Assessing the Life Cycle Performance in the Metallurgical Sector: A Case Study in Italy

Vinci Giuliana, Barricella Carlo, Ruggeri Marco

Abstract: This study compared two types of sheets: one made of steel and one made of aluminum, using Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Social Life Cycle Assessment (S-LCA). The LCA results show that the aluminum sheet had a greater environmental impact than the steel one in 11 out of 18 impact categories, such as a 5% higher Global Warming Potential, 3% higher Stratospheric Ozone Depletion, and 72% higher Ionizing Radiation. The main contributing factors were energy-intensive processes and bauxite processing associated with aluminum production. The LCC results also supported the findings of the LCA, demonstrating that the raw material, electricity, and labor costs for aluminum sheets were higher compared to steel ones, with the aluminum sheets costing €163 and the steel ones costing €19. However, the S-LCA results presented a contrasting perspective. They indicated that steel sheets exhibited poorer social performance compared to aluminum ones, particularly regarding child labor and discrimination, primarily due to the harsh working conditions in Ghana, the primary source of iron used in steel production. Overall, this study highlights the environmental superiority of steel screens over aluminum ones but also underscores the social challenges associated with steel production.

Keywords*: *Aluminum, Life Cycle Thinking, Steel, Sustainability

I. INTRODUCTION

In recent decades, the need for sustainable development has become increasingly evident in many sectors. Among them, the steel and aluminum sectors have gained significant attention due to their substantial contribution to global economies and their environmental and social impacts [1]. From an economic perspective, the steel industry, comprising the aluminum and steel sector, makes a significant contribution to global GDP, as it comprises various activities, including mining, refining, smelting, and manufacturing [2], which collectively generate significant economic value and employment opportunities [3]. Therefore, it plays a crucial role in infrastructure development, construction, automotive manufacturing, and other industries, contributing significantly to GDP in many countries and regions of the world. From an environmental perspective, however, it generates significant impacts as both the aluminum and steel sectors are energy intensive, accounting for 1% [4] and 7% [5] of global greenhouse gas emissions, respectively. The aluminum industry is estimated to consume about 3-5% of global electricity production [5]. The smelting process is responsible for most of these emissions [6], mainly from fossil fuel consumption and the release of carbon dioxide (CO_2) and perfluorocarbons (PFCs). The primary sources of emissions in the steel sector also include the use of fossil fuels for heating and the reduction of iron ore (resulting in CO_2 emissions) and the production of coke, a carbon-intensive fuel [6]. But this also includes a number of social impacts associated with steel and aluminum production, mainly related to critical raw materials, i.e., those natural resources are essential for the functioning of certain industries and economies but characterized by high supply risk and economic importance [7]. Or even to the conditions of workers, and the occupational hazards involved in the aluminum and steel industries, especially as they work with heavy machinery, high temperatures, and potentially hazardous materials [8]. Without adequate safety measures, inadequate training, and insufficient protective equipment, workers can be exposed to risks such as accidents, injuries, respiratory problems, burns, and other occupational hazards [8]. The steel and aluminum sectors, therefore, are integral components of modern economies but face significant environmental and social sustainability challenges. Balancing economic importance with sustainability is therefore a key challenge and the application of tools such as life cycle assessment can help identify opportunities to improve the economic performance of the sectors while minimizing their environmental impact. Therefore, in light of this, the objective of this paper is to conduct a sustainability assessment in the aluminum and steel sectors through a life cycle thinking perspective by applying Life Cycle Assessment (LCA) [9-10], Life Cycle Costing [11] and Social Life Cycle Assessment (SLCA) [12]. LCA is a comprehensive methodology that assesses the environmental impacts of a product, process, or system throughout its life cycle, from raw material extraction to end-of-life disposal. LCC and SLCA, on the other hand, extend the assessment to include socio-economic aspects, focusing on the social implications of a product's life cycle stages. An Italian company that produces steel and aluminum screens was chosen as a representative case study for the sustainability assessment, and whose name has been blacked out for reasons of Privacy.

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II. MATERIALS AND METHODS

A. Case study description

A company operating in Campania, Italy, was chosen as a case study, specializing in precision sheet metal and mechanical carpentry, producing for the naval, railroad, aeronautical, and electronics industries. It was founded in 1989 as part of a program to diversify its previous industrial plant construction business with the intention of providing its production services to medium to large companies, initially employing only five or six workers, to undertake a remarkable growth over the past decade, going from a workforce of about 15 employees to its current 55 employees, while maintaining its family company structure and evolving in management methods and production systems. The company's production activities were initially located in the Isclero Valley in the province of Benevento, later expanding to include the nearby *Limatola* plant, which covers an area of 18,000 square meters, 3500 of which are used for production and offices.

B. Life Cycle Assessment (LCA)

LCA allows the evaluation of a product or service's potential environmental, social, and economic impacts. It is a standardized method based on the ISO 14040:2006 and ISO 14044:2006 and it consists of four stages, as shown in Figure 1: 1) Goal and scope definition; 2) Life Cycle Inventory (LCI); 3) Life Cycle Impact Assessment (LCIA) 4) Interpretation.

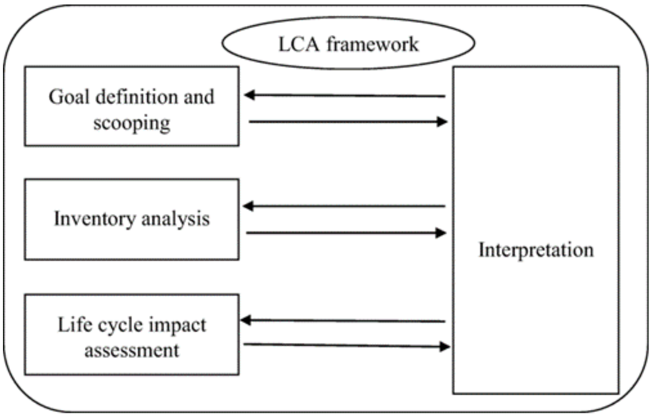

Fig. 1. Life Cycle Assessment Framework

Regarding the goal of the study, it was to provide a LCA of two types of sheet metal (screens), and then compare their impacts and draw assessments. Two materials, in particular, were considered, namely aluminum and steel, which are considered among the most widely used metals in manufacturing processes. The production of a 200-unit batch, i.e., packaging for the packaging of such products, was chosen as the functional unit. Relative to the system boundaries, for the analysis, it was chosen to study the impacts from cradle to gate (Figure 2), considering the production of raw materials (steel and aluminum) and auxiliary materials, processing, packaging, and shipping to Timisoara in Romania.

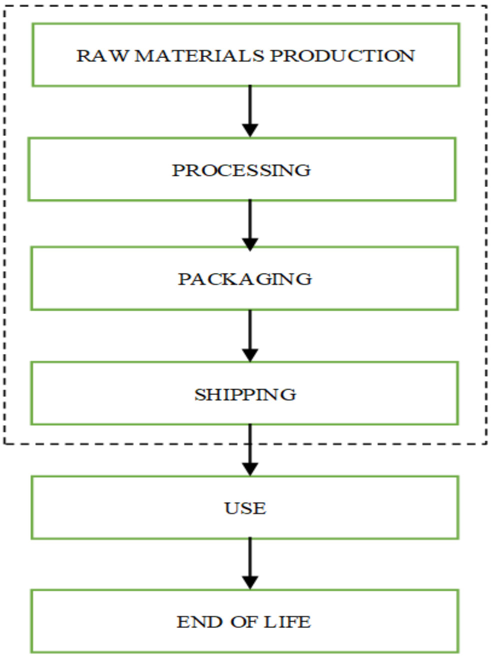

Fig. 2. System boundaries of the processes

Considering the wide variability of applications of the schemes and the multiple configurations they can have during installation; it was decided to exclude the product use phase. In addition, the end-of-life phase of the product was excluded because the organization, as a B2B company, has no influence on its management and therefore does not have the related data. Relative to the inputs and outputs used in the study, are listed in Table I and included raw materials (such as steel and aluminum), ancillary materials (anything used to fulfill particular processes, such as powder coating for painting), and utilities, such as electricity and nitrogen.

Table 1: Life Cycle Inventory

Input	**Unit**	**Steel sheet**	**Aluminum sheet**
Steel AISI 304 BA	kg	19.18	-
Aluminum 5754 H111	kg	-	70.00
Kapton (polyamide film)	kg	0.27	-
Cardboard (boxes)	kg	0.60	1.5
SURTEC (Trivalent Chromium)	cl	-	15.00
Powder coating (epoxy/polyester)	kg	0.003	-
Film (polyolefin)	kg	0.23	0.46
Polyethylene	kg	0.002	0.005
Filling paper	kg	0.42	0.84
Vellum Label	kg	0.001	0.007
Electricity	kWh	1.53	3.24
Nitrogen	m^3/h	0.16	2.38
Output	**Unit**	**Steel sheet**	**Aluminum sheet**
Scrap	kg	0.96	42.00
Sheet	p	20,000	20,000

As for the LCIA, in this study, we followed the ReCiPe 2016 MidPoint (I). SimaPro 9.5. was used, and the 18 impact categories considered are:

Global Warming Potential (GWP); Stratospheric Ozone Depletion (SOD); Ionizing radiation (IR); Ozone Formation, Human Health (OFHH); Fine Particulate Matter Formation (FPMP); Ozone formation, Terrestrial ecosystems (OFTE); Terrestrial acidification Potential (TAP); Freshwater Eutrophication Potential (FEP); Marine Eutrophication Potential (MEP); Terrestrial Ecotoxicity (TEC); Freshwater Ecotoxicity (FEC); Marine Ecotoxicity (MEC); Human Carcinogenic Toxicity (HCT); Human Non-Carcinogenic Toxicity (HNCT); Land Use (LU); Mineral Resources Scarcity (MRS); Fossil Resources Scarcity (FRS); Water Consumption (WC).

C. Life Cycle Costing (LCC)

Life Cycle Costing (LCC) (ISO 15686-5), is used to calculate the lifecycle cost of a product or service, starting from pre-production stages to its final disposal, with the aim of minimizing production costs. The goal is to achieve better economic sustainability of one's product or service. However, often, LCC might be a difficult analysis to implement because the necessary data are often sensitive for companies that hardly tend to disclose them. Therefore, some estimates can be made based on data available in the literature or by drawing on public databases of large market analysis companies (e.g., Bloomberg). In this study, in the absence of specific data, some values were estimated by considering the most impactful cost categories in the product life cycle. Specifically, the market price of aluminum and steel, the price of electricity required for the proper operation of machinery labor cost, and the cost of labor. In the first category, the market prices of steel (471.28€/ton) and aluminum (2067.23€/ton) were considered [13]. Regarding the price of energy, data provided by the Energy Services Manager was taken as a reference, which is 114.8 €/mWh [14]. Finally, regarding labor cost, the one surveyed by the International Labor Organization was considered, which in 2022 for the manufacturing sector was €29.20/hour per employee. Once data were collected, costs for individual categories were calculated.

D. Social Life Cycle Assessment (S-LCA)

The guidelines of the Product Social Impact Life Cycle Assessment (v3) (PSILCA) [15] were followed. Two stakeholder categories (workers and local community) and 8 impact categories (child labor, forced labor, fair wages, working hours, labor rights, discrimination, health and safety, and immigration) were selected for this study. In turn, the 8 categories were defined by 8 sub-categories, each of which was defined by an indicator, chosen based on available data and in relation to relevance across sectors and impact categories. Relative to social performance, we do not speak in this sense of impact, but of risk. This is because, if the information on social effects is not available at the product level, social effects cannot be attributed with certainty, and, therefore, possible risks are considered [16]. In fact, it is not possible to know with certainty the social impact of producing a specific good or service, but it is sufficient to know the probability that a product is associated with a given externality. Then for each indicator, the results were normalized according to PSILCA guidelines, considering the five risk scales defined by the database: very low risk, low risk, medium risk, high risk, and very high risk.

III. RESULTS AND DISCUSSIONS

A. Life Cycle Assessment

The results of the LCIA are shown in Table II.

Table 2: Life Cycle Impact Assessment of the two processes

Impact categories	Unit	Aluminum sheet	Steel sheet
GWP	kg CO$_2$ eq	1,276.8	1,220.5
SOD	kg CFC11 eq	0.0003	0.0002
IR	kBq Co-60 eq	0.761	0.443
OFHH	kg NO$_x$ eq	5.179	6.297
FPMP	kg PM$_{2.5}$ eq	0.265	0.021
OFTE	kg NO$_x$ eq	5.241	6.379
TAP	kg SO$_2$ eq	6.201	4.242
FEP	kg P eq	0.011	0.001
MEP	kg N eq	0.005	0.008
TEC	kg 1,4-DCB	195.15	34.48
FEC	kg 1,4-DCB	4.566	5.807
MEC	kg 1,4-DCB	1.932	2.296
HCT	kg 1,4-DCB	0.581	0.573
HNCT	kg 1,4-DCB	57.62	62.51
LU	m^{2}a crop eq	24.72	11.22
MRS	kg Cu eq	11.18	1.87
FRS	kg oil eq	323.03	367.97
WC	m^3	21.29	0.62

The comparison of the two types of screens makes it clear that the aluminum screen is more impactful than the steel screen in 11 out of 18 impact categories. For example, the aluminum screen has a GWP, of 5% greater a SOD of 3%, and an IR of 72% greater. In fact, aluminum production involves energy-intensive processes such as bauxite refining and smelting, which can contribute to higher GHG emissions and energy consumption than steel production. This then leads to greater production of gases such as CO2 and ionizing radiation, sometimes resulting from the use of nuclear energy for electricity production [17]. These data are also confirmed by the FPMF, which is about 12 times higher for the aluminum screen manufacturing process than for steel. In fact, the refining and smelting processes involved in aluminum production are energy intensive and often use high-temperature operations [18]. These processes can involve the combustion of fossil fuels, which can contribute to particulate emissions, especially if adequate pollution control measures are not in place. Steel production also has its own refining and smelting processes, but particulate emissions may be relatively lower due to differences in operating characteristics and technologies used [19]. Other noteworthy impacts for the aluminum screen manufacturing process are FEP, TEC, LU, MRS, and WC, which are 9, 5.6, 2.2, 6, and 35 times greater, respectively, than the steelmaking process. This is because bauxite mining requires land and water because of site exploration and preparation, a process that often involves the use of land for geological surveys, sampling, and analysis [20].

But also, because large amounts of water are used to break down dust, process the ore, cool equipment, and maintain the site. And finally, after the mining operation is completed, the land must be rehabilitated to mitigate environmental impacts and restore the site, requiring reclamation activities such as revegetation, soil stabilization, and erosion control [20]. In general, LCIA results suggest that the choice between aluminum and steel should be based on a comprehensive assessment of all environmental impacts and economic considerations. For example, if the main goal is to reduce greenhouse gas emissions, steel sheets may be the best choice. On the other hand, if the main goal is to minimize dependence on fossil fuels, aluminum sheet metal might be preferable. However, it should be kept in mind that these results are based on data specific to the manufacturing process of the aluminum and steel sheets used in the study. Environmental impacts may vary depending on the source of raw material supply and the production process used. Therefore, these results should be used as a general guide, but not as a product-specific assessment. Finally, it is important to note that LCA can provide valuable information on environmental improvement options for a product. For example, it may be possible to reduce the environmental impact of aluminum or steel sheet by improving the manufacturing process, using renewable energy sources, or reducing water consumption. Taken together, these data indicate that the choice of material greatly influences the environmental impacts of the product. However, it is also important to consider other factors, such as the product's durability, its ability to be recycled and reused, and energy efficiency in its use.

B. Life Cycle Costing

Results of LCC are presented in Table III.

Table 3: Life cycle costing results

Categories	Aluminum sheet	Steel sheet
Raw material	144.71€	9.04 €
Electricity	7.18 €	5.22 €
Labor	11.17€	5.16€
Total	163.05€	19.42 €

For the aluminum screen, the raw material cost is 144.71€, the electricity price is 7.18€, and the labor cost is 11.17€, for a total of 163.05€. For the steel screen, the raw material cost is 9.04€, the electricity price is 5.22€, and the labor cost is 5.16€, for a total of 19.42€. It can be seen that the raw material cost for the aluminum screen is much higher than that of the steel screen, but the costs associated with electricity and labor for the aluminum screen are also much higher, leading to a much higher total cost than the steel screen. Therefore, the LCC shows that aluminum production is very energy intensive, confirming the results of the LCA, affecting both the environment and the scarcity of raw materials, and the cost of production.

C. Social Life Cycle Assessment

The social dimension study sought to provide a general overview of the potential risks that aluminum and steel production could generate along the aluminum and steel supply chain. Therefore, four countries-Australia, Brazil, Ghana, and Italy-were considered based on the origin of the raw materials needed for steel and aluminum production. Specifically, the bauxite from which aluminum oxide (or alumina), which is needed for aluminum production, is obtained comes from deposits located in Brazil and Australia. Iron ore and chromium, needed for steel production, come from Australia and Ghana, respectively. Italy was considered the country where the transformation and processing of raw materials into the final product takes place. In the case of steel and aluminum production, the mining and manufacturing sectors were considered [15]. The results are expressed in Table IV. Then, for both aluminum and steel, an arithmetic mean was made of the various indicators, and normalized according to the risk scales defined by the PSILCA guidelines. Therefore, each risk was given a score. Specifically: very low risk = 1; low risk = 2; medium risk = 3; high risk = 4; very high risk = 5. In this way, it was possible to graphically express the various risks (Figure 3). The results of the S-LCA show how, of the two materials, the one that shows worse social performance is steel, although both, for various categories, have equal values. In particular, it emerges that the two categories for which steel has worse values than aluminum are child labor and discrimination. Specifically, relative to child labor, steel shows a very high risk that child exploitation situations may occur, given that in Ghana, thousands of children work in artisanal mines, including iron and coal mining, and on a small scale [21], in dangerous conditions, although both Ghanaian and international law prohibit child labor. Relative to discrimination, however, discrimination involves a difference in wages at the labor level, especially since there is a 73% imbalance between men and women in Ghana. Although significant progress has been made in promoting girls' education in Ghana, disparities in access and completion rates still exist. Factors such as cultural norms, poverty, early marriage, and teenage pregnancy can hinder girls' educational opportunities and contribute to the gender gap in literacy rates and school enrollment. In addition, women in Ghana face difficulties in accessing decent work and achieving economic empowerment [21]. Gender gaps exist in employment rates, wage levels, and representation in leadership positions. Women are more likely to be engaged in informal and vulnerable work that often lacks job security, social protection, and equal pay, such as in the mining sector. Finally, also noteworthy is the worker’s rights category, which is used to assess how liberal and vibrant the union culture is and how much the right to organize freely is guaranteed by those working in the aluminum and steel supply chains. Higher density values have been considered an indicator of better or more liberal associational conditions.

Table 4: Social Life Cycle Assessment Results

Stakeholders	Subcategories	Social indicators	Aluminium			Steel		
			BRA	AUS	ITA	GHA	AUS	ITA
Workers	Child labour	% of children in employment ages 5–14	5%	n.a.	n.a.	20%	n.a.	n.a.
	Forced labour	Cases × 1000 inhabitants	1.79	0.65	2.43	4.84	0.65	2.43
	Fair salary	Sector average wage per month (score)	2.5	5.8	2.9	2	5.8	2.9
	Discrimination	Gender gap (%)	−10%	20%	25%	73%	20%	25%
	Health & Safety	Fatal accident at workplace (Cases x 100,000 employees)	21	n.a.	22.4	n.a.	n.a.	n.a.
	Working time	Risk of improper working hours (Weekly hours of work for employees)	43	43	38	46	43	38
	Workers right	Trade union density (%)	13%	13%	32.5%	19%	14%	32.5%
Local community	Migration	Migrant workers in the mining sector (% of total workers in the sector)	5%	28%	14%	2%	28%	14%

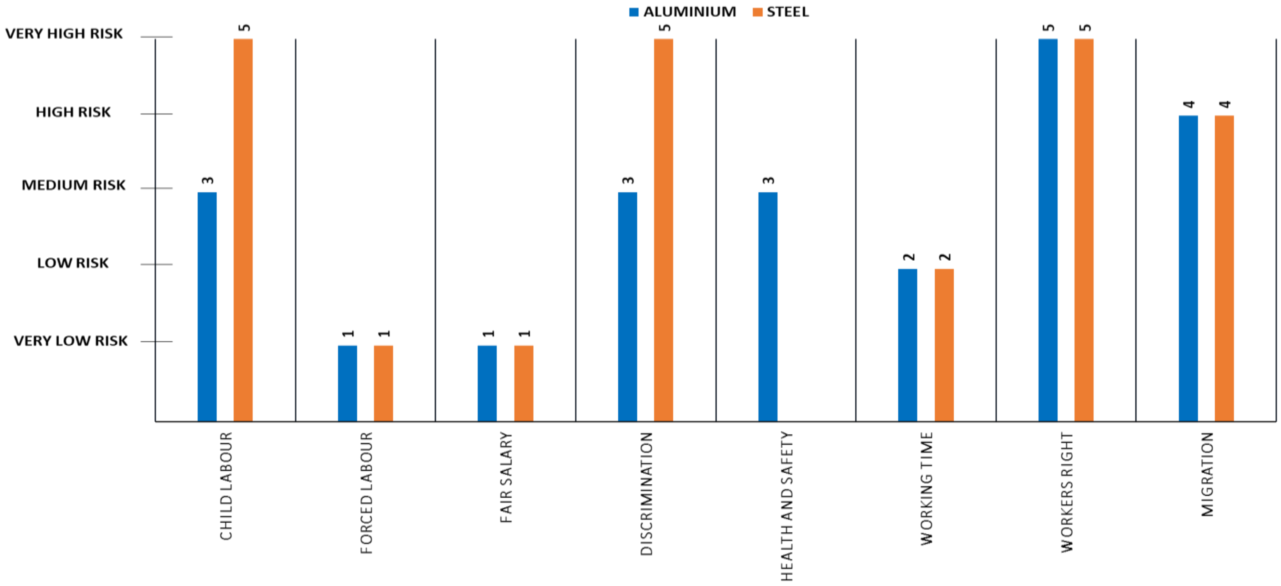

Fig. 3. Social Life Cycle Assessment Results (normalized)

In fact, except for Italy, the remaining countries in the two supply chains show rather low rates (Table IV) and are an expression of a very high risk that workers may not organize in trade unions. However, it is important to note that trade unions operate in a more or less dynamic environment influenced by economic, social, and political factors, and the role and influence of trade unions can vary across sectors and over time as labor markets evolve and new challenges emerge. Finally, the last particularly noteworthy category is migration, due primarily to the presence of a high rate of labor migrants in mining in Australia, where Bauxite and Iron are mined. This could be attributable to two reasons:

1. Temporary Skill Shortage Visas: The Temporary Skill Shortage (TSS) visa is one of the most commonly used skilled migration visas for the mining sector [22]. It allows employers to sponsor foreign workers with specific skills and qualifications for a temporary period to fill labor shortages.
2. Fly-in Fly-out (FIFO) and Drive-in Drive-out (DIDO) workforce: The mining industry in Australia often uses a FIFO or DIDO workforce model [23]. This model involves workers going to remote mining sites for a specified period and then returning to their place of residence. These workers may reside in different regions of Australia or be temporary migrants from overseas.

In this context, however, while the foreign workforce could be seen as an opportunity, the high percentage of foreign workers, on the other hand, could also induce a high risk of discrimination, racism, and social conflicts due to high immigration, especially related to the possibility of experiencing unequal treatment, prejudice or negative stereotypes due to the cultural background or nationality of workers.

IV. CONCLUSIONS

In this study, two types of sheets, one made of steel and one made of aluminum, were compared and evaluated through the LCA, LCC, and S-LCA. The results of the LCA show that the aluminum screen is more impactful than the steel screen in 11 out of 18 impact categories, including, for example, 5% higher GWP, 3% higher SOD, and 72% higher IR, mainly due to the energy-intensive processes and bauxite processing. These data are also confirmed in the LCC, which shows that raw material and electricity and labor costs for aluminum screens are higher than for steel schemes, leading to a substantial difference in the final price, of €163 for aluminum screens vs. €19 for steel screen. In contrast, however, the S-LCA results show that of the two materials, the one that shows worse social performance is steel, especially for child labor and discrimination, due to the insane working conditions that occur in Ghana, the country where most of the iron is mined.

DECLARATION

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Authors Contributions	All authors have equal participation in this article.

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