

## A COMPARATIVE LIFE CYCLE COST AND SOCIAL LIFE CYCLE ASSESSMENT OF MATERIALS FOR LIGHTING POLE MANUFACTURING

Hasan S. Algornazy and Abdulbaset M. Alemam

Department of Mechanical and Industrial Engineering, Faculty of Engineering, University of Tripoli- Libya

Email: hasanalgornazy725@gmail.com

Received 27 September 2025; Revised 27 December 2025; Accepted 15 March 2026; Published 20 March 2026

### دراسة ومقارنة تكلفة دورة حياة المواد المستخدمة في تصنيع أعمدة الإنارة وتقييمها الاجتماعي

حسن سالم الجرنازي، عبد الباسط محمد الإمام

قسم الهندسة الميكانيكية والصناعية، كلية الهندسة، جامعة طرابلس، ليبيا

#### الملخص

يُشجّع المصنّعون على اتباع ممارسات مستدامة وإجراء تحليل لدورة حياة المنتج. تتوفر منهجيات راسخة لتقييم دورة الحياة (LCA) للتأثيرات البيئية. لا يزال التفاعل بين التأثيرات الاقتصادية والاجتماعية يُشكل تحديًا كبيراً. تُعالج الدراسة هذه الفجوة من خلال عرض إطار عمل مزدوج لتكلفة دورة الحياة (LCC) وتقييم دورة الحياة الاجتماعية (SLCA) وتطبيقه على إنتاج أعمدة الإنارة. تدرس الدراسة الآثار الاقتصادية والاجتماعية لاستخدام مواد وهي الفولاذ والفولاذ المجلفن والفولاذ المقاوم للصدأ والألمنيوم. تم استخدام كل من تحليلات التكلفة التقليدية والتكلفة البيئية على حد سواء لتقييم التكاليف المالية. أما في تقييم دورة الحياة الاجتماعية فتم التركيز على كيفية تأثير عمليات اللحام لكل مادة على صحة العمال وسلامتهم. أظهرت نتائج تقييم دورة الحياة التقليدية أن الفولاذ هو الخيار الأفضل اقتصاداً. ويعود ذلك إلى انخفاض تكاليف المواد الخام وكذلك انخفاض تكاليف الإنتاج. من ناحية أخرى، يظهر الألمنيوم بتكاليف أولية عالية. ومع ذلك، يُظهر تقييم تكاليف البيئية (E-LCC) أن الألمنيوم يتحمل أقل تكلفة بيئية. رغم انخفاض تكاليف الفولاذ المجلفن التقليدية، إلا أنه يُظهر تكاليف بيئية مرتفعة. يُسلط تقييم دورة الحياة الاجتماعية (SLCA) الضوء على لحام الفولاذ المقاوم للصدأ باعتباره يُشكل أعلى المخاطر الصحية المحتملة على العمال. تُؤكد الدراسة على ضرورة إجراء تقييم شامل للاستدامة، مع الأخذ في الاعتبار التوازن بين الكفاءة الاقتصادية والأثر البيئي والمسؤولية الاجتماعية في اختيار المواد.

**الكلمات المفتاحية:** حساب تكلفة دورة الحياة، تقييم دورة الحياة الاجتماعية، التصنيع المستدام، الأثر البيئي، التحليل الاقتصادي.

#### ABSTRACT

Manufacturers are encouraged to use sustainable practices and implementing an analysis of the life cycle of a product. Existing life cycle assessment (LCA) methodologies are available for environmental effects. The interplay of economic and social impacts remains a challenge. This gap is addressed in the study through the presentation of a dual Life Cycle Costing (LCC) and Social Life Cycle Assessment

(SLCA) framework applied to the lighting pole production, which is an essential infrastructure component. This paper analyzes the economic and social implications of the used materials which are, steel, galvanized steel, stainless steel and aluminum. Both conventional and E-LCC analyses are used in the evaluation of the financial expenditures. The SLCA is an examination of how welding processes affect the health and safety of workers for each material. The conventional cost results show that steel is the most economical option. This is due to low raw material costs as well as low production costs. On the other hand, aluminum has high initial costs. Nonetheless, E-LCC shows aluminum has the lowest environmental cost. Despite the moderate conventional costs associated with galvanized steel, its environmental costs are notably higher. SLCA highlights stainless steel welding as posing the highest potential health risks to workers. The study emphasizes the necessity of a holistic sustainability assessment, revealing trade-offs between economic efficiency, environmental impact, and social responsibility in material selection.

**KEYWORDS:** Life Cycle Costing (LCC), Social Life Cycle Assessment (SLCA), Sustainable Manufacturing, Environmental Impact, Economic Analysis.

## INTRODUCTION

The need for sustainable manufacturing is picking up a lot of steam due to growing concerns about the environment and society [1]. Manufacturers are increasingly being asked to analyze the life cycle impacts of their products, going from the classical cradle-to-gate to a more comprehensive cradle-to-grave [2]. LCA methodologies help in analyzing the environmental burden that a product or process imposes at the different stages of its life. However, they are not perceived by manufacturers to be directly advantageous; consequently, they remain undeveloped. As such, it is important to ensure that environmental assessments have economic and social dimensions to achieve take-up by industry for truly sustainable manufacturing [3].

Life cycle costing (LCC) appears as an essential instrument to bridge this gap and as a methodology to assess the economic performance of products from an entire life cycle perspective [4, 5]. Conventional LCC takes into consideration purchase costs, operational costs, maintenance costs, and disposal costs, providing a comprehensive financial view to make informed decisions. Moreover, by developing E-LCC, which takes environmental externalities into account when considering cost, a more comprehensive trade-off between economy and environment can be achieved. In addition to the economic and environmental dimensions described above, social life cycle assessment (SLCA) offers a system for assessing the social impacts of products during their life cycle [6]. SLCA analyzes a variety of social indicators such as labor rights, worker health and safety, community engagement and human rights, and thus also encompasses societal aspects related to manufacturing processes, extraction of raw materials, and the use and disposal of products [7]. Although the significance of SLCA was acknowledged, its usage with LCC and LCA within practical industrial applications is limited, underlining the necessity for rigorous and pragmatic assessment frameworks.

This paper covers the challenges previously mentioned and contributes to the analysis of LCC and SLCA for the case of lighting poles. Lighting poles are one of the essential elements in urban and transport networks, which contribute to maintaining safety and efficiency. Its production requires high energy costs, extensive processing, and

may have ecological and social reverberations. This paper evaluates the economic, environmental, and social performances of lighting poles made from four different materials: mild steel, galvanized steel (same base steel with an inorganic zinc (IOZ) coating applied), austenitic stainless steel (316 family), and aluminum. The study compares the conventional and eco-life cycle costs of lighting poles manufacturing for each material option, including material, and energy costs. It also evaluates the social impact of welding practices on worker safety, focusing on health risks.

## LITERATURE REVIEW

While the expected benefits of combining conventional life cycle costing (CLCC) with eco-life cycle costing is understood, academic literature often reviews the two methodologies separately. Previous studies have revealed the possible weakness of CLCC in tackling sustainability from an environmental perspective. In particular, CLCC tends to narrow the focus to economic costs at the expense of broader ecological consequences of a product or process [8]. However, this economic focus, while useful for the financial analysis, is inadequate to assess the overall sustainability of an enterprise.

Conversely, E-LCC, while designed to incorporate environmental considerations, has encountered critiques regarding its inherent complexity and the difficulties associated with the robust monetization of diverse environmental impacts. A significant impediment to the widespread adoption of E-LCC is the current absence of universally standardized methodologies for seamlessly integrating environmental costs within the established LCC framework [9]. This lack of methodological consensus and the inherent challenges of assigning economic values to non-market environmental goods and services have hindered the consistent and comparable application of E-LCC across various contexts.

The integration of CLCC and E-LCC, despite the aforementioned challenges, presents a compelling pathway towards enhanced decision-making. Firstly, the synthesis of economic and environmental cost analyses facilitates more comprehensive evaluations of product or service sustainability, allowing decision-makers to adopt a more holistic perspective [3], [5]. Secondly, the incorporation of environmental costs into the LCC framework can strategically guide resource allocation towards cost-effective interventions aimed at mitigating harmful environmental impacts [4], [6]. Finally, and perhaps most crucially, this combined approach fosters the development of genuinely sustainable solutions by systematically considering both economic viability and environmental responsibility throughout the entire life cycle of a product or service.

There is a smaller but growing literature combining SLCA with cost methods. Chang et al. applied SLCA to welding technologies and developed the potential hazard model for welding fumes used in this study [10]. Their inventory and parameterization provide a benchmark for process-level SLCA in welding contexts. In other works the integration of social indicators with LCA and LCC in the manufacturing and energy storage sectors is discussed. However, the combination of monetary and social indices is rarely reported. This limits the direct comparability of the results and motivates the present integrated CLCC + ECLCC + SLCA approach.

A significant body of life cycle assessment (LCA) research prioritizes environmental impact categories, while social dimensions are often superficially treated or entirely omitted. This disparity can be attributed, in part, to the inherent complexities in quantifying social impacts and the current absence of universally accepted and standardized methodological frameworks [11]. Furthermore, developing robust social indicators necessitates the accumulation of detailed empirical data from every stage of a

product's life cycle. This is a significant challenge because such data is often unavailable or otherwise difficult to acquire [12]. Consequently, there is a pressing need for the development of adaptable and responsive methodological frameworks capable of integrating dynamic data streams and offering real-time insights into social performance, particularly within sectors such as construction and manufacturing [13], [14].

## METHODOLOGY

This study employs a twofold methodology incorporating LCC and SLCA to evaluate the sustainability performance of lighting poles manufactured from different materials. The system boundary encompasses the manufacturing stage, including raw material acquisition, production processes (welding, machining), and the associated energy consumption.

All four lighting poles are compared based on the following functional unit: structural support for mounting lighting fixtures at an appropriate height above the ground of 9 meters. The lifespan of steel poles is about 30 years [15]. Galvanized steel, stainless steel, and aluminum poles are estimated at 50 years [16]. To calculate the reference flow, the functional unit period is divided by the use period of the material. The reference flow for each material is multiplied by all corresponding values of the elementary flow. Table (1) presents the four reference flows derived to provide the service corresponding to the functional unit.

**Table 1: Results of the reference flows.**

<b>Material</b> <b>Lifespan</b>	<b>Steel</b>	<b>Galvanized steel</b>	<b>Stainless steel</b>	<b>Aluminum</b>
Functional unit (year)	30	30	30	30
The use (year)	30	50	50	50
Reference flows	1	0.6	0.6	0.6

The LCC analysis is conducted using both conventional and E-LCC approaches. Conventional LCC focuses on direct economic costs incurred by the manufacturer, while E-LCC expands the scope to include environmental externalities monetized using environmental prices.

### Conventional Life Cycle Cost (CLCC)

To conduct an economic assessment of the manufacturing process, the conventional life cycle cost analysis was broken down into three key components: energy consumption, asset depreciation, and raw materials.

Energy consumption costs are calculated based on energy consumption (kWh) during manufacturing processes and the local electricity price. Energy consumption data for each material (steel, galvanized steel, stainless steel, aluminum) is derived from [17].

Depreciation costs are calculated using a units-of-production method. This method allocates the asset's cost  $B$ , salvage value  $SV_N$  (the estimated value at the end of its useful life) proportionally to the total units of production expected during the asset's lifespan  $EPU$ . This method assumes a linear depreciation pattern, meaning the depreciation expense is spread evenly over the units produced. The depreciation rate is calculated as shown in equation (1) [18]:

$$\text{Units of production depreciation} = \frac{B - SV_N}{EPU} \quad (1)$$

Initial machine costs for steel, galvanized steel, and stainless-steel production lines are estimated at 1,974,000 LYD, and for aluminum, 2,574,000 LYD [19]. Salvage value is assumed to be 20% of the initial cost [20], and the lifespan of welding machines is 15 years (total products of about 37,500 poles), while other manufacturing machines have a lifespan of 26 years (total products of about 65,000 poles) [21], [22].

Raw material costs include the costs of coil material (steel, galvanized steel, stainless steel, and aluminum), electrodes, and welding gas. Electrode costs are calculated based on material-specific electrode types (ER 70S-6 for steel and galvanized steel, E308/308L for stainless steel, E4043 for aluminum) and consumption rates. Coil and electrode costs are obtained from World Steel database and Markets Insider [23]. Welding gas costs are calculated based on gas cylinder cost (420 LYD per 125 cubic feet) and material-specific gas flow rates (steel and galvanized steel: 25 f<sup>3</sup>/h, stainless steel: 30 f<sup>3</sup>/h, aluminum: 35 f<sup>3</sup>/h) and a standardized welding time of 0.5 hours per pole was assumed for all materials to facilitate direct comparison, although in practice, aluminum welding speeds may differ due to thermal conductivity.[24]. The cost implications of galvanization for steel poles have been calculated. A two-part inorganic zinc (IOZ) coating system was employed to address the issue of corrosion on the steel pole. The system under consideration consists of a zinc-rich primer and an organic topcoat. A minimum dry film thickness of 3 mils (0.076 mm) was mandated to ensure adequate corrosion protection for the steel substrate. The calculated galvanization cost is 195 LYD per pole [25].

#### Eco-Life Cycle Cost (E-LCC)

The E-LCC approach is predicated on the premise of incorporating environmental externalities by assigning a monetary value to environmental impacts. Environmental impact scores are converted into monetary values through the application of environmental prices, which are obtained from the Environmental Prices Handbook EU28 [26]. The calculation employs the euro-to-Libyan dinar exchange rate according to the following conversion rate: 5.2 Libyan dinars (LYD) are considered equivalent to 1 euro (EUR), as illustrated in Table (2).

**Table 2: Midpoint level environmental prices.**

Impact categories	Environmental price per environmental impact (€/kg)	Environmental price per environmental impact (LYD/kg)
Climate change	0.13 CO <sub>2</sub> -eq.	0.676
Freshwater ecotoxicity	0.0309 1,4 DB-eq.	0.1606
Marine ecotoxicity	0.0047 1,4 DB-eq.	0.0244
Terrestrial ecotoxicity	8.69 1,4 DB-eq.	45.188
Carcinogenic - human toxicity	5.25 1,4 DB-eq.	27.3
Non-carcinogenic human toxicity potential	0.097 1,4 DB-eq.	0.504
Ozone layer depletion	29.1 CFC-eq.	151.32
Particulate matter formation	39 PM <sub>10</sub> -eq.	202.8
Acidification	6.46 SO <sub>2</sub> -eq.	33.592
Photochemical oxidant formation	1.15 NMVOC-eq.	5.89

### Social Life Cycle Assessment (SLCA)

The SLCA methodology follows the framework of the goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and interpretation, similar to environmental LCA approach [27]. Workers are identified as the primary stakeholder group, with a focus on health and safety impacts related to welding processes.

The study utilizes a potential hazard model to assess the relative risk (Gefährdungszahl, GZ) associated with welding fumes for different materials and welding procedures. The following equation (2) is used to assess the potential risk GZs arising from the welding fumes [10]:

$$GZs = Efumes \times L \times R \times Kb \quad (2)$$

where  $Efumes$  is the emission from the welding process,  $L$  is the ventilation factor; while  $R$  represents the spatial factor. If the location condition remains constant, it is reasonable to assume that  $R$  will be equal to 1, given that all scenarios were studied at the same factory site, and  $Kb$  is the factor of relative distance between the welding operator and the fume source, with a range of 1 to 4, with 1 indicating far distance (automated welding) and 4 indicating close distance (spot welding and manual welding).

### RESULTS

The results of the LCC analysis are presented for both the conventional and E-LCC methods. The conventional life cycle cost results illustrate the economic consequences of different materials selection, whereas the E-LCC results reveal the financial implications of the associated environmental burdens. The results of the social life cycle assessment will also be addressed and presented.

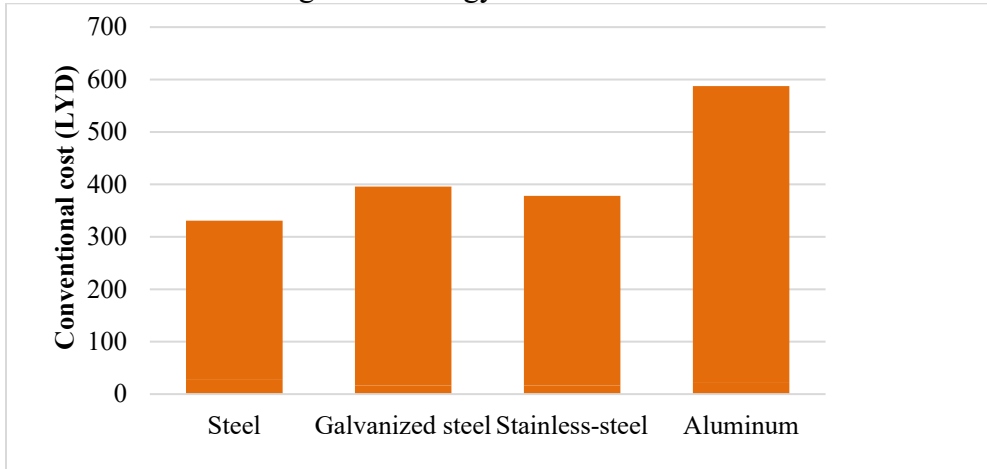
#### Conventional Cost

Table (3) presents a comprehensive analysis of the conventional costs associated with various alternative lighting poles. This analysis considers the costs incurred throughout the product system, encompassing energy consumption, depreciation, and raw material expenditures.

**Table 3: Conventional cost for all material of lighting poles.**

Material Cost (LYD)		Steel	Galvanized steel	Stainless steel	Aluminum
Energy		0.8	0.5	0.5	0.4
Depreciation		26.5	16	16	21
Raw material	Coil	244	149	278	393
	Electrode	18	11	53	138
	Gas	42	25	31	35
	Zinc	-	195	-	-
Total (LYD)		331	396.5	378.5	587.4

Figure (1) shows for all material of lighting poles. Steel has the lowest raw materials cost. Galvanized steel and stainless steel are relatively similar, while aluminum is significantly higher. Depreciation shows a moderate cost for all materials, with no significant differences among them. Energy costs show the lowest cost for all materials.



**Figure 1: Conventional cost for all material of lighting poles.**

#### Environmental Costs

The E-LCC analysis quantifies the environmental burden of each material by multiplying its environmental impact result [17] by the corresponding price (in €). The price is then converted into Libyan dinar at the prevailing exchange rate. For example, consider climate change, whose reported impact is 0.03 kg CO<sub>2</sub>-eq per kg of steel, and whose environmental price is 0.676 LYD per kg CO<sub>2</sub>-eq. The E-LCC in LYD is:

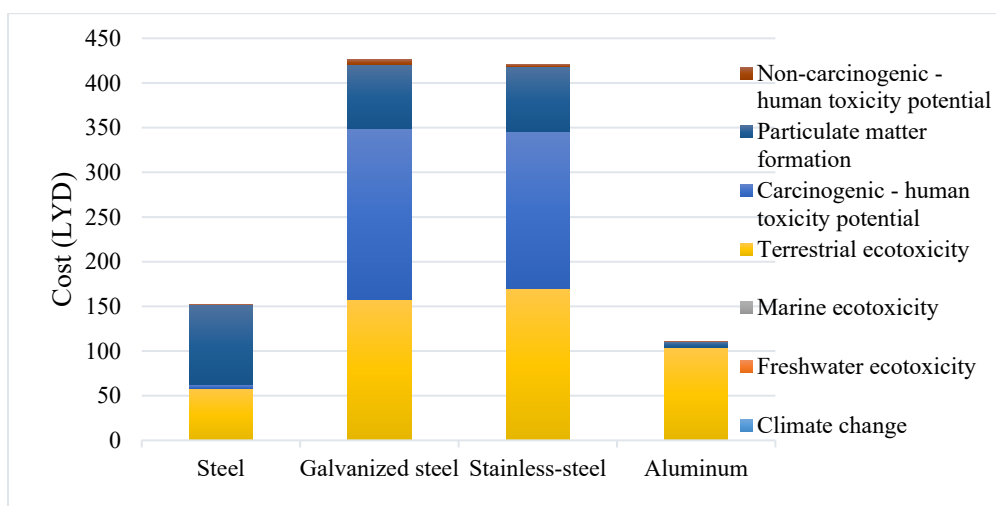
$$0.03 \text{ kg CO}_2\text{-eq} \times 0.676 \text{ LYD/kg CO}_2\text{-eq} = 0.02 \text{ LYD}$$

The environmental impact (EI) and E-LCC results for each material are shown in Table (4).

**Table 4: E-LCC for all material of lighting poles.**

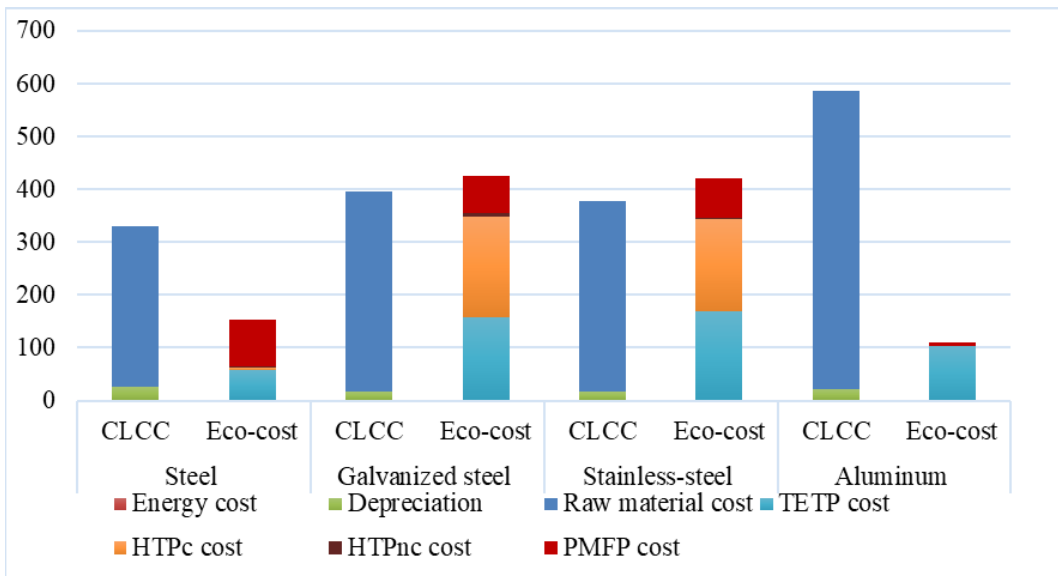
Material \ Impact category	Steel		Galvanized steel		Stainless-steel		Aluminum	
	EI	E-LCC	EI	E-LCC	EI	E-LCC	EI	E-LCC
Climate change	0	0	0	0	0	0	0	0
Freshwater ecotoxicity	0	0	0	0	0	0	0	0
Marine ecotoxicity	1	0	3	0	3	0	0	0
Terrestrial ecotoxicity	1	59	4	158	4	170	2	104
Carcinogenic - human toxicity	0	4	7	191	6	175	0	0
Non-carcinogenic - human toxicity	1	1	11	5	4	2	1	0
Particulate matter formation	0	89	0	71	0	73	0	7
Total (LYD)	4	153	25	426	18	421	3	111

The categories (terrestrial ecotoxicity, carcinogenic-human toxicity potential, noncarcinogenic-human toxicity potential, and particulate matter formation) have the most impact on the environmental cost. As for the remaining categories, all materials have a small environmental cost and can be neglected. Figure (2) provides a visual representation of the total E-LCC for each material. It clearly shows that galvanized steel has the highest overall environmental impact cost, subsequently stainless steel, then steel, and lastly, aluminum, which has the lowest cost.



**Figure 2: E-LCC of all material of lighting poles.**

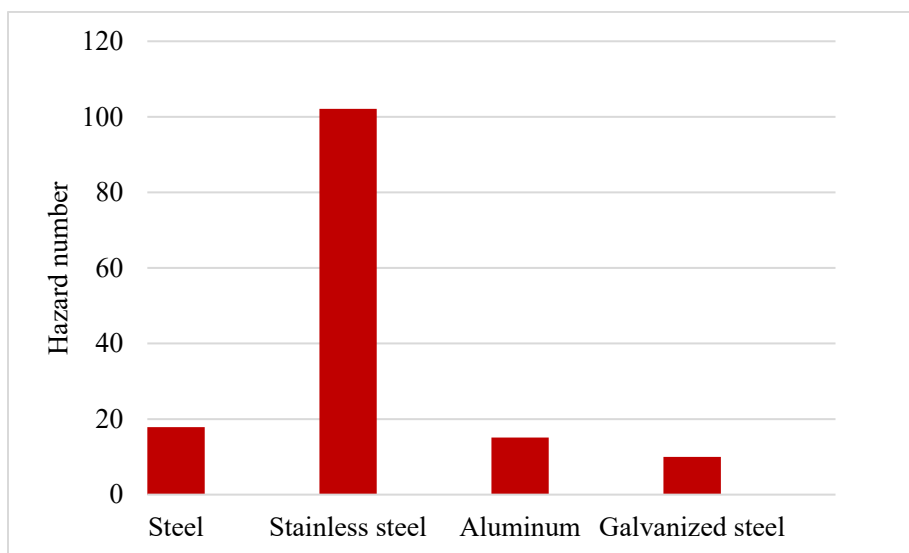
Figure (3) presents a comparative cost impact assessment of the four materials. The materials were evaluated across several cost categories, including toxicity potentials cost, particulate matter formation potential cost, energy cost, depreciation, and raw material cost. Steel displays the lowest CLCC 331 LYD and a modest E-LCC 153 LYD, stainless-steel follows with a CLCC of 379 LYD and an E-LCC of 420 LYD, galvanized steel incurs a CLCC 396 LYD due to the elevated raw material cost 380 LYD, and E-LCC 426 LYD, owing to the TETP 158 LYD and HTPc 191 LYD costs. Aluminum, despite zero TETP, HTPc and HTPnc burdens, registers the highest CLCC 587 LYD due to its very high raw-material cost 566 LYD, yet yields the lowest E-LCC 111 LYD. When the balance of costs is considered, steel emerges as the most economical choice due to its overall low costs across most categories, except for its raw material cost. Therefore, it can be concluded that steel is a viable option for applications where cost efficiency is a priority (464 LYD), followed by aluminum (698 LYD), then stainless steel (800 LYD), and finally galvanized steel (823 LYD).



**Figure 3: Comparative cost impact assessment of different metals.**

### Social Life Cycle Assessment

The study identifies the potential risk (Gefährdungszahl, GZ) of the welding procedures to indicate the relative potential harm posed by fumes to welders' health. Process-specific fume emissions related to the working environment were taken into account. Stainless steel presents the highest hazard number, indicating the greatest potential for worker health risks during welding. Steel displays moderate hazard numbers. Galvanized and aluminum demonstrate the lowest hazard number, indicating a lower risk compared to the other materials. Figure (4) shows the relative harm posed by fumes to welders' health.



**Figure 4: Comparative hazard potential of welding fumes by material type.**

Furthermore, integrating Social Life Cycle Assessment (SLCA) adds a vital social dimension to decision-making. Welding stainless steel carries a substantially higher hazard potential, raising serious worker health and safety concerns. Manufacturers committed to social responsibility must address these risks—potentially incurring higher operational costs for enhanced protective measures. By contrast, choosing materials like galvanized steel or aluminum can reduce health risks to workers; although these options often involve higher upfront costs, they may deliver important social benefits. Nevertheless, the environmental performance of galvanized steel still warrants careful evaluation.

## **CONCLUSION**

This study presents a comprehensive dual framework that combines life cycle costing (LCC) and social life cycle assessment (SLCA) to evaluate the sustainability of lighting pole production, demonstrating the critical importance of Assessing economic, environmental, and social dimensions using materials for comparison. The findings reveal that steel is the most economically viable option based on conventional LCC, while aluminum shows the lowest environmental burden according to the E-LCC. However, stainless steel welding poses the highest potential health risks to workers, based on the SLCA results. Galvanized steel presents a moderate conventional cost but elevated environmental and societal costs.

The framework of life cycle costing and social life cycle assessment approach provides manufacturers with valuable insights to make informed decisions towards sustainable lighting pole production. It underscores that a holistic sustainability assessment, considering economic efficiency, environmental impact, and social responsibility, is essential for achieving truly sustainable manufacturing practices. Future research could expand the scope of SLCA to include a broader range of social indicators and stakeholders, and should extend studies across multiple companies, industries, and geographical regions. This approach allows for the capture of variability in economic and social impacts resulting from regional differences in energy sources, raw material availability, and regulatory standards.

## **DECLARATION OF CONFLICTING INTERESTS**

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## **FUNDING**

These authors received no financial support for the research, authorship, and/or publication of this article.

## **DECLARATION OF GENERATIVE AI AND AI-ASSISTED TECHNOLOGIES IN THE WRITING PROCESS**

During the preparation of this work, the authors used Gemini 3 and deepl to improve language and grammatical correctness. After using these tools, the authors reviewed and edited the content as needed and takes full responsibility for the final content of the publication.

## REFERENCES

- [1] E. Fregonara and D. G. Ferrando, “The discount rate in the evaluation of project economic-environmental sustainability,” *Sustainability*, vol. 15, no. 3, p. 2467, 2023, doi: 10.3390/su15032467.
- [2] P. Kerdlap and S. Cornago, “Life cycle costing: Methodology and applications in a circular economy,” in *Circular Economy and Sustainability*. Singapore: Springer, 2021, pp. 499–525, doi: 10.1007/978-981-15-8510-4\_25.
- [3] W. T. França, M. V. Barros, R. B. Salvador, A. C. de Francisco, M. T. Moreira, and C. M. Piekarski, “Integrating life cycle assessment and life cycle cost: A review of environmental-economic studies,” *Int. J. Life Cycle Assess.*, vol. 26, no. 2, pp. 244–274, 2021, doi: 10.1007/s11367-020-01857-y.
- [4] L. Gu, B. Lin, Y. Zhu, D. Gu, M. Huang, and J. Gai, “Integrated assessment method for building life cycle environmental and economic performance,” *Build. Simul.*, vol. 1, no. 2, pp. 169–177, 2008, doi: 10.1007/s12273-008-8414-3.
- [5] M. C. Dejacó *et al.*, “Combining LCA and LCC in the early-design stage: A preliminary study for residential buildings technologies,” *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 588, no. 4, p. 042004, 2020, doi: 10.1088/1755-1315/588/4/042004.
- [6] K. Joachimiak-Lechman, D. Garstecki, M. Konopczyński, and A. Lewandowska, “Implementation of life cycle based tools in the circular economy context—Case study of plastic waste,” *Sustainability*, vol. 12, no. 23, p. 9938, 2020, doi: 10.3390/su12239938.
- [7] M. Koese, C. F. Blanco, V. B. Vert, and M. G. Vijver, “A social life cycle assessment of vanadium redox flow and lithium-ion batteries for energy storage,” *J. Ind. Ecol.*, vol. 2, no. 1, pp. 223–237, 2023.
- [8] R. Bocharé, M. Dagliya, and M. Kadam, “Assessment of economic performance of an industrial building using life cycle cost and refined benefit-cost analysis—A case study,” *J. Build. Eng.*, 2024, doi: 10.1016/j.jobe.2023.108397.
- [9] A. Abdeljaber, O. Mostafa, and M. Abdallah, “Applications of life cycle costing in waste-to-energy projects,” in *Waste-to-Energy Projects*. Springer Nature, 2023, pp. 77–115, doi: 10.1007/978-3-031-40993-6\_4.
- [10] M. Cellura, A. I. De Luca, N. Iofrida, and M. Mistretta, “Social life cycle assessment of batteries,” in *Social Life Cycle Assessment*. Springer International Publishing, 2024, pp. 291–306, doi: 10.1007/978-3-031-48359-2\_17.
- [11] P. C. Vitória, “Life cycle thinking: A study of applications on building projects,” *Contrib. Cienc. Soc.*, vol. 17, no. 13, p. e14096, 2024, doi: 10.55905/revconv.17n.13-495.
- [12] I. Barbero, Y. Rezgui, T. Beach, and I. Petri, “Social life cycle assessment in the construction sector: Current work and directions for future research,” *Int. J. Life Cycle Assess.*, 2024, doi: 10.1007/s11367-024-02341-7.
- [13] F. Ş. Fidan, E. K. Aydoğan, and N. Uzal, “Comprehensive analysis of social subcategories throughout life cycle assessment approach for the textile industry,” *Int. J. Life Cycle Assess.*, 2024, doi: 10.1007/s11367-024-02340-8.
- [14] H. Algornazy and A. Alemam, “Life cycle assessment of sustainable manufacturing processes: A comparative analysis of materials used for lighting poles,” *Univ. Zawia J. Eng. Sci. Technol.*, vol. 3, no. 1, pp. 43–56, 2025.

- [15] "What is the best material for light poles?," *Krut - LED Lighting Wholesaler*, Nov. 3, 2023. [Online]. Available: <https://www.krutled.com/what-is-the-best-material-for-light-poles/>
- [16] E. P. Najafabadi, A. Heidarpour, and S. Raina, "Hot-dip galvanizing of high and ultra-high strength thin-walled CHS steel tubes: Mechanical performance and coating characteristics," *Thin-Walled Struct.*, vol. 164, p. 107744, 2021.
- [17] W. G. Sullivan, E. M. Wicks, and C. P. Koelling, *Engineering Economy*. Pearson Australia Pty Limited, 2015.
- [18] "Steel light pole production line light pole making machine," *Tewei Machine*. [Online]. Available: <https://www.polemachines.com/>. [Accessed: Apr. 15, 2024].
- [19] M. Asplund, "What fraction of a capital investment is sunk costs?," *J. Ind. Econ.*, vol. 48, no. 3, pp. 287–304, 2000.
- [20] "How long does a welding machine last? Tips to improve its lifespan," *Tools Advisor*, Nov. 20, 2023. [Online]. Available: <https://www.toolsadvisor.org/how-long-does-a-welding-machine-last/>. [Accessed: Apr. 15, 2024].
- [21] A. A. Erumban, "Lifetimes of machinery and equipment: Evidence from Dutch manufacturing," *Rev. Income Wealth*, vol. 54, no. 2, pp. 237–268, 2008.
- [22] "Data," *Worldsteel.org*, Jun. 5, 2025. [Online]. Available: <https://worldsteel.org/data/>
- [23] A. D. Althouse, C. H. Turnquist, W. A. Bowditch, K. E. Bowditch, and M. A. Bowditch, *Modern Welding*, 12th ed. The Goodheart-Willcox Company, Inc., 2019.
- [24] "Report of life-cycle cost calculator," *American Galvanizers Association*. [Online]. Available: <https://lccc.galvanizeit.org/report/2564a0c67d271ee54080a793b65bfabb>. [Accessed: Apr. 26, 2024].
- [25] S. De Bruyn *et al.*, "Environmental prices handbook EU28 version," CE Delft, 2023.
- [26] G. Finnveden *et al.*, "Recent developments in life cycle assessment," *J. Environ. Manage.*, vol. 91, no. 1, pp. 1–21, 2009.
- [27] Y. J. Chang *et al.*, "Environmental and social life cycle assessment of welding technologies," *Procedia CIRP*, vol. 26, pp. 293–298, 2015.