

 Ingeniería e Industria	A MORE SUSTAINABLE SCOOTER APPROACH USING NATURAL COMPOSITE MATERIALS	TECNOLOGÍA DE MATERIALES
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A MORE SUSTAINABLE SCOOTER APPROACH USING NATURAL COMPOSITE MATERIALS

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DOI: <https://doi.org/10.52152/D11496> | Recibido: 18/jul/2025 • Inicio Evaluación: 21/jul/2025 • Aceptado: 31/oct/2025

To cite this article: RANZ, David; MARTÍN-COMPAIRED; PINA, Carmelo; MIRALBES, Ramon; BARBURSKI, Marcin; GÓMEZ, José A. A MORE SUSTAINABLE SCOOTER APPROACH USING NATURAL

COMPOSITE MATERIALS. DYNA January February 2026. Vol. 101, n.1, pp. 76-80 | DOI: <https://doi.org/10.52152/D11496>

ABSTRACT:

Electric scooters have become a key element of urban mobility in recent years, offering an efficient, sustainable and agile alternative for city transport. They are powered by electric motors powered by lithium-ion batteries, allowing them to reach speeds of between 20 and 40 km/h with a range of up to 40 km. Factors such as increasing traffic congestion, the need to reduce carbon emissions and the support of legislation in many cities have accelerated the growth of their use and integration into the transport ecosystem. In terms of structure, conventional electric scooters are mainly made of aluminium alloys, which makes them heavy products, detracting from their autonomy. This work proposes the use of natural composite materials to achieve a lighter solution, with a structural performance similar to current proposals. In this way, sustainable solutions will be achieved with a reduction in mass that not only facilitates their transport and manoeuvrability, but also reduces the energy demand of the motor, which contributes to lower electricity consumption and greater battery autonomy. In addition, a manufacturing system using direct generation of 3D printing moulds is proposed. This technology allows to reduce costs, development times and environmental impact through the use of recyclable materials and energy efficient manufacturing processes. The environmental impacts of the different configurations (current and proposed) are analyzed under IPCC 2013 GWP 100a v1.03 methodology. The phases of the scooter's life cycle that are most sensitive to the proposed natural composite materials are also explored in depth. The Life Cycle Analysis (LCA) methodology will be used to carry out the environmental study.

Keywords: Scooter, Natural Composites, Sustainability, Life Cycle Analysis, Urban Mobility.

FUNDING

The research work shown in this publication was made in the framework of the SustDesignTex project (Nº 101079009 — HORIZON-WIDERA-2021-ACCESS-03). The authors would like to thank also to the INGEGRAF association.

1. - INTRODUCTION

In the current landscape of urban mobility, electric scooters have emerged as an increasingly popular form of individual transportation. Their ease of use, low physical demand, zero emissions, and high efficiency for urban travel have made them an attractive and sustainable micromobility alternative for a broad demographic. In Spain, this impact is particularly notable, as it ranks among the countries with the highest number of users in Europe. According to the Brand Tracker report conducted by Tier Mobility, Spain is the second most welcoming European country to electric scooter use, following only Poland [1].

On the other hand, due to rising fuel prices, restrictions on the circulation of non-ECO-labeled private vehicles in certain Spanish cities, and growing environmental awareness, many users have been influenced to choose more sustainable and economical modes of transportation. Consequently, there has been a significant increase in demand for these kinds of vehicles, both from individual users and companies specializing in scooter rentals. In fact, according to the Spanish Federation of Personal Mobility Vehicles, there are over 700,000 electric scooters currently in circulation in Spain [2].

This surge in popularity has led to ongoing advancements in their design and manufacturing, aiming to optimize critical aspects such as range, utility, and manoeuvrability through structural weight reduction.

From an environmental perspective, one of the main concerns associated with electric scooters lies in the materials used for manufacturing their chassis or platform, which are typically aluminium alloys known for their strength and lightness. The extraction and

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processing of aluminium are energy- and resource-intensive processes. Aluminium production requires the extraction of bauxite, followed by an electrolysis process that consumes vast amounts of electricity, typically derived from non-renewable sources [3, 4]. Finally, the structural profiles of the platform are formed through extrusion, a process that also demands high energy input. These steps collectively contribute significantly to environmental degradation and greenhouse gas emissions. Moreover, the production of aluminium alloys involves additional metals such as copper and zinc, whose own extraction and refinement processes further exacerbate the environmental impact [3].

The objective of this study is to develop a new scooter platform constructed using sustainable composite materials, incorporating natural reinforcements and cores, along with bio-based resins. Specifically, flax fibers [5], bioepoxy resin [6], and cork core [7, 8] are proposed. These natural reinforcements have already been studied and mechanically characterised for other applications in both the transport sector [9, 10] and the sports field [11]. Additionally, the moulds for manufacturing will be produced directly through 3D printing, aiming to reduce costs, development time, and environmental impact through the use of recyclable materials and low energy manufacturing processes. This new platform must comply with the structural requirements defined by the UNE-EN 17128:2020 standard, "Light motorized vehicles for the transportation of persons and goods and related facilities not subject to road homologation" [12]. Accordingly, the design will be constrained by the material and manufacturing process limitations, followed by finite element numerical simulations to optimize material configuration, thicknesses, and fiber orientations.

To validate the simulation results and assess the feasibility of using 3D-printed moulds, a prototype will be fabricated and tested alongside a traditional scooter platform made of 6061 T6 aluminium alloy, in order to compare their mechanical performance.

Finally, a comparative life cycle assessment (LCA) was conducted for both electric scooter platforms. Using the IPCC 2021 GWP 100a methodology and modelling with SimaPro 9.6.0.1 and data from Ecolnvent v3.10, the carbon footprint was quantified under cradle-to-gate system boundaries [4, 13]. Results indicate that the natural composite platform can reduce the carbon footprint by up to four times compared to aluminium, with raw material production being the most impactful stage. While aluminium's recyclability offers potential mitigation, natural composites provide advantages in biodegradability but face challenges in recycling. This preliminary study highlights the importance of conducting more LCAs using primary data and cradle-to-grave approaches, emphasising ecodesign to improve environmental sustainability.

2. - SCOOTER PLATFORM DEVELOPMENT

2.1.- DESIGN

Design plays a crucial role in the development of efficient and safe electric scooters. Specifically, in the design of the platform, a balance must be achieved between the structural integrity required to meet safety standards and weight reduction to enhance energy efficiency and portability. Furthermore, the advantages and limitations of additive manufacturing, as an innovative technique, must be taken into consideration for the design of the moulds used in the platform's production.

In this context, the exploration of natural composite materials—which combine mechanical advantages with environmental benefits—emerges as a promising solution. In this case, a sandwich type structure will be employed, consisting of two rigid skins made of flax fiber and bioepoxy resin, bonded to a core (Fig. 1-right). Cork has been selected as the core material due to its natural origin. This solution offers an excellent stiffness-to-weight ratio.

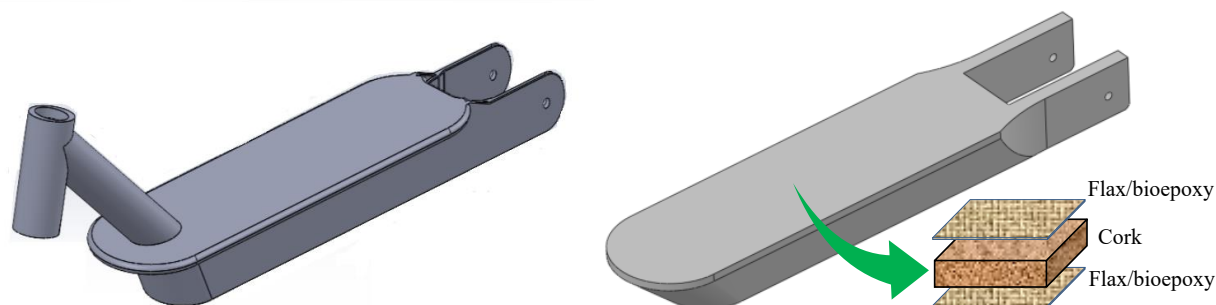


Fig. 1. Scooter platforms: left) Xiaomi Mi Electric Scooter 3; right) Sustainable solution.

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The Xiaomi Mi Electric Scooter 3 model will be used as the reference model (Fig. 1-left), thereby providing a baseline geometry for the platform with dimensions of 700 mm in length, 150 mm in width, and 70 mm in height. This approach enables a direct comparison between the results obtained and those of the prototype subsequently manufactured using composite materials.

2.2.- NUMERICAL ANALYSIS

The software used for structural analysis was SW Simulation, which allows static mechanical analyses to be performed using the finite element method. This analysis will follow the test procedure described in Section 12.2.1.2 of the UNE-EN 17128:2020 standard, which consists of "Progressively applying a mass of 1 kN or, where greater, a mass equal to the maximum permissible payload indicated on the vehicle, multiplied by a safety factor of 2.5, for 1 minute using a flat device with a contact surface of 100 mm × 100 mm positioned at the center of the floor."

To this end, an initial model of the Xiaomi scooter platform is developed in order to obtain a reference value for vertical displacement, which will serve as a bench-mark for the optimization of the sustainable platform. This model employs the material properties of the platform's constituent material, 6061 T6 aluminium alloy. The model is discretized into a total of 210,000 solid quadratic integration elements (Fig. 2-left). For an applied load of 1 kN, a maximum vertical displacement of 0.7 mm is obtained, which will serve as the target during the optimization process of the sustainable platform.

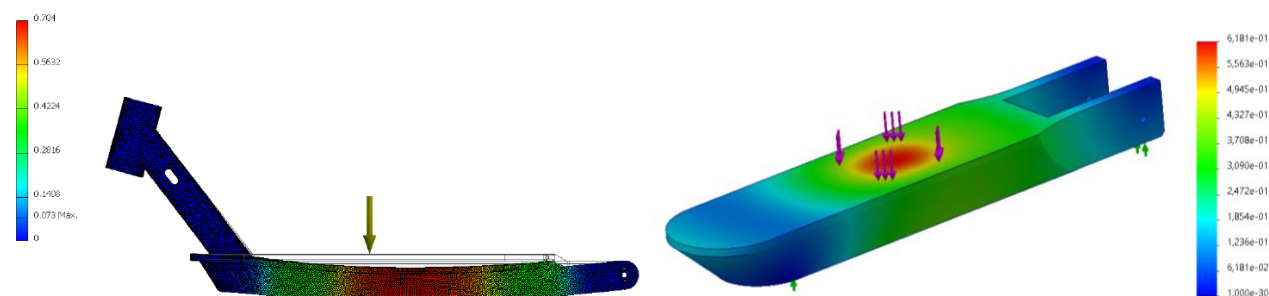


Fig. 2. Vertical displacement: left) Xiaomi Mi Electric Scooter 3; right) Sustainable solution.

For the optimization of the platform using natural materials, a mould is constructed comprising 7,526 shell elements for the flax fiber/bioepoxy resin skins, which form the external structure, and 35,112 solid elements for simulating the internal cork core (Fig. 2-right). The adopted solution, which achieves stiffness values comparable to the aluminium-based counterpart, consists of 7 mm-thick skins on the top and bottom surfaces of the scooter. These skins are composed of 6 mm of unidirectional flax fiber and 1 mm of biaxial flax fabric. Meanwhile, the vertical walls of the scooter platform have a thickness of 3 mm, consisting of 2 mm of unidirectional fiber and 1 mm of biaxial fiber.

2.3.- MANUFACTURING

2.3.1.- Mould manufacturing

The prototype mould will be produced using additive manufacturing with polylactic acid (PLA) on a Crealty K1 FDM printer. PLA was selected as the mould material due to its nature as a biodegradable thermoplastic polymer derived from corn starch. It exhibits favourable mechanical and processing properties, making it a viable alternative to petroleum based polymers. Due to the limited build volume of the FDM printer bed, the mould was divided into three sections, along with an insert for the rear area. The three mould sections will be joined using dovetail joints and further bonded with a two component epoxy adhesive (Fig. 3). Prior to assembly, the sections undergo sanding to improve the surface finish in areas that contact the part and to enhance adhesion at the joint interfaces.

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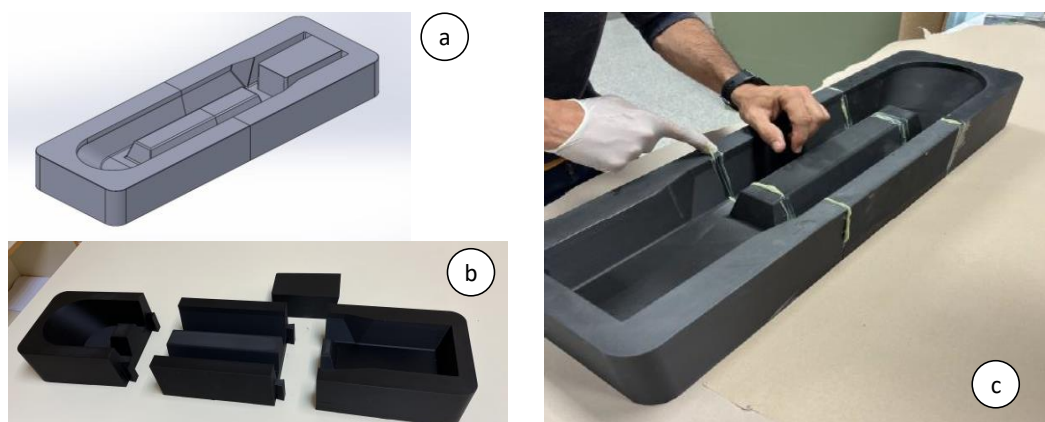


Fig. 3. Mould manufacturing: a) 3D model; b) printed parts; c) mould assembly.

2.3.2.- Prototype manufacturing

The fabrication of the prototype requires prior preparation of the constituent materials. The cork core is precisely machined and divided into several pieces to ensure a proper fit between the mould and the core, allowing the required thickness of the fabric layers to be achieved and preventing excess resin accumulation. The unidirectional (UD) and biaxial fabric patterns are also cut to match the thickness determined by the numerical simulation.



Fig. 4. Prototype manufacturing steps a) Material cutting; b-c) wet lay-up; d) vacuum compaction.

Subsequently, manual wetting of the fabrics is performed using the Greenpoxy resin system (Sicomin), and the fabrics are placed inside the mould, fully enclosing the cork core. The upper section is covered with a peel ply and a breather fabric; the former facilitates the removal of the breather, while the latter ensures uniform vacuum distribution. The vacuum is applied by sealing the assembly with a nylon bag affixed to a lower plate using tacky tape. A vacuum pump is used to remove excess resin and achieve compaction under a pressure of 1 bar (Fig. 4-d).

Under these conditions, the part is cured in an oven at 60 °C for 4 hours. Finally, the prototype is demoulded and subjected to a post-curing cycle in the oven at 80 °C for an additional 4 hours. Fig. 5 shows the final prototype, where surface imperfections can be observed due to excessive exothermic reaction, which damaged the mould.

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Fig. 5. Flax fiber/bioepoxy prototype.

2.3.- TESTING AND RESULTS

For the real testing, the same conditions as those in the simulation are applied according to the UNE-EN 17128:2020 standard, with a load ranging from 3 to 4 kN applied to a square surface of 100 mm per side, with a support distance of 540 mm. Additionally, a similar load is applied in a four-point bending test, using the same support distance and a 180 mm roller spacing. In both cases, the load is applied at a speed of 1.5 mm/min using an Instron model 8032 universal testing machine, which records the applied load and displacement values (Fig. 6.- left and mid).

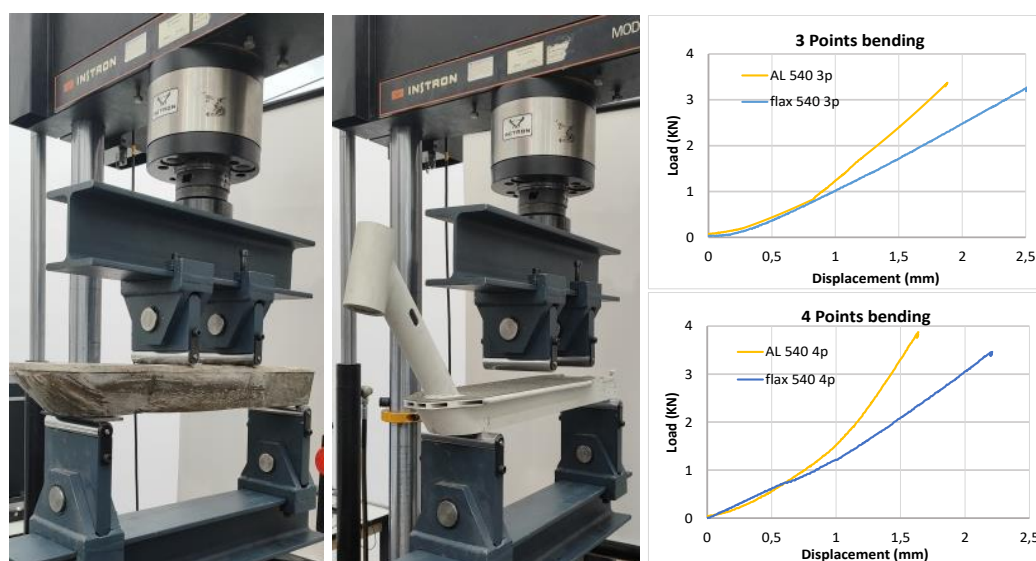


Fig. 6. Bending testing: left) Flax platform; mid) Xiaomi; right) results 3 and 4 points.

As shown in Fig. 6-right, both scooters exhibit similar behavior up to a load of 1 kN, with a displacement of 1 mm. Beyond this load, the flax/bioepoxy scooter demonstrates a more flexible response. No signs of failure were observed in any of the tests, as established by the standard [12]. Furthermore, a high safety factor is evident, as the load achieved exceeds three times that established in the standard [12]. For a load of 3.3 kN in the three-point bending test, the displacement is 1.8 mm for the aluminium scooter, compared to 2.5 mm for the flax/bioepoxy scooter. Therefore, although the sustainable solution is slightly more flexible, it demonstrates good mechanical performance and could serve as an alternative to the conventional aluminium platform.

3. – LIFE CYCLE ANALYSIS

In the context of increasing concern for sustainability and the need to reduce the environmental impact of products, Life Cycle Assessment (LCA) emerges as a fundamental tool for evaluating the environmental burdens associated with a product throughout all

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stages of its life cycle, from raw material extraction to final disposal. This section aims to conduct a comparative LCA of two electric scooter platforms, whose designs have been previously described. The comparison will focus on the Carbon Footprint, using the IPCC 2021 GWP 100a methodology, in order to quantify and contrast the global warming potential associated with each of the proposed solutions: one platform manufactured from 6061 T6 aluminum alloy and the other constructed from natural composite materials. Although other studies have already compared the environmental impact of different composite materials for a similar application [9], this environmental analysis aims to complement the other technical assessments presented above.

3.1.- OBJECTIVE AND SCOPE

The primary objective of this Life Cycle Assessment (LCA), as defined by ISO 14040 and ISO 14044 standards [14, 15], is to compare the Carbon Footprint of an electric scooter platform manufactured from 6061 T6 aluminum alloy against a functionally equivalent platform designed and fabricated using a natural composite sandwich structure (comprising flax fiber skins, bioepoxy resin, and a cork core).

3.2.- FUNCTIONAL UNIT AND SYSTEM BOUNDARIES

The functional unit is defined as an electric scooter platform capable of meeting the structural requirements established by the UNE-EN 17128:2020 standard.

The system boundaries for this study encompass cradle-to-gate stages, including raw material extraction, processing, and transportation, as well as the manufacturing processes involved in the production of the scooter platform. Energy consumption associated with the manufacturing processes will be taken into account. The use phase and end-of-life stage of the scooter are excluded from the scope of this initial analysis, although their potential implications will be discussed qualitatively.

3.3.- SOFTWARE, DATABASES AND IMPACT CATEGORIES

Inventory data were sourced from the Ecoinvent v3.10 database. In accordance with its market (GLO) criteria, datasets have been used to account for the transportation of raw materials from average global suppliers to the alloy manufacturing facility. The LCA was modeled using SimaPro 9.6.0.1, and the selected impact assessment methodology is IPCC 2021 GWP 100a [16]. This method is also widely employed due to its societal relevance, as it aligns with global efforts to reduce greenhouse gas (GHG) emissions. Another methodology widely used is ReCiPe 2016 [17], which evaluates 17 weighted impact categories grouped into three endpoint categories: damage to human health, damage to the ecosystem and increased resource costs, with the aim of obtaining a single score. This single score allows for easy interpretation of the results, however, the weighting used to obtain it means that the uncertainty of these data is high.

3.4.- LIFE CYCLE INVENTORY

The inventory of the main materials and processes considered for each of the scooter platforms is detailed below. The data have been compiled based on the design descriptions. For the platform made of aluminum 6061 T6, the AlMg3 aluminum alloy from the Ecoinvent database has been selected, as it contains 3% magnesium and is otherwise compositionally similar to the 6061 alloy. The weight of the aluminum platform is 7.120 kg. Given the preliminary nature of this analysis and the lack of specific inventory data for the large-scale manufacturing of the composite scooter platform, several estimations have been made, and the sources of generic data used are indicated accordingly (Table 1). European flax fibers—both long and short—available in the Ecoinvent database were selected.

Material	Weight
Flax fibers	1.141 kg
Epoxy resin	1.037 kg
Cork slab	2.425 kg
Consumables	Weight
Vacuum bag nylon	0.0285 kg
Peel ply polyester	0.015 kg
LDPE tube for vacuum	0.0487 kg

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Sealing tape, aluminium/PE 50mm wide	0.1305 kg
Total	4.826 kg

Table 1. Weight of sustainable platform.

3.4.- LCA RESULTS

Following the implementation of the life cycle inventories in SimaPro 9.6.0.1 and using data from the Ecoinvent v3.10 database, the environmental impacts associated with both design alternatives were quantified (Table 2). This study demonstrates that natural composite materials contribute to reduce up to 4 times the environmental impact in carbon footprint compared to the aluminum platform. Breaking the result down on the different stages of the process included in the inventory is possible to know each process's contribution to the complete impact (Table 2). The most significant contribution is associated with raw material production, which constitutes the largest share of the total impact in both cases.

IPCC [kg CO ₂ eq.]	Aluminium	Natural Composite Materials
Material production	54.1	13.8
Manufacturing processes	2.4	0.2
Total	56.5	14

Table 2. IPCC [kg CO₂eq.] phases of one scooter platform.

The production of aluminum alloy represents the phase with the most significant contribution to the Carbon Footprint of the aluminum platform, primarily due to the high electrical energy consumption associated with alumina electrolysis. However, aluminum is highly recyclable, which could potentially mitigate its initial impact. Conversely, natural composite materials offer advantages in terms of biodegradability or lower toxicity compared to certain materials; nevertheless, the recyclability of composites is more complex.

4. – CONCLUSIONS

The development of an electric scooter platform was approached through a comprehensive and integrative methodology, encompassing material selection, technical design validation via numerical simulations, prototyping, experimental testing, and environmental impact assessment. The structural optimization process, guided by the UNE-EN 17128:2020 standard, allowed for the validation of a natural composite sandwich structure—comprising flax fiber skins with bioepoxy resin, and a cork core—as a viable alternative to traditional aluminium-based solutions. The prototype, manufactured using additive techniques for mould creation and vacuum-assisted hand layup, exhibited mechanical performance within acceptable safety margins, despite increased flexibility compared to the aluminium benchmark. Moreover, the Life Cycle Assessment (LCA), conducted using SimaPro and Ecoinvent datasets under the IPCC 2021 GWP 100a framework, revealed that the natural composite platform could achieve a reduction of up to four times in carbon footprint relative to its metallic counterpart. These findings highlight the critical importance of adopting a holistic engineering approach—integrating structural, manufacturing, and environmental considerations—to enable the design of mobility solutions aligned with ecodesign strategies [18].

This initial study also underscores the need for more detailed and comprehensive life cycle assessments, incorporating primary data specific to real manufacturing processes and extending the analysis to a cradle-to-grave scope. Additionally, other sustainability requirements—such as design for durability, reparability, and extended service life—will be essential to further minimize environmental impact across the full product lifecycle.

In future work, it is expected that a more comprehensive development and analysis will be carried out to include all parameters influencing the life cycle of this product.

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