut-off score of 3. However, a negative impact is noted for the local community, as its average stakeholder score falls below 3, while the impact on customers is neutral.

3 Results and discussion

3.1 Demographic data

Based on the collected social inventory data, a demographic analysis of the parent and spin-off companies was performed. The demographic findings at the organizational level revealed a predominantly blue-collar workforce, constituting 70% of employees, while white-collar roles account for 30%. The workforce is largely composed of Belgian nationals (94%), with only 6% representing foreign nationals, indicating limited international diversity. Age-wise, 63% of the employees were in the age group of 30 to 50 years, 29% were in the age group above 50 years, and 8% were in the age group of less than 30 years. Although 9% of the total workforce was female, women held 17% of managerial positions and above, suggesting slightly better gender inclusion in leadership roles. Eighty-eight percent of employees were covered by collective bargaining agreements, establishing fair wages and working conditions. The minimum salary offered was 38% above the national poverty threshold, indicating fair wages being paid. The lost time injury frequency rate (LTIFR) reported was 0.9, above the sectoral average of 0.65 for the steel industry.

A total of 1300 suppliers were involved who collectively contributed to the creation of over 7000 indirect jobs. This highlights the parent company's significant influence on employment creation beyond its direct workforce. The total shipments of 5 million metric tonnes to various customers were reported annually. The customer base consists of various steel-consuming industries like distribution, construction, automotive, primary transformation, packaging, and other sectors including machinery, chemicals, energy, and shipping industries.

At the local community level, the company directly employs 5,800 individuals, playing a critical role in regional employment. This is reflected in the regional unemployment rate (2.9%) which is substantially lower than the national average (5.9%) (European Employment Services 2025). Furthermore, the region's average income is 7% higher than the national average, while the poverty risk rate (6%) is significantly lower than the national rate of 12% (Clapson 2023). However, an employment gap of 6.3% was seen between the native- and foreign-born workers in the region, placing foreign-born workers at a higher risk of unemployment (OECD, n.d.). Additionally, the air pollution level, characterized by PM2.5 concentration, was 11 μg/m^3, which is more than double the WHO's recommended limit of 5 μg/m^3 (Sciensano 2022).

From a broader societal perspective, the company's financial report estimates an annual turnover of 5 billion euros. Furthermore, investments totaling 133 million euros were allocated to various projects. With Belgium's Corruption Perception Index at 73/100, the public sector presents a relatively low risk of corruption, reinforcing a stable business environment. These demographic figures highlight the company's significant contribution to economic growth, job creation, and regional development and areas for improvement particularly in workplace safety, equal opportunities for women and foreign workers, and better air quality. The demographic data is summarized in Table 6.

3.2 SO-LCA findings

All individual social indicators were evaluated based on the assessment criteria, and average scores at stakeholder and life cycle levels were calculated. The social indicator scores at the subcategory level are summarized in Fig. 4. The subcategories that have a score below the cut-off score are interpreted as social hotspots due to their negative performance and hence, efforts are needed to address these social hotspots to minimize the negative impact of WAAM production and repair services on its stakeholders.

The scores of subcategories were averaged at stakeholder and life cycle levels (refer to Fig. 5). Overall, the average life

Table 5 Aggregation model used in this study

Stakeholder	Subcategory	Number of indicators per subcategory	Number of indicators per stakeholder (N_i)	Indicator score (1–5) ($S_{i,j}$)	Average stakeholder score (A_i)	Min–max average stakeholder score
Society	Public commitment to sustainability issues	1	5	3	3.2	1–5
	Prevention and mitigation of conflicts	1		3		
	Contribution to economic development	1		4		
	Corruption	1		4		
	Technology transfer	1		2		
Workers	Freedom of association and collective bargaining	2	10	5	3.9	1–5
				3		
	Child labor	1		5		
	Social security	1		4		
	Fair salary	1		5		
	Hours of work	1		5		
	Forced labor	1		5		
	Discrimination and equal opportunities	2		1		
				4		
	Health and safety	1		2		
Suppliers	Fair competition	1	4	4	3.75	1–5
	Respect of intellectual property rights	1		5		
	Supplier relationship	1		4		
	Promoting social responsibility	1		2		
Local community	Delocalization and migration	1	7	1	2.71	1–5
	Local employment	1		3		
	Community Engagement	1		4		
	Cultural heritage	1		4		
	Access to material resources	2		4		
				2		
	Safe and healthy living conditions	1		1		
Consumer	Health and safety	1	4	2	3	1–5
	Feedback mechanism	1		2		
	Privacy	1		4		
	Transparency	1		4		
		Total	30	101	3.37	1–5

cycle score for WAAM production and repair service (3.37) was seen as slightly above the cut-off score of 3. Hence, a slightly positive social impact of WAAM production and repair service on its stakeholders is inferred. At the stakeholder level, a positive impact on workers is observed that can be attributed to strong implementation policies against child and forced labor, better work-life balance, salaries above non-poverty wage, high social security coverage, and freedom of association and bargaining. Likewise, a positive impact on society and suppliers is seen due to better performance in social indicators like contribution to economic development, corruption, fair competition, and respect for intellectual property rights. However, for the local community, a slightly negative impact is observed that can be mainly attributed to poor air quality arising from high dust and NO_x emissions (especially during steel production). The social impacts for each subcategory in each stakeholder are discussed further in the next sub-section.

Table 6 Demographic data relevant to this study

Stakeholder group	Details	Source
Workers		
Employment type	– 70% blue-collar employees – 30% white-collar employees	Company Sustainability Report
Nationality	– 94% Belgian nationals – 6% foreign nationals	
Age distribution	– 63% (30–50 years) – 29% (above 50 years) – 8% (below 30 years)	
Collective bargaining agreements	– 88% workforce is covered by collective bargaining agreements	
Wages	– Minimum wage 38% above the national poverty threshold	Company financial report
Gender ratio	– 9% of the workforce are women – 17% of managerial positions held by women	Company Sustainability Report
Lost time injury frequency rate (LTIFR)	0.9 (vs. sectoral average of 0.65)	Company Sustainability Report
Customer		
Annual shipments	5 million metric tonnes	Company financial report
Customer distribution (% sales)	Distribution (25%) Construction (19%) Automotive (17%) Primary Transformation (14%) Packaging (2%) Others (23%)	
Suppliers		
No. of suppliers	1400 different suppliers	Company Sustainability Report
Supplier employment	Over 7000 jobs supported by suppliers	
Local community		
Unemployment rate	2.9% (vs. national rate of 5.5%)	(European Employment Services 2025)
Average income	7% above the national average	(Clapson 2023)
Poverty risk rate	Poverty risk rate: 6% (vs. national rate of 12%)	(Statistiek Vlaanderen 2025)
Unemployment gap between native- and foreign-born workers	6.3%	(OECD, n.d.)
Annual PM 2.5 conc	11 μg/m^3 (vs. WHO recommended 5 μg/m^3)	(Sciensano 2022)
Society		
Estimated annual turnover	5 billion euros	Company Sustainability Report
Investments	133 million euros	
Corruption Perception Index (CPI)	73/100	(Transparency International 2023)

4 Discussion

4.1 Impact on society

4.1.1 Public commitment to sustainability issues

Sustainability is one of the core values of the companies involved. WAAM service is being offered for repair and rebuild of large metal parts saving a lot of material and costs associated with procuring new parts. The parent organization's sustainability report states that it aims to reduce its CO_2 emissions by 25% by 2030 and has a well-defined roadmap to achieve its net zero targets through different decarbonization initiatives. The fulfillment of sustainability-related commitments and agreements is overseen by an executive-level Climate Change and Sustainable Development Committee. However, the same report acknowledges challenges in achieving these sustainability-related commitments such as excessive PM2.5 and NOx emissions during steel production, external waste recovery and disposal, and asbestos-containing material disposal. Hence, it is inferred that while publicly available commitments on sustainability issues do exist, but more efforts are needed in the enforcement and monitoring of these sustainability-related commitments. Therefore, this indicator is assigned a score of 3 out of 5 based on its evaluation criteria outlined in Table 4, resulting in a neutral social impact.

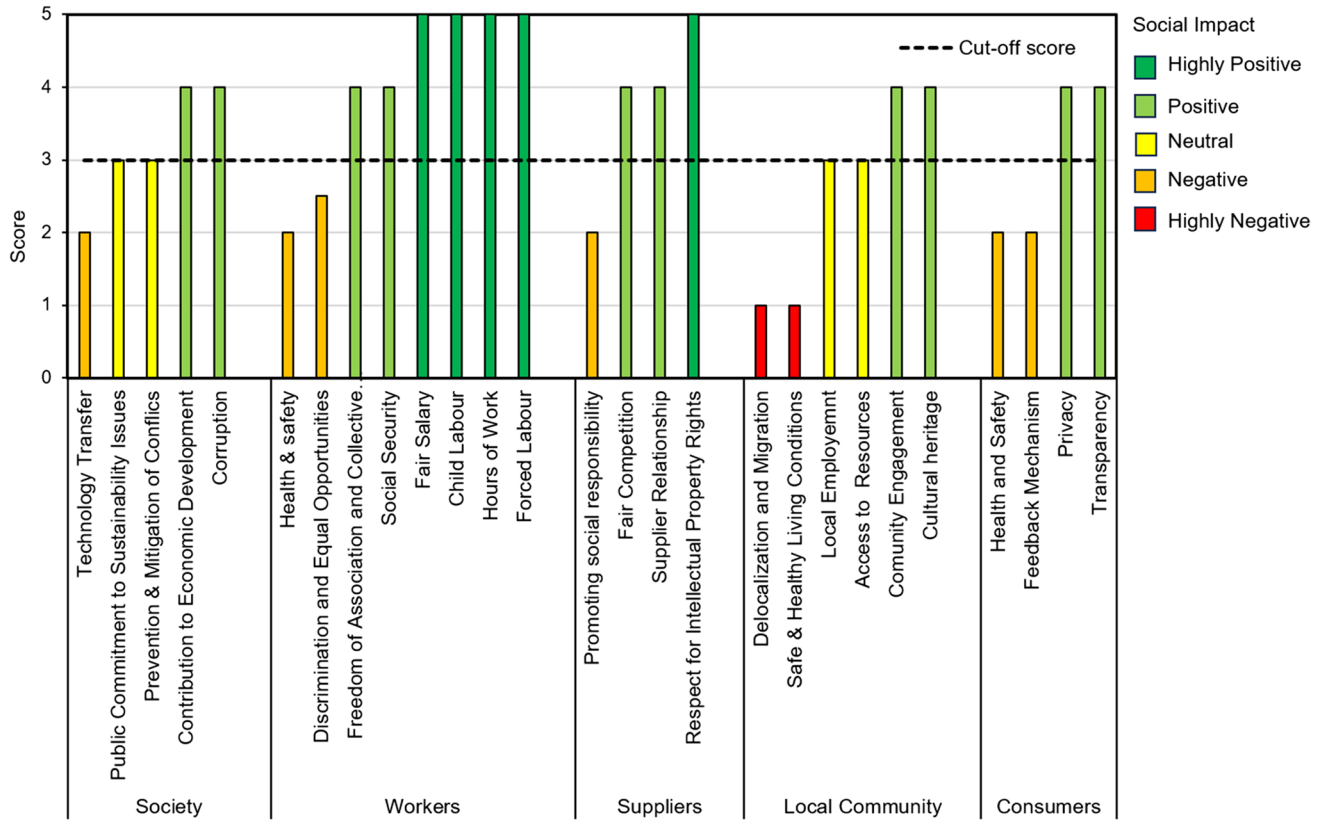

Fig. 4 Scores for each subcategory considered in this study

4.1.2 Prevention and mitigation of conflicts

The annual report of the parent organization states that it does not do business in a region with ongoing conflicts and so far, has not been impacted adversely due to any ongoing conflict. The parent organization follows a code of business conduct that mandates compliance with relevant UN and domestic sanctions or resolutions related to conflict-affected areas. The General Manager stated during the interview that the WAAM spin-off does not conduct business in the defense sector and hence, is not involved in the development of disputed products like arms and ammunition. As a result, no evidence of the organization's direct or indirect involvement in escalation of conflicts was found. However, the annual report does not mention any de-escalation efforts undertaken by the parent organization or its WAAM spin-off. Hence, this indicator is scored of 3 out of 5 according to its assessment criteria in Table 4, and results in a neutral social impact.

4.1.3 Contribution to economic development

The contribution of WAAM production and repair service to the economic development of the society is measured using gross value added (GVA) per employee of the organization. GVA is a productivity metric that refers to the amount value of goods and services produced minus the cost of all inputs involved in their production. During the interview, the General Manager revealed that the WAAM spin-off brought a GVA exceeding one million euros to its parent organization, in 2023. This results in a GVA per employee of about 100,000 € (the WAAM spin-off has 10 employees, including the management). This is significantly higher than the national GVA per employee of about 88,000 € in Belgium (OECD 2022). As this GVA per employee (100,000 €) is 13.6% higher than the national average, a corresponding score of 4 has been assigned to this indicator (refer to Table 3). Hence, it is concluded that the WAAM spin-off had a positive net economic contribution to the national economy.

4.1.4 Corruption

To assess the risk of an organization's involvement in corruption, the Corruption Perception Index (CPI) of the country of the organization's operation, i.e., Belgium by experts and businesses was also taken into consideration. Overall, Belgium ranks 16 th in the world with a CPI score of 73/100 (Transparency International 2023), indicating a low corruption risk. Hence, this indicator is marked 4 out of 5 as the CPI score lies in the range 60–80, as outlined in Table 3, resulting in a positive social impact.

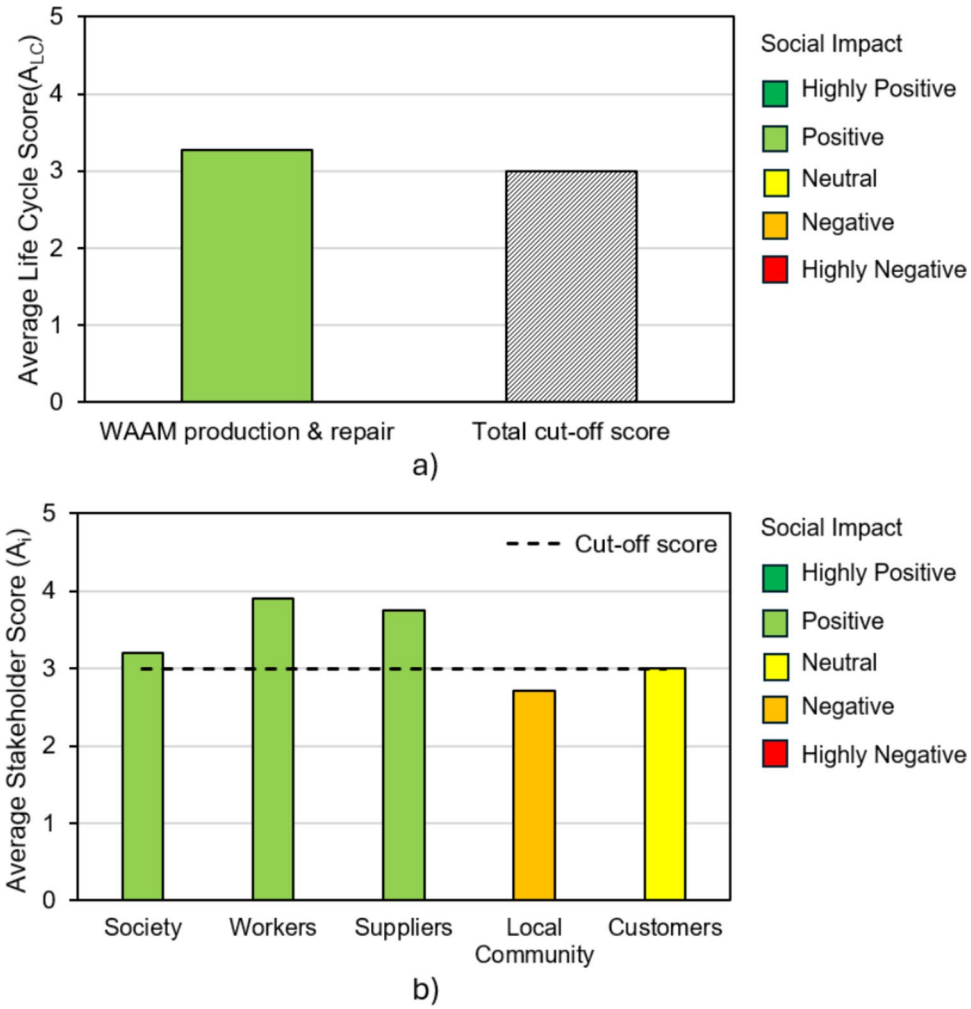

Fig. 5 Aggregated scores **a** at stakeholder level and **b** at overall life cycle level

4.1.5 Technology transfer

During the interview, the General Manager stated that the WAAM spin-off does not have a structured technology transfer program, but it has partnered with other academic and public research institutions in research projects focussing on WAAM innovations. While these partnerships enable WAAM-related knowledge transfer, they do not constitute a formalized technology transfer program. Hence, a score of 2 is assigned to this indicator (refer to Table 4) as the company has been involved in some WAAM-related projects that facilitate knowledge transfer but lacks a structured technology transfer program.

4.2 Impact on workers

4.2.1 Freedom of association and collective bargaining

The sustainability report of the parent organization revealed that 88% of the total employees are covered by collective bargaining agreements, indicating a very high coverage rate. Additionally, around half of the employees (49.1%) are part of a trade union in Belgium, indicating a moderate level of trade union density. Hence, based on the reference scales in Table 3, the social indicators "collective bargaining agreement coverage" and "trade union density" are marked 5 and 3, out of 5, respectively.

4.2.2 Child and forced labor

The parent company has a strict policy framework prohibiting child labor, forced labor, or any other form of human exploitation within its own operations, ventures, and value chains. It has multiple accessible channels to anonymously report violations or misconduct, supported by standardized procedures for investigating and addressing these complaints. No allegations or legal proceedings related to forced labor or child labor involving the parent company or its spin-off were found in the annual report. Also, none of worker participants in this study reported being coerced or forced to accept employment terms. Overall, cases of child labor are extremely rare in Belgium (United Nations, n.d.) and the

prevalence of any kind of forced, coercive, and exploitative labor is one of the lowest in the world (Walk Free 2023). Hence, strict enforcement and monitoring of policies prohibiting child and forced labor is observed leading to a highly positive impact with a full score of 5 out of 5 in these two social indicators in accordance with their evaluation criteria in Table 4.

4.2.3 Social security

In Belgium, employers need to pay compulsory social security contributions of 27% of the gross employee remuneration, by law (OECD 2020b). This covers compensation for unemployment, health care, family allowances, pensions, childcare, work-related accidents, and work-related illness among others. Based on the parent organization's expenditure data and 27% contribution rate, the average annual social security expenditure per employee was calculated to be approximately 7690 €. This corresponds to the "strong employer social security contribution" level in Table 3, implying a score of 4 out of 5. Hence, a positive social impact on workers in the social security subcategory is realized.

4.2.4 Fair salary

The parent organization has a policy of paying competitive wages based on local market assessments and compensates its employees at or above the minimum living wage. The General Manager confirmed that the lowest salary offered by the company corresponds to the government-mandated minimum wage of 1,994.18 € (WageIndicator Foundation, n.d.), while the national poverty threshold for a single person stands at 1,450 € (STATBEL 2024). Therefore, the minimum wage is 38% above the poverty threshold, implying a score of 5 out of 5 (refer to Table 3). Hence, it can be deduced that the workers are paid well above the non-poverty wage, positively impacting their lives.

4.2.5 Discrimination and equal opportunities

The parent company has a formal Inclusion and Diversity policy where unlawful discrimination based on race, sex, age, religion, national or social origin, or any other basis is not allowed. However, the gender ratio in both steel making and WAAM operations is skewed in favor of men with women being underrepresented. Women accounted for 9% of the total workforce and 17% of managerial and higher-level positions in the parent company, as opposed to the EU average of 32.8% (Eurostat 2024). On interviewing the General Manager of the WAAM spin-off, it was revealed that the company is striving to improve its gender ratio and has no entry barriers for women. Women candidates had been interviewed in the past for WAAM-associated roles. As the proportion of female employees was less than 20%, a score of 1 out of 5 was assigned to this social indicator according to its reference scale in Table 3, indicating a highly negative impact. No information regarding gender-wise payment differences was available in the company reports. Hence, the gender pay gap data for the Belgian manufacturing sector was assessed. According to the Belgian statistical office (StatBel), female employees in manufacturing are paid around 9.5% lower wages than their male counterparts (STATBEL). Hence, a score of 4 was assigned to indicate "gender pay gap (%)" based on its reference scale in Table 3. However, efforts are needed to investigate and minimize the barriers that prevent the entry of women into the workforce of both parent and spin-off companies.

4.2.6 Hours of work

The Belgian law limits general working hours to 48 h a week or lower with maximum working hours including overtime to 56 h per week. In Belgium, only 4.3% of the employees reported working above 50 h per week (OECD 2020c). The parent and WAAM spin-off companies have a working week of a maximum of 45 h a week and 9 h a day, complying with legal requirements. Out of the five WAAM operators, three operators stated that they have never worked overtime while two operators stated that they have worked overtime less than 5 h a week. As no worker reported working more than 50 h a week, a score of 5 was assigned to this indicator based on the criterion outlined in Table 3.

4.2.7 Health and safety

For assessing health and safety, the lost time injury frequency rate (LTIFR) indicator is used. The LTIFR is defined as the number of injuries that result in workers taking time off work per million hours worked. The General Manager stated that no fatalities or serious injuries occurred at the WAAM production line. All the WAAM operators agreed that adequate occupational safety measures such as the provision of personal protective equipment, fume extraction, and ventilation were taken at the WAAM facility. According to the sustainability report, the majority of injuries and fatalities occurred in the steel-making phase due to reasons such as explosions in the coking plant, and unloading of raw materials, among others. According to the same report, the LTIFR rate for the site was 0.9, higher than the global average of 0.65 for the steel industry (World Steel Association 2023). Hence, a negative impact is seen in this subcategory with a score of 2 out of 5 based on the reference scale outlined in Table 3.

4.3 Impact on suppliers

4.3.1 Fair competition

The parent organization and WAAM spin-off have established a formal code of business conduct where the competition and antitrust laws are aimed at maintaining supplier relationships based on integrity fairness and mutual respect. During the interview, the General Manager confirmed that suppliers of the company are evaluated based on objective criteria such as quality, cost, utility, and performance. For monitoring fair competition and antitrust policies, the Belgian authorities have established a point of contact for Fair Competition, where an individual or company can file a complaint against an individual or company involved in unfair competition practices and social fraud (Belgian Social Information and Investigation Service 2024). Hence, this indicator is marked as 4 out of 5, implying a positive impact as per the reference scale established in Table 4.

4.3.2 Respect for intellectual property rights

The intellectual property rights policy of the parent company mandates the use of the intellectual property of third parties only after obtaining proper licenses. The parent company has also established well-defined procedures to identify and address the potential security risks related to the intellectual property of third parties. According to the annual report, no lawsuits related to the infringement of the intellectual property of a third party were reported. Hence, a fully protective policy with strict enforcement and monitoring to prevent abuse of intellectual property rights is observed and a full score of 5 is designated to this indicator based on its reference scale in Table 4.

4.3.3 Supplier relationship

According to the financial report of the parent company, roughly 77% of the total economic expenditure (that includes all tax contributions, employee wages, and social security, supplier and contractor payments, payments to creditors, capital expenditure, and R&D) made by the parent organization was spent as payment to suppliers. This indicates a strong reliance on suppliers as compared to in-house production of supplies, indicating a positive impact on suppliers. Hence, a corresponding score of 4 out of 5 is assigned to this indicator based on the reference scale established in Table 3.

4.3.4 Promoting social responsibility

The parent company has adopted a responsible procurement policy that mandates sourcing of raw materials for steel making from certified suppliers, requiring them to meet environmental, social, governance, health and safety, human rights, and ethical standards. It also evaluates its suppliers and contractors annually based on environmental, social, and governance standards. However, during the interview, the General Manager informed that the WAAM spin-off does not explicitly evaluate its suppliers based on these ethical standards. As a result, although a formal policy exists, it is not enforced or monitored in the context of socially responsible procurement and does not have any impact on purchasing decisions. Hence, a score of 2 out of 5 is assigned to this indicator as per the reference scale outlined in Table 4, indicating a negative social impact.

4.4 Impact on local community

4.4.1 Delocalization and migration

This subcategory aims to assess the social impact on delocalized/migrated workers. The regional-level data was used to assess the social impact on migrant workers. Based on OECD data for the employment of native-born workers and foreign-born workers in Belgium, it is seen that a severe unemployment gap of 6.3% with a disadvantage for foreign-born workers compared to foreign-born workers exists as opposed to the OECD average of 0.4% (OECD 2023). This results in a highly negative social impact in this subcategory, with a score of 1 out of 5 attributed based on the reference scale determined in Table 3.

4.4.2 Local employment

This subcategory assesses if the hiring policies of the organizations studied prefer local workers. During an interview with General Manager, it was revealed that the hiring policy does not favor explicitly local candidates, and non-local candidates are equally considered if they possess the required skill sets. Hence, a score of 3 out of 5 is allocated to this subcategory based on its reference scale in Table 4 and it is concluded that the hiring policies have a neutral impact on local employment.

4.4.3 Community engagement

The sustainability report revealed that the parent organization hosts annually "Open Company Day" where local residents, local resident groups, and the general public are invited to visit the site. Moreover, an Environmental Meeting Day is organized every two years where local residents are informed about the organization's environmental initiatives. The residents are given contact points to present their material aid and financial support is offered for different local charity organizations working for underprivileged

sections of the society. Hence, it is seen that the organization regularly engages with the local community with a structured program and dedicated resources. As a result, a score of 4 out of 5 is allotted based on the evaluation criteria in Table 4, indicating a positive social impact.

4.4.4 Cultural heritage

In this subcategory, it is assessed whether relevant organizational information is available to the community members in their spoken language(s). Dutch is the official and most widely spoken language in the Flemish region of Belgium. Most of the organizational documents uploaded on the organization's websites are available in Dutch along with French and English, ensuring better communication with the local community. However, few documents such as annual reviews, and financial and sustainability reports were available only in English, indicating a minor gap in this indicator. Consequently, a score of 4 out of 5 is assigned to this indicator based on the reference scale established in Table 4, implying a positive social impact.

4.4.5 Access to resources

The steel-making phase is a water and energy-intensive phase (World Steel Association, n.d.) and these resources are used from local sources. Hence, these resources should be used judiciously without limiting the access of local communities to these resources. Therefore, indicators like water recycling rate and proportion of energy used from renewable and recovered energy sources for the processes studied are considered in this subcategory. Based on the sustainability report provided by the parent organization, approximately 73% of the total water used in industrial processes is recycled, indicating strong recycling with lower strain on local freshwater sources. Hence, this social indicator is marked as 4 out of 5 based on its reference in Table 3, indicating a positive impact on the local community. According to the same report, nearly 38% of the site's total energy consumption comes from renewable and recovered sources, demonstrating a higher reliance on fossil energy sources. This corresponds to a score of 2 out of 5, indicating a negative social impact (refer to Table 3). Therefore, further improvements in these two indicators are necessary to reduce the adverse impacts of excessive resource consumption and support greater resource availability for local residents.

4.4.6 Safe and healthy living conditions

The operations of an industry can negatively impact the living conditions of local residents due to a rise in pollution levels. Dust and airborne emissions such as NO_x, SO_x, and dioxins are a major concern in the manufacturing of steel products. Hence, the concentration of fine dust, more particularly known as fine particulate matter (PM2.5) relative to the World Health Organization's (WHO) recommendation of 5 µg/m^3, is used as an indicator in this subcategory. The PM2.5 and NOx concentrations in the region were 220% (11 µg/m^3) and 85% respectively, higher than the concentrations recommended by WHO (Sciensano 2022) (refer to Fig. 6). Hence, a negative impact on the safe and healthy living conditions of the local community

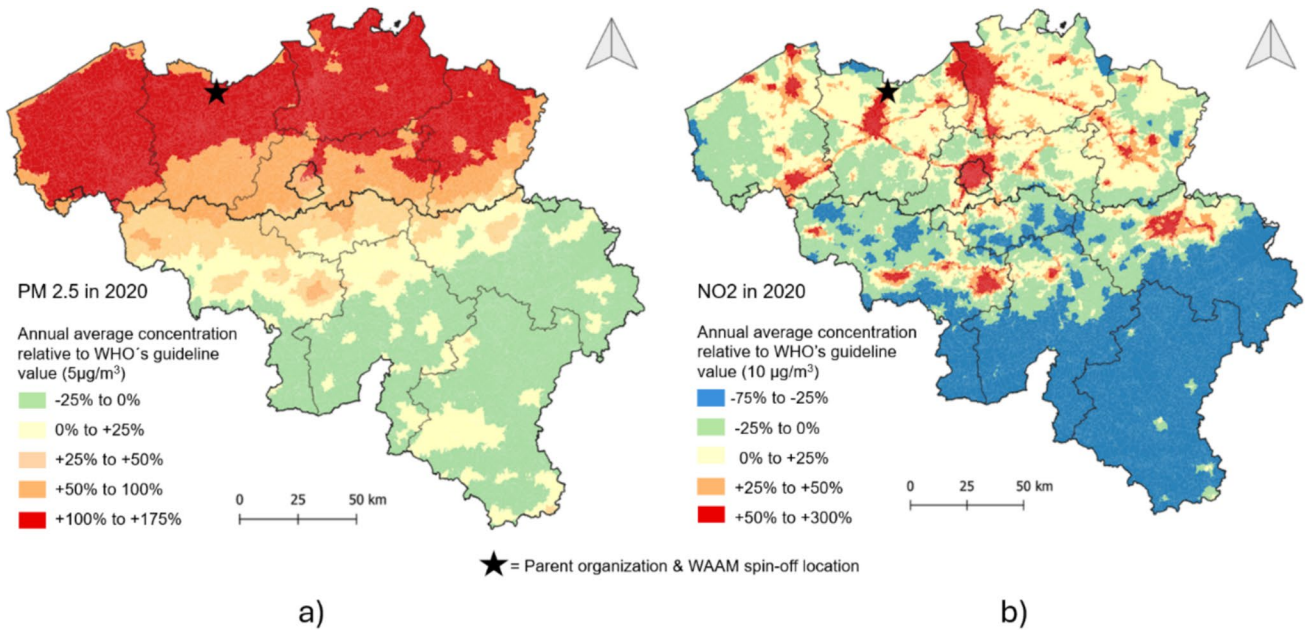

Fig. 6 Annual average concentration relative to WHO guideline **a** PM2.5 and **b** NOx in Belgium (Sciensano 2022)

is identified, resulting in a score of 1 out of 5 based on the evaluation criteria in Table 3. Although the parent organization has taken steps such as the installation of a dust filter facility that has improved the air quality over the past few years, more efforts are needed to lower dust and nitrous oxide emissions.

4.5 Impact consumers

4.5.1 Health and safety

According to the General Manager, no complaints were received regarding the WAAM product failures affecting the health and safety of its customers. However, WAAM parts undergo quality control processes like Non-Destructive Testing (NDT) along with mechanical and microstructural characterizations, aimed at reducing the risk of premature failure and associated health and safety hazards. Hence, this indicator is rated at 2 out of 5, signifying a negative social impact on customers (refer to Table 4) due to the lack of systemic measures to assess customer health and safety.

4.5.2 Feedback mechanisms

During the interview, the General Manager reported that annual meetings are held with WAAM service customers to discuss their grievances, and the organization does not have an explicit formal mechanism such as conducting surveys to measure customer satisfaction to collect feedback from its WAAM customers. Hence, this indicator is assigned a score of 2 out of 5 (refer to Table 4) due to the lack of a structured customer feedback mechanism.

4.5.3 Privacy

As far as customer privacy is concerned, the organization has well-documented data protection measures for the collection, use, processing, and protection of the private data of the customer, preventing its access to unauthorized third parties. No complaints regarding breaches of customer privacy were found in the company's annual report, indicating good compliance with customer data protection measures. However, limited information was available on the review and monitoring mechanisms of these measures. Therefore, this indicator is designated a score of 4 out of 5, based on the reference in Table 4, indicating a positive impact on customers.

4.5.4 Transparency

The parent organization publishes annual reports disclosing their environmental, economic, and social impacts to be more transparent to its stakeholders. The Global Reporting Initiative (GRI) is a well-known international standards organization that provides widely used sustainability reporting standards, covering a wide range of topics ranging from tax, waste, emissions, diversity and equality, health and safety, among others (Global Reporting Initiative, n.d.). According to the organization's annual report, 77% of its sustainability reports adhere to GRI standards, indicating good transparency. This translates to the indicator score of 4 out of 5 according to the reference scale outlined in Table 3, resulting in a positive social impact. Hence, it can be concluded that organizations involved in this study are adequately transparent but adherence to GRI reporting standards can be further improved.

4.5.5 Issues of social concern and recommendations for improvement

From a societal perspective, the organization's non-involvement in technology transfer programs is assessed as an indicator of improvement. WAAM-based production and repair approaches have exhibited promising environmental and economic potential and can significantly reduce the environmental impacts and production costs (Priarone et al. 2020, 2021; Campatelli et al. 2020; Pagone et al. 2022; Kokare et al. 2023b). The technology transfer of WAAM-based production and repair solutions to low-technology companies and those in emerging economies with rapid economic growth but higher levels of pollution can help them lower their environmental footprint without compromising economic growth. Additionally, this technology transfer may facilitate a positive impact on the economy and human capital development in these economies (Zhang and Hsu 2024; Sajid et al. 2024; Simms and Frishammar 2024). Hence, measures could be taken in the future to facilitate this technological exchange as the business operations of the WAAM spin-off expand beyond Belgium.

The health and safety of workers, particularly in the steelmaking phase, is identified as a social hotspot as the accident rate (characterized by LTIFR) for the site was higher than the global average in the steel sector. The parent organization has a well-defined safety policy and should continue its efforts in the analysis of accidents, implementation of safety rules, reduction in ergonomically challenging tasks, risk assessment, shared vigilance, and prevention of stress, among others.

Poor air quality with higher concentrations of dust (PM2.5) and NOx emissions is found to be an issue of concern for local community. Although the parent organization has dramatically reduced its dust and NOx emissions, their concentrations are above the WHO-recommended threshold. Hence, the need to continue ongoing efforts like monitoring of emissions, upgradation of dust

filter installations, and selection of raw materials with lower contents of nitrogen and sulfur is realized.

The WAAM spin-off company evaluates its suppliers based on traditional criteria like cost, quality, utility, and performance and does not yet include environmental, social, and ethical criteria in its procurement policy. Therefore, collaborating with suppliers on establishing environmentally, socially, and ethically responsible business practices, and assisting suppliers in identifying and improving business activities that fall below the requirement of these standards is recommended to reduce risks of negative social impacts. From a customer's perspective, efforts need to be made to track the performance of WAAM fabricated or repaired products in their industrial environment and assess if they are prone to failure, risking the health and safety of workers. Furthermore, the establishment of robust feedback mechanisms for customers is recommended for assessing customer satisfaction with WAAM production and repair services. The social hotspots or other areas for improvement and recommendations for minimizing their adverse social impacts are summarized in Table 7.

4.5.6 Limitations and future research directions

While conducting this study, some limitations were realized. Firstly, the scope of this study did not include activities like the mining of iron ore, coal, and other minerals used in steel-making due to a lack of data. Hence, future works should incorporate the social impacts of mining in addition to steel making and WAAM phases. Secondly, some social indicators were assessed based on sector, regional, or county-specific data as no organization-specific data was available. Hence, it was assumed that the same social trends prevalent in the region are reflected in the WAAM spin-off and its parent company. Furthermore, a single expert interview was used to assess some social indicators that constrain the representativeness of different stakeholder perspectives. Future works should focus on obtaining more organization-specific data and conducting multiple interviews with different stakeholder groups to accurately characterize the social impacts of WAAM. Lastly, the performance in some social indicators, especially those related to human rights such as workers' freedom of association and collective bargaining, child labor, forced labor, delocalization, and migration is

Table 7 Social issues of concern or improvement and recommendations for improvement

Stakeholder	Subcategory	Social issues of concern/improvement	Recommendations
Society	Technology transfer	No involvement in the transfer of technology	Involvement in technology transfer of WAAM solutions to emerging economies with higher environmental emissions
Workers	Health and safety	LTIFR is higher than the global average for the sector	• Accident analysis • Enforcing safety regulations • Minimizing tasks with ergonomic challenges • Conducting risk assessments • Promoting shared vigilance
Suppliers	Promoting social responsibility	Lack of ethical, environmental, and social criteria in supplier selection	• Engaging with suppliers to establish business practices that align with environmental, social, and ethical responsibilities • Identifying and enhancing activities that do not meet these standards to minimize the risks associated with negative social impacts
Local community	Safe and healthy living conditions	Unhealthy concentrations of PM 2.5 and NOx concentrations in the air	• Continuation of monitoring emissions • Upgrading dust filter installations • Selecting raw materials with lower nitrogen and sulfur contents
Consumer	Health and safety	The performance of WAAM parts on the health and safety of consumers is unknown	• Monitor the performance of WAAM products • Assess potential risks of WAAM product failures and risks to the health and safety of users
	Feedback mechanism	Absence of a formal feedback mechanism	Establishing robust feedback mechanisms to evaluate customer satisfaction

influenced by the country of operation, legal framework, and strength of its law enforcement. Hence, the findings of this study cannot be generalized to other companies implementing WAAM technology. Therefore, more studies are required in different geographical and legal contexts to fully understand the social impacts of WAAM on its stakeholders.

5 Conclusions

This study used SO-LCA methodology, in line with UNEP/SETAC guidelines, to assess the social impacts of WAAM production and repair services offered by a company in Belgium, and to identify social issues of concern while providing actionable solutions to promote socially sustainable manufacturing practices. Five stakeholders namely society, workers, local communities, suppliers, and consumers were considered. Relevant social impact subcategories and indicators were identified for each stakeholder and social inventories were collected from organizational reports, national and international databases, and an interview with top management personnel. Based on the data collected, each social indicator was assigned a score, and these scores were aggregated at stakeholder and life cycle levels.

The SO-LCA methodology enabled a structured stakeholder-wise assessment of positive and negative social impacts across the value chain. The SO-LCA results indicated a positive impact on its stakeholders, with positive effects observed on workers, society, and suppliers, while a neutral impact was seen on consumers. However, a slightly negative impact on the local community was noted, primarily due to air quality issues in the region arising from particulate matter (PM 2.5) and nitrous oxide (NO_x) emissions during steel production.

The SO-LCA also highlighted several issues of concern and proposed actionable solutions to improve the social impact of WAAM-based production and repair services. For society, the organization's non-participation in technology transfer programs was identified as an area for improvement. Hence, transferring WAAM technology to low-tech companies and emerging economies is suggested in the future to share the environmental and economic benefits of WAAM. Health and safety concerns, specifically in the steel-making phase, were also highlighted as social hotspots for workers, emphasizing the need for continuous efforts in accident prevention and safety measures. A lower proportion of women in the workforce was found, recommending measures such as mentorship programs and addressing entry barriers for women. For the local community, issues, such as air poor quality employment disparities, and lower employment rates among foreign-born workers, were recognized as social issues of concern. Recommendations include career guidance and training programs to bridge the gap between foreign-born and native workers. To improve the air quality, efforts are advocated to monitor and further decrease dust and NOx concentrations. The SO-LCA also revealed that the organization's supplier evaluation lacks consideration for environmental, social, and ethical criteria. Collaboration with suppliers to establish responsible practices is recommended. Customer-focused efforts are suggested to track WAAM product performance and establish robust feedback mechanisms for customer satisfaction.

Overall, the SO-LCA framework contributed to assessing social impacts associated with WAAM production and repair services on its different stakeholders and to identifying social hotspots that require attention and improvement. These insights can serve as a valuable reference for stakeholders, policymakers, and industry in making informed decisions and developing more socially sustainable WAAM practices. Future research is encouraged to incorporate mining impacts, obtain more company-specific data, and explore the varied influences of legal frameworks on social indicators in different geographical contexts.

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