

Sustainability Assessment Using Life Cycle Analysis Applied to the Structural and Aerodynamic Design of a Prototype Vehicle

Evaluación de sostenibilidad mediante análisis de ciclo de vida aplicado al diseño estructural y aerodinámico de un vehículo prototipo

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Abstract

The automotive industry currently faces the challenge of reducing the environmental impact associated with vehicle manufacturing and operation processes, driving the development of methodologies focused on sustainable design and the optimization of material use. In this context, this study evaluated the environmental performance of the structural and aerodynamic components of a prototype vehicle by applying the Life Cycle Assessment (LCA) methodology, using SolidWorks Sustainability as the computational tool. The research was conducted using a "Cradle to Grave" approach, considering the stages of raw material extraction, manufacturing, transportation, use, and final disposal. Two structural configurations for the main chassis were compared: ASTM A36/A500 structural steel and 6061-T6 aluminum alloy. Additionally, the environmental impacts generated by the vehicle's aerodynamic elements were analyzed. The results showed that the use of 6061-T6 aluminum significantly reduced structural weight and lowered energy consumption during the vehicle's operational phase, contributing positively to the reduction of CO₂ equivalent emissions. Furthermore, the environmental analysis revealed significant differences in indicators related to carbon footprint, atmospheric acidification, and cumulative energy demand.

Keywords: life cycle analysis, automotive sustainability, eco-design, SolidWorks Sustainability, sustainable manufacturing, structural materials.

Resumen

La industria automotriz enfrenta actualmente el desafío de reducir el impacto ambiental asociado a los procesos de fabricación y operación vehicular, impulsando el desarrollo de metodologías orientadas al diseño sostenible y a la optimización del uso de materiales. En este contexto, el presente estudio evaluó el comportamiento ambiental de los componentes estructurales y aerodinámicos de un vehículo prototipo mediante la aplicación de la metodología de Análisis de Ciclo de Vida (LCA, Life Cycle Assessment), utilizando como herramienta computacional SolidWorks Sustainability. La investigación se desarrolló bajo un enfoque "Cradle to Grave", considerando las etapas de extracción de materia prima, manufactura, transporte, utilización y disposición final. Se compararon dos configuraciones estructurales para el chasis principal: acero estructural ASTM A36/A500 y aleación de aluminio 6061-T6. De manera complementaria, se analizaron los efectos ambientales generados por los elementos aerodinámicos del vehículo. Los resultados obtenidos evidenciaron que la utilización de aluminio 6061-T6 permitió reducir significativamente el peso estructural y disminuir el consumo energético durante la etapa operacional del vehículo, contribuyendo favorablemente a la reducción de emisiones de CO₂ equivalentes. Asimismo, el análisis ambiental demostró diferencias relevantes en indicadores relacionados con huella de carbono, acidificación atmosférica y demanda energética acumulada.

Palabras clave: análisis de ciclo de vida, sostenibilidad automotriz, ecodiseño, SolidWorks Sustainability, manufactura sostenible, materiales estructurales.

Introduction

Over the past few decades, the sustained growth of the vehicle fleet has significantly increased global energy demand and pollutant emissions resulting from vehicle manufacturing and use, driving the development of technologies focused on sustainability and energy efficiency in the transportation sector (Mayyas et al., 2012). Currently, the automotive industry faces the need to reduce its environmental impact through strategies related to eco-design, structural optimization, and the selection of materials with a lower environmental impact.

The transportation sector is one of the main sources of greenhouse gas emissions globally. Various studies have shown that a significant portion of the environmental impact associated with vehicles is not limited solely to the operational phase but also extends to the stages of raw material extraction, industrial processing, manufacturing, and final disposal of structural components (Hawkins et al., 2013). From this perspective, the integration of environmental assessment methodologies into vehicle design processes has become a priority for the development of more sustainable mobility systems.

In this context, Life Cycle Assessment (LCA) is one of the most widely used methodological tools for comprehensively evaluating the environmental impacts

associated with industrial products and manufacturing processes (Rebitzer et al., 2004). This methodology allows for the quantification of indicators related to pollutant emissions, cumulative energy consumption, atmospheric acidification, and the depletion of natural resources, facilitating decision-making oriented toward sustainable manufacturing and environmental optimization (Hauschild et al., 2018).

At the same time, the use of lightweight materials has gained prominence in modern automotive engineering due to its direct impact on reducing vehicle mass and improving energy efficiency. Recent studies have shown that the use of aluminum alloys and composite materials can significantly contribute to reducing energy consumption and CO₂ emissions during a vehicle's operational phase (Wang et al., 2022).

However, material selection should not be limited exclusively to mechanical or economic criteria but should simultaneously consider environmental variables related to carbon footprint, cumulative energy consumption, and the sustainability of the manufacturing process (Ashby, 2016). From this perspective, computational tools such as SolidWorks Sustainability allow environmental analyses to be integrated directly into computer-aided design stages, facilitating comparative evaluations among different construction scenarios and structural materials (Finkbeiner, 2014).

Recent research on sustainable automotive manufacturing shows that reducing structural weight is a technically viable strategy for decreasing cumulative environmental impacts throughout a vehicle's life cycle (Duflou et al., 2012). Likewise, various studies have established that the transition toward lightweight designs represents a priority trend within modern automotive innovation processes aimed at energy efficiency and the reduction of pollutant emissions (Sullivan et al., 2010).

Consequently, the objective of this research was to evaluate the environmental performance of the structural and aerodynamic components of a prototype vehicle by conducting a comparative life cycle analysis between ASTM A36/A500 structural steel and 6061-T6 aluminum, considering indicators related to carbon footprint, energy consumption, and manufacturing sustainability. In addition, the study sought to determine the influence of structural mass reduction on the overall environmental performance of the vehicle system.

Materials and Methods

The geometric design of the prototype vehicle was carried out using computer-aided design (CAD) tools, taking into account structural, aerodynamic, and functional criteria aimed at weight reduction and energy- e optimization. The three-dimensional model included the vehicle's main mechanical and structural subsystems, including the main chassis, support elements, and external aerodynamic components.

The structural configuration was designed taking into account parameters of mechanical strength, geometric stability, and manufacturability, while simultaneously ensuring adequate safety and operational efficiency. The modeling allowed for the establishment

of precise physical properties—such as mass, volume, and geometric distribution—necessary for subsequent environmental analysis.

Metallurgical Challenges

Welding 6000-series aluminum alloys presents difficulties associated with the natural formation of a surface layer of aluminum oxide (Al_2O_3), which has a melting point considerably higher than that of the base metal. This characteristic can affect the proper bonding of the material during the welding process, leading to defects such as porosity and inclusions in the joint if not properly controlled (Bachmann et al., 2025).

Life Cycle Assessment Methodology

The environmental assessment was conducted using the Life Cycle Assessment (LCA) methodology, implemented through the SolidWorks Sustainability software module. The study was structured using a “Cradle to Grave” approach, comprehensively considering the stages of raw material extraction and processing, manufacturing, transportation, operational use, and final disposal of the vehicle system (Rebitzer et al., 2004).

Regulatory Symbolology

The environmental analysis incorporated indicators associated with:

- carbon footprint;
- cumulative energy consumption;
- atmospheric acidification;
- eutrophication;
- air and water pollution.

The environmental database integrated into the software made it possible to estimate equivalent impacts by considering actual industrial processes associated with each evaluated material (Hauschild et al., 2018).

Standard Symbolology (ASME Standard)

Plant engineering is based on ASME graphical standards to standardize the representation of industrial processes using universal symbols. This methodology uses geometric figures to identify operations, inspections, transport, delays, and storage within the manufacturing system. Its application allows for a clear visualization of the production flow, facilitating the detection of inefficiencies and opportunities for improvement in the industrial process (Citti et al., 2021).

Figure 1. Symbols according to the ASME–ISO standard

Actividad	Símbolo	Descripción
Operación		▪ Indica las principales fases del proceso, método o procedimiento.
Inspección		▪ Indica que se verifica la calidad y/o cantidad de algo.
Transporte		▪ Indica desplazamiento o movimiento de empleados, material y equipo de un lugar a otro.
Espera		▪ Indica demora en el desarrollo de los hechos.
Almacenamiento		▪ Indica el deposito de un documento o información dentro de un archivo, o de un objeto cualquiera dentro de un almacén.

Source: Adapted from Diagrams for Analyzing and Planning Production, by L. Magallanes Ríos, n.d., EPT (<https://ept.pe/index.php/component/sppagebuilder/?view=page&id=90>).

Geometric Discretization (Mesh Generation)

Geometric discretization and mesh convergence are fundamental factors in finite element analyses applied to complex mechanical structures. Recent research shows that mesh quality and refinement directly influence the accuracy of results, especially in the prediction of stresses and strains. Furthermore, the use of optimized meshes improves numerical stability and computational efficiency during structural simulations (Wobbes et al., 2024; S. Wang et al., 2025; Haider, 2024).

Structural Evaluation Scenarios

To compare the environmental performance of the structural system, two main configurations were established.

Scenario 1: ASTM A36/A500 structural steel

This is the base model conventionally used in automotive structural applications due to its high mechanical strength, commercial availability, and relatively low cost. This material has a wide range of industrial applications due to its mechanical properties and ease of manufacturing (Ashby, 2016).

Scenario 2: 6061-T6 Aluminum Alloy

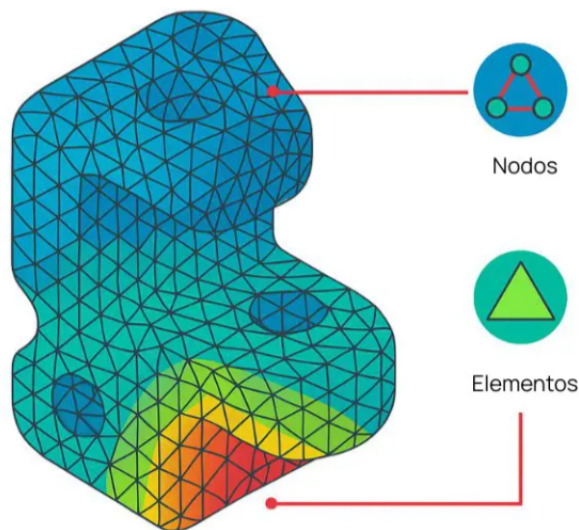
Proposed configuration aimed at reducing structural weight and improving energy efficiency through the use of lightweight materials with high specific strength. Various studies have shown that aluminum alloys can significantly reduce vehicle weight and improve environmental performance during the operational phase (Wang et al., 2022).

In both scenarios, the model's geometric conditions were kept constant to ensure comparability of results and minimize variations associated with external factors.

Types of Finite Elements

Tetrahedral elements are widely used in the finite element method to model complex three-dimensional structures. Their main advantage lies in their ability to adapt to irregular geometries, allowing for efficient discretization of volumes. Furthermore, recent studies highlight improvements in their numerical accuracy, stability, and convergence through advanced formulation and computational integration techniques (Pasternak et al., 2024; Xie & Zhang, 2024).

Figure 2. Tetrahedral



González, E. (July 4, 2025). Finite Element Method: A Cornerstone of Engineering 4.0. Structuralia. <https://blog.structuralia.com/metodo-de-elementos-finitos>

Results

The results obtained revealed significant differences among the materials analyzed. The model fabricated from 6061-T6 aluminum exhibited a considerable reduction in structural mass compared to ASTM A36/A500 steel, yielding positive effects on the vehicle's overall energy performance.

The weight reduction made it possible to lower the energy demand associated with the prototype's operation during its operational phase, while simultaneously contributing to a reduction in carbon dioxide equivalent emissions.

In environmental terms, the analysis showed that structural steel had higher impact values in categories related to:

- CO₂ emissions;
- cumulative energy consumption;
- atmospheric acidification;
- indirect generation of industrial pollutants.

On the other hand, aluminum demonstrated significant advantages during the operational phase due to the reduction in the total mass of the vehicle system, although its initial processing required higher energy inputs during manufacturing.

Results of the Aerodynamic Fairing

The environmental assessment of the aerodynamic components made it possible to identify the effect that material selection has on the overall performance of the prototype vehicle. The results obtained using SolidWorks Sustainability showed that the materials used in the bodywork directly influence the total mass of the system, energy efficiency, and emissions associated with the vehicle's life cycle.

The analysis showed that the incorporation of lower-density materials contributed positively to reducing total weight, simultaneously decreasing aerodynamic drag and energy requirements during the operational phase. This factor is a key aspect of sustainable design, as even small reductions in mass can lead to significant cumulative decreases in energy consumption over the long term.

Additionally, the environmental indicators associated with the bodywork revealed significant differences in categories related to carbon footprint, cumulative energy consumption, and acidification potential. Although certain composite materials involve energy-intensive manufacturing processes, their operational benefits partially offset the initial impacts resulting from production and industrial processing.

From an engineering standpoint, the optimized aerodynamic design improved the vehicle's efficiency by reducing drag forces during travel, leading to more efficient performance from both an energy and environmental perspective.

Carbon Footprint and Cumulative Energy Demand

The comparative carbon footprint analysis showed that the structural configuration based on 6061-T6 aluminum resulted in lower equivalent CO₂ emissions during the operational phase compared to the model made of structural steel. The reduction in mass allowed for a decrease in the energy required to move the vehicle, generating cumulative environmental benefits throughout its service life.

Regarding cumulative energy demand, steel required less energy during the initial industrial processing phase; however, aluminum offered significant advantages during operational use due to the improved energy efficiency associated with weight reduction.

The results indicate that the selection of lightweight materials constitutes a technically viable strategy for reducing environmental impacts within the automotive sector, especially in scenarios focused on sustainable mobility and the reduction of pollutant emissions.

Table 1. *Scenario Indicators*

Impact Indicator		Scenario A: ASTM A36 Steel	Scenario B: Aluminum 6061-T6	Variation (%)
Chassis Mass		30.25 kg	10.40 kg	-65.6% (Reduction)
Carbon Footprint		79 kg CO ₂	150 kg CO ₂	+89.8% (Increase)
Total Energy Consumed		1,000 MJ	1,900 MJ	+90.0% (Increase)
Atmospheric Acidification		0.271 kg SO ₂	1.0 kg SO ₂	+269% (Increase)
Water Eutrophication		0.080 kg PO ₄	0.034 kg PO ₄	-57.5% (Decrease)

Source: SolidWorks Sustainability

Prepared by: Authors, 2026

The results obtained in this study are consistent with various recent studies related to automotive sustainability and life cycle analysis applied to vehicle systems. Research published in the *Journal of Cleaner Production and Sustainability* has shown that the incorporation of lightweight materials into automotive structures can significantly reduce emissions generated during the operational phase of vehicles.

The reduction in structural mass observed through the use of 6061-T6 aluminum is consistent with the findings of studies focused on lightweight design, which establish that reducing vehicle weight is one of the most influential factors on energy efficiency and the reduction of greenhouse gas emissions.

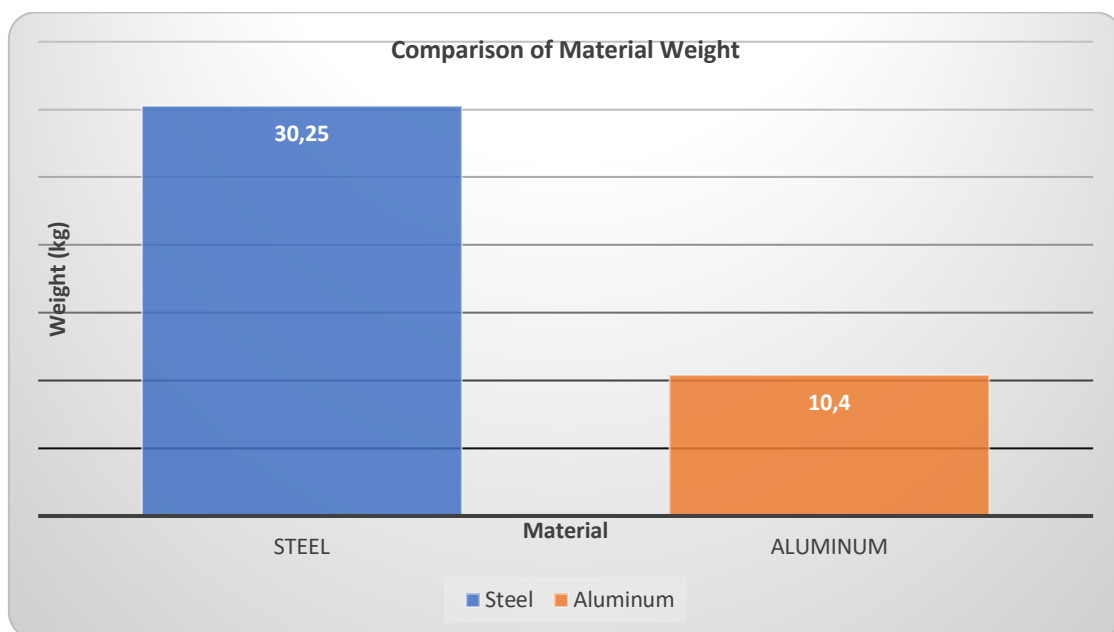
Furthermore, the results obtained demonstrate that automotive sustainability does not depend exclusively on the operational phase, but rather on the system's overall performance throughout its entire life cycle. In this regard, although aluminum requires greater amounts of energy during extraction and refining processes, its operational performance partially offsets these impacts due to reduced energy consumption during vehicle use.

Furthermore, the analysis conducted using SolidWorks Sustainability enabled the integration of environmental variables directly into the computer-aided design process, facilitating the simultaneous comparison of structural performance and environmental sustainability. This integration represents a significant advantage in modern automotive engineering processes, where design decisions must simultaneously consider mechanical, economic, and environmental variables.

Compared to previous research on vehicle eco-design, this study provides an integrated assessment of structural and aerodynamic components using a full life-cycle approach, enabling the identification of material selection criteria geared toward sustainable manufacturing and energy efficiency.

Finally, the results demonstrate that the transition to lightweight materials and environmentally optimized design processes constitutes a viable strategy for contributing to the development of more sustainable mobility systems, especially in scenarios where environmental regulations increasingly demand lower pollutant emissions and greater energy efficiency. objectives or research questions posed in the introduction.

Figure 3. Comparison of chassis mass: Steel vs. Aluminum



Source: SolidWorks Sustainability

Conclusions

The application of the Life Cycle Assessment methodology allowed for a comprehensive evaluation of the environmental performance of the prototype vehicle's structural and aerodynamic components, identifying significant differences among the materials analyzed.

The use of 6061-T6 aluminum offered significant advantages related to reduced structural mass, improved energy efficiency, and lower equivalent CO₂ emissions during the vehicle's operational phase.

The results demonstrated that material selection directly influences environmental indicators associated with carbon footprint, cumulative energy consumption, and

atmospheric acidification, highlighting the importance of incorporating sustainability criteria during the initial stages of automotive design.

The use of computational tools such as SolidWorks Sustainability facilitated the integration of environmental variables into the computer-aided design process, enabling the development of comparative assessments aimed at sustainable manufacturing and energy optimization.

Finally, it is concluded that the implementation of eco-design and lightweight design strategies represents a technically viable alternative for contributing to the development of more sustainable and environmentally efficient mobility systems within the contemporary automotive industry. Key points presented in the document.

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