EVALUATION OF ENERGY CONSUMPTION AND ENVIRONMENTAL IMPACT BASED ON THE CO_2 FOOTPRINT IN THE CASE OF SIGNALING PANEL

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Rezumat. *Lucrarea prezintă o analiză a consumului de energie și a impactului asupra mediului al panourilor de semnalizare din perspectiva amprentei de carbon, utilizând metodologia evaluării ciclului de viață (LCA). Studiul își propune să identifice etapele care generează cele mai mari emisii de* CO_2 *și oportunitățile de reducere a acestora. Etapele analizate includ extracția și producția de materii prime, fabricarea, transportul și utilizarea, considerând un panou de semnalizare standard reprezentativ. Rezultatele arată că producția de materiale contribuie cel mai mult atât la amprenta de carbon, cât și la consumul total de energie, în timp ce faza de utilizare devine semnificativă în funcție de durata de funcționare. Compararea scenariilor de funcționare de 24 de ore/zi, 16 ore/zi și 12 ore/zi evidențiază impactul direct al timpului de funcționare asupra emisiilor și consumului de energie. Analiza consumului de energie confirmă importanța eficienței energetice în reducerea impactului asupra mediului. Studiul propune strategii precum utilizarea materialelor cu impact redus, optimizarea proceselor de producție, implementarea tehnologiilor LED eficiente din punct de vedere energetic și a sistemelor inteligente de control al energiei. Concluziile subliniază necesitatea unei abordări integrate pentru dezvoltarea de produse sustenabile și responsabile din punct de vedere ecologic.*

Abstract. *The paper presents an analysis of the energy consumption and environmental impact of signage panels from a carbon footprint perspective, using the life cycle assessment (LCA) methodology. The study aims to identify the stages that generate the highest* CO_2 *emissions and the opportunities for their reduction. The analyzed stages include raw material extraction and production, manufacturing, transport, and use, considering a representative standard signage panel. The results show that material production contributes the most to both the carbon footprint and total energy consumption, while the use phase becomes significant depending on the operating duration. The comparison of operating scenarios of 24 hours/day, 16 hours/day, and 12 hours/day highlights the direct impact of operating time on emissions and energy consumption. The energy consumption analysis confirms the importance of energy efficiency in reducing environmental impact. The study proposes strategies such as the use of low-impact materials, optimization of production processes, implementation of energy-efficient LED technologies, and intelligent energy control systems. The conclusions emphasize the need for an integrated approach to develop sustainable and environmentally responsible products.*

Keywords: Carbon footprint (CO_2), Energy consumption, Product life cycle, Signaling panels, Sustainability.

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1. Introduction

In recent years, concern for the environment has intensified due to the visible effects of climate change. An important aspect of discussions on pollution and sustainability is the carbon footprint (CO_2 footprint). This represents the total amount of carbon dioxide (CO_2) and other greenhouse gases released into the atmosphere as a result of human activities, ranging from energy production and transportation to the consumption of goods and services. This issue is not limited to the global level, but also affects local communities, public health, and the quality of available natural resources [2].

The CO_2 footprint is an essential indicator for understanding the impact that each individual, company, or country has on the planet. Calculating and reducing this footprint have become global priorities, being directly linked to efforts to combat global warming and the transition toward a sustainable development model [7]. By assessing the carbon footprint, sectors and processes with the greatest impact can be identified, enabling the implementation of targeted measures to reduce emissions and promote a greener economy [8].

In a world where natural resources are limited and the effects of pollution are becoming increasingly evident, awareness of the CO_2 footprint represents an important first step toward responsible environmental behavior [3].

2. Concept and Methodology

The carbon footprint represents the total greenhouse gas emissions, expressed in CO_2 equivalents, associated with a product over its entire life cycle [1]. In this analysis, approximate data and estimates were used, including raw materials, energy consumption during production, transportation, and the annual use of the product, in order to provide a realistic yet indicative assessment of environmental impact.

Fig. 1. Conceptual image of information panel

The objective is to highlight the main emission-generating stages and to identify opportunities for reducing environmental impact [4].

For the purpose of this assessment, estimates were made based on a standard panel (Fig. 1) with typical dimensions and characteristics, considered representative of the type of product analyzed (Table 1).

Table 1. Contribution of Life Cycle Stages to CO_2 Emissions, 24 h/day Operation, 1 Year

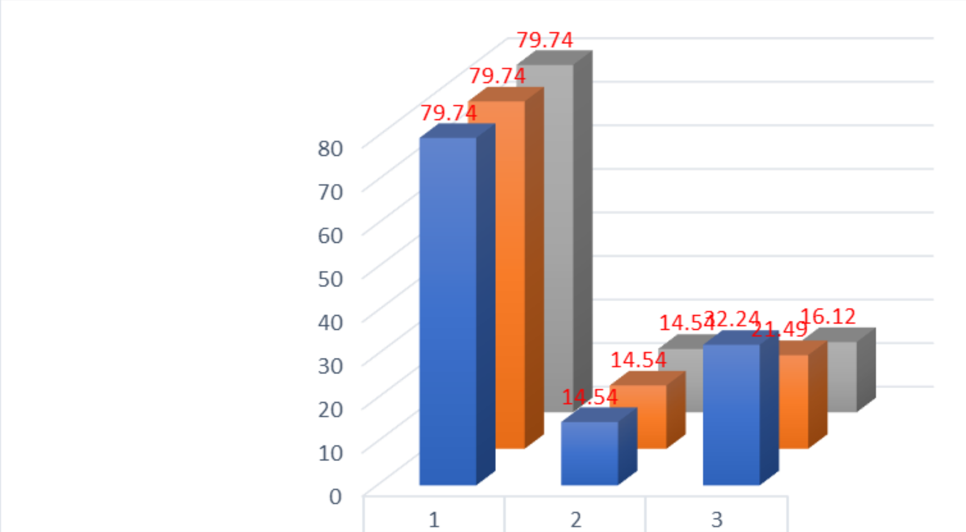
Stages	*Life Cycle Stage*	*Description*	*CO_2e Emissions (kg)*	*Percentage (%)*
1	Raw Material Extraction and Production	Production of Aluminum, Steel, PMMA, LEDs, etc.	79,74	63%
2	Production + Assembly + Transportation	Manufacturing, Finishing, and Delivery Processes	14,54	11,5%
3	Use	LED Strip Operation over One Year	32,24	25,5%
Total			126,52	100%

The following section presents the values corresponding to operating scenarios with reduced durations, namely 16 hours per day and 12 hours per day (Table 2), in order to highlight the impact on CO_2 emissions depending on the intensity and duration of product use. This analysis allows for the comparison of different scenarios and the identification of general trends regarding greenhouse gas emissions.

Table 2. Contribution of Life Cycle Stages to CO_2 Emissions, 12 h/day, 1 Year – 16 h/day, 1 Year

Stages	*Life Cycle Stage*	*CO_2e Emissions 16h/day, 1 Year (kg)*	*Percentage (%)*	*CO_2e Emissions 12h/day, 1 Year (kg)*	*Percentage (%)*
1	Raw Material Extraction and Production	79,74	69%	79,74	72,3%
2	Production + Assembly + Transportation	14,54	12,5%	14,54	13,2%
3	Use	21,49	18,5%	16,12	14,5%
Total		115,77	100%	110,4%	100%

In the Fig. 2 and Fig. 3, the operating time are: blue – 24 h/day, 1 year; orange – 16 h/day, 1 year; gray – 12 h/day, 1 year.



	1	2	3
Extraction and production of materials Production, assemply and transport Use	79.74	14.54	32.24
Extraction and production of materials Production, assemply and transport Use	79.74	14.54	21.49
Extraction and production of materials Production, assemply and transport Use	79.74	14.54	16.12

Fig. 2. CO_2 Emissions (kg) Across Life Cycle Stages by Usage Scenario

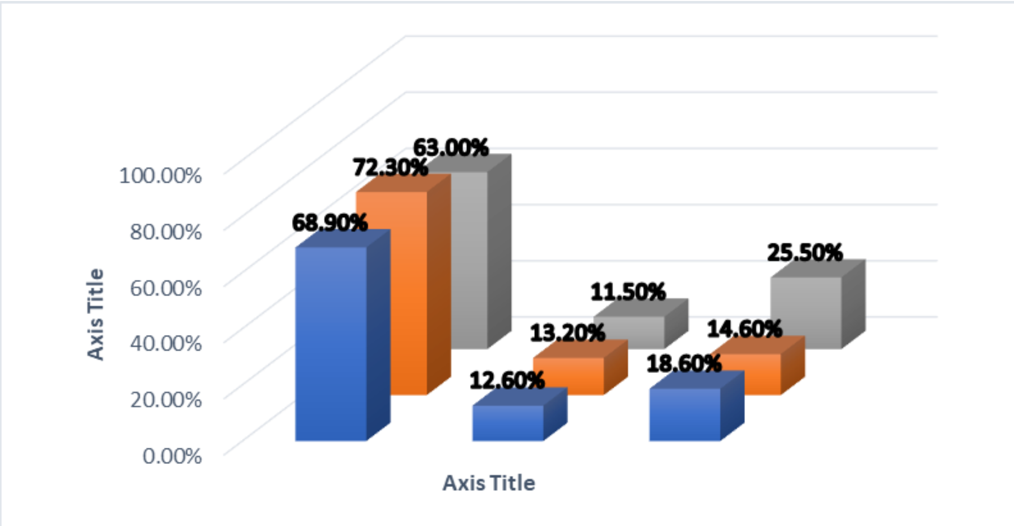


Fig. 3. Percentage Contribution of Life Cycle Stages to the CO_2 Footprint by Usage Scenario

3. Energy Consumption over the Life Cycle

After analyzing CO_2e emissions for each stage of the life cycle, the next step is the assessment of electrical energy consumption (kWh), which provides essential information for understanding the energy efficiency of the product and for identifying the stages with the highest energy demand. The analysis of energy consumption offers a clear perspective on the environmental impact of signage panels, highlighting the contribution of each life cycle stage and the role of operating duration in total energy consumption. Furthermore, this evaluation enables the comparison of different usage scenarios and the implementation of optimization strategies (Table 3 and Table 4).

Table 3. Energy Consumption (kWh), 24 h/day Operation, 1 Year

No.	*Life Cycle Stage*	*Description*	*Consumption (kWh)*	*Percentage (%)*
1	Raw Material Extraction and Production	Production of Aluminum, Steel, PMMA, LEDs, etc.	171,02	66%
2	Production + Assembly + Transportation	Manufacturing, Finishing, and Delivery Processes	18,4	7%
3	Use	LED Strip Operation over One Year	70,08	27%
4	Total		126,52	100%

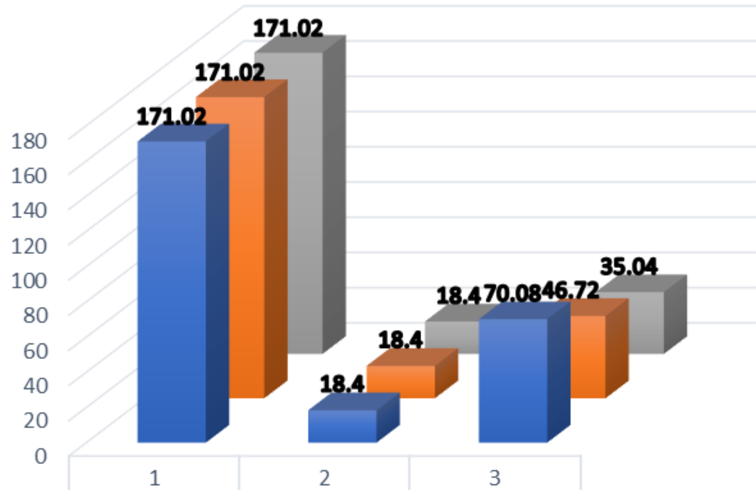
Table 4. Energy Consumption (kWh), 12 h/day – 16 h/day Operation, 1 Year

Stages	*Life Cycle Stage*	*Consumption 16h/day, 1Year (kWh)*	*Percentage (%)*	*Consumption 12h/day, 1Year (kWh)*	*Percentage (%)*
1	Raw Material Extraction and Production	171,02	72,8%	171,02	76,2%
2	Production + Assembly + Transportation	18,4	7,7%	18,4	8,1%
3	Use	46,72	19,5%	35,04	15,7%
Total		236,14	100%	224,46	100%

It can be observed that the duration of use influences the total values across the life cycle stages, meaning that the longer the product operates per day, the greater the contribution of the use phase to overall energy consumption. Therefore, it is highlighted that optimizing operating time or adopting more energy-efficient usage scenarios can significantly reduce environmental impact without affecting product functionality.

The values used to determine both energy consumption and the CO_2 footprint represent estimates based on average factors taken from the specialized literature, combined with direct calculations, in order to obtain an assessment as close to reality as possible.

In the Fig. 4 , the operating time are: blue – 24 h/day, 1 year; orange – 16 h/day, 1 year; gray – 12 h/day, 1 year.



	1	2	3
■ Extraction and production of materials Production, assemply and transport Use (blue)	171.02	18.4	70.08
■ Extraction and production of materials Production, assemply and transport Use (orange)	171.02	18.4	46.72
■ Extraction and production of materials Production, assemply and transport Use (gray)	171.02	18.4	35.04

Fig. 4. Energy Consumption (kWh) Across Life Cycle Stages by Usage Scenario

The resulting graphs from the Fig. 5 facilitate the comparison of different scenarios and highlight the importance of an integrated approach to reducing both energy impact and the product's carbon footprint. These comparisons allow the identification of critical stages in terms of both consumption and emissions, highlighting opportunities for optimization.

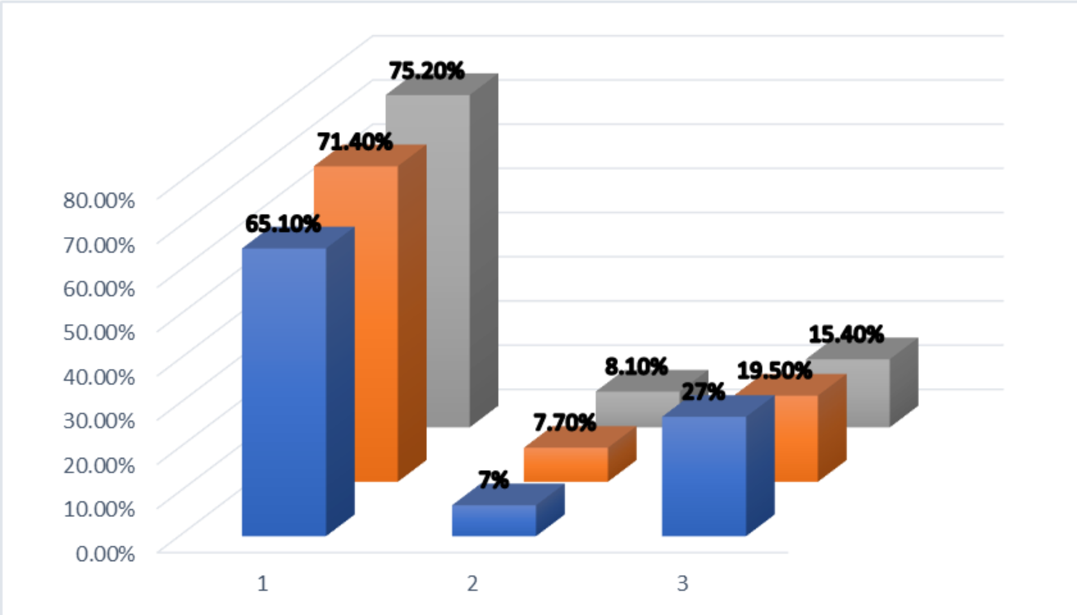


Fig. 5. Percentage Contribution of Life Cycle Stages to Energy Consumption by Scenario

The analysis of energy consumption and the CO_2 footprint shows that each life cycle stage contributes significantly to the total environmental impact, with raw material extraction and production dominating in reduced-use scenarios, while the operational phase emphasizes energy consumption and CO_2 emissions. This clear distribution of contributions allows for the prioritization of impact reduction efforts, focusing both on low-emission materials and the optimization of energy use during operation.

The use of the obtained data enables the identification of critical stages and optimization opportunities, emphasizing the need for integrated decisions regarding materials, design, and product operation. By comparing operational scenarios (24 h, 16 h, and 12 h per day), strategies can be developed that are tailored to different usage conditions, providing alternatives to reduce the carbon footprint without compromising performance.

Specifically, this holistic approach provides a solid basis for sustainable strategies aimed at reducing environmental impact and developing energy-efficient products that are responsible in terms of carbon emissions. In the long term, a general optimization of the product's life cycle can be achieved through improvements in transportation and logistics, waste reduction, increased material recycling rates, and the use of renewable energy sources [6].

4. Strategies for Impact Reduction

To reduce the carbon footprint and energy consumption throughout the product's entire life cycle, an integrated approach is essential. This includes optimizing the materials used by selecting alternatives with lower CO_2 emissions and reduced energy demand, improving production and assembly processes through the use of higher-efficiency technologies, minimizing losses and unnecessary transportation, and implementing sustainable logistics solutions. These measures not only reduce environmental impact but can also generate significant long-term cost savings in production.

Regarding product use, adopting shorter operating scenarios or implementing intelligent energy control systems can significantly reduce direct CO_2 emissions and energy consumption. Additionally, the introduction of LED components and highly efficient electrical systems, as well as promoting modular designs that allow easy replacement of high-impact parts, contributes to reducing the overall impact of the product.

When applied simultaneously across all life cycle stages, these measures enable an optimal balance between performance, energy efficiency, and environmental responsibility. In this way, a sustainable product can be achieved that meets user needs without compromising planetary resources, reducing the overall environmental impact, and supporting sustainable development.

The analysis shows that: Raw materials are the main source of emissions; the extraction and processing of materials involve high energy consumption and generate significant amounts of CO_2, highlighting the importance of selecting materials with a reduced environmental impact.

Product use has a significant impact, influenced by operating duration and energy efficiency. Different usage scenarios demonstrate that reducing operating time or using LED technologies and efficient electrical systems can considerably decrease energy consumption and associated emissions.

Production and transportation processes contribute less but remain relevant for overall life cycle optimization. Even if their share is smaller, improving these stages through cleaner processes, reducing losses, and optimizing transportation routes can provide significant long-term benefits.

CO_2 emission reduction strategies may include: Using recycled or lower-energy-impact materials. Replacing energy-intensive raw materials with sustainable alternatives helps reduce environmental impact without compromising product performance.

Optimizing energy consumption during use. Implementing intelligent control systems and energy-efficient technologies can reduce consumption during the operational phase.

This synthesis, combined with graphical visualization, provides a useful tool for sustainable design decisions, resource management, and environmental reporting. The graphs allow for the rapid identification of critical stages, comparison of operating scenarios, and quantification of the potential benefits of optimization measures. In addition to CO_2 emissions, the product's energy consumption over its life cycle is an essential indicator for assessing environmental impact.

Energy consumption originates from three main sources: Extraction and production of raw materials, which involve energy-intensive processes. This stage includes both the energy required for processing and the energy involved in transporting raw materials to production units. Production, assembly, and transportation of components. Actual product use, whose energy share depends on the duration and mode of operation (e.g., 24 h/day vs. 16 h/day or 12 h/day).

By analyzing energy consumption alongside CO_2 emissions, critical stages and optimization opportunities can be identified, both for reducing carbon impact and for overall energy efficiency. An integrated approach—including sustainable materials, process optimization, and reduced consumption during use—enables the creation of a more environmentally responsible product while maintaining performance and life span [5].

Conclusions

The conducted analysis highlights that the carbon footprint and energy consumption of the product are significantly influenced by material selection, manufacturing processes, and the duration of use (Fig.6).

Raw material extraction and production account for the largest share of environmental impact, while the actual use of the product, depending on operating time, can add a considerable contribution to total energy consumption and CO_2 emissions.

Reduced operating scenarios (16 h/day and 12 h/day) show that optimizing usage duration can help reduce direct impact; however, material- and production-related stages remain critical, emphasizing the need for an integrated approach. Effective strategies include the use of recycled materials, high-efficiency components, modular design, sustainable logistics, and renewable energy.

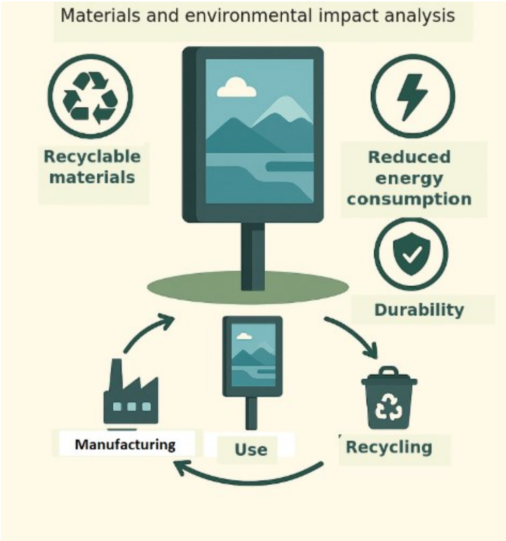


Fig. 6. Overview of analysis for Sustainable Information Panels

Overall, this analysis provides a solid foundation for decision-making regarding the development of sustainable, energy-efficient, and carbon-responsible products, demonstrating that reducing environmental impact requires measures applied across the entire life cycle of the product.

Acknowledgments

This research was carried out within the project: "*Innovation, Research and Construction of the signage production factory*", ID MySMIS 338462, financed by North-East Regional Program 2021-2027; PR/NE/2024/P1/RSO1.1_RSO1.3/1 -RDI projects and SME investments [9].

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