

Article

Integrating Circularity Micro-Indicators into Automotive Product Development to Evaluate Environmental Trade-Offs and Guide Sustainable Design Decisions

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Abstract

This study explores the integration of circular design principles into automotive product development, focusing on the environmental implications of design decisions related to geometry, material selection, and assembly methods. A case study approach was used to iteratively redesign a plastic automotive component, incorporating structural reinforcements and glass fiber (GF) to enhance performance. While these changes improved mechanical properties, they negatively impacted recyclability due to increased material heterogeneity and irreversible assembly using ultrasonic welding. Circularity performance was evaluated using the Recycling Desirability Index (RDI), Material Circularity Indicator (MCI), and circular design guidelines (CDGs). Despite achieving 20% recycled content, recyclability remained limited. Alternative design strategies—such as eliminating GF, replacing welding with mechanical fasteners, and enabling take-back systems—led to significant improvements in circularity scores. Notably, MCI analysis indicated that energy recovery pathways offered better circularity outcomes than landfilling. The findings highlight the importance of early-stage material standardization and assembly planning to enhance end-of-life recovery. This study underscores the environmental trade-offs inherent in current automotive design practices and calls for stronger collaboration between engineers, designers, and sustainability experts to align product development with circular economy goals. Findings emphasize the need for systemic changes in product development processes and industrial mindsets, including overcoming resistance to design modifications and fostering cross-departmental collaboration, to effectively implement circular economy principles in the automotive sector.



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1. Introduction

Increasingly, regulations, customers, and even consumers demand more sustainable products [1]. The mass production of products from virgin raw materials consumes vast natural resources, accelerating scarcity [2]. To address this, the European Commission recommends minimizing virgin material and energy use, reducing waste, and rethinking design, production, and end-of-life strategies to reinforce circularity [3–5].

Implementing circular economy principles can reduce environmental, social and economic impacts by slowing, reducing, and closing material and energy cycles [6]. However, adoption remains slow due to resistance from companies, investors, and policymakers [7,8].

This underlines the need for flexible policy approaches that accommodate sector diversity and local contexts, promoting ecological innovation [9].

Accelerating this transition requires designing products that reduce environmental impact, promote social responsibility, enhance resource efficiency, strengthen competitiveness, and comply with regulations [10]. Designing for longevity, repair, reuse, remanufacturing, and recycling closes material and product life cycles [11]. Key considerations during planning include replacing hazardous materials, reducing water and energy use, minimizing waste in production and distribution, and facilitating disassembly and recycling [12].

Although sustainability integration in product development has been discussed for over 20 years, few works link sustainability with traditional product development or offer tools to support sustainable decision-making [13,14]. Many companies still follow traditional cost–profit models, treating sustainability as an add-on, which hinders effective implementation [15]. Including a sustainability specialist in product development is crucial to ensure the effective integration of sustainability principles and expertise into environmental regulations. This role guides material selection, circular design, recyclability, and waste minimization throughout the product life cycle [16–18]. Moreover, fostering stakeholder engagement across the value chain aligns expectations and supports collaborative innovation [19].

Monitoring the economic, environmental, and social effects of product development actions is essential [20–22]. Decision-making tools like circularity micro-indicators evaluate circular practice implementation in products and processes, helping identify improvements such as material substitution, redesign, or recycled input use [11]. The success of these initiatives also depends on tailored regulatory frameworks and the responses of people and organizations to them [23].

The objective of this work is to demonstrate the relevance of applying circularity micro-indicators in the early stages of the product development process and to propose how this can be achieved. For this purpose, we monitored a product development team from a Tier II automotive manufacturer during the development of an automotive plastic product in a business context. We applied and studied circularity micro-indicators to assess the impact of decisions on circularity throughout the development process. Simultaneously, in pursuit of more sustainable and circular product development, we adjusted and redesigned the current product development process under study and proposed a new methodology that integrates circularity indicators.

2. Methodologies

Several product development methodologies have been proposed in the literature over the last two centuries, varying in level of detail, number of steps, degrees of complexity, and technical terminologies [11]. However, product development methodologies have evolved under the influence of multiple disciplines, including engineering, design, project management, and marketing, with the first two being the most prominent [24,25].

The earliest product development methodologies in the literature primarily focused on functional and aesthetic aspects. Bruno Munari proposed a product development methodology centered on design, emphasizing observation and the experimental process as fundamental steps for creative and innovative product development. A key factor in this methodology is recognizing the need to formulate a clear problem statement at the project's outset [25].

Gui Bonsiepe proposed a methodology similar to Munari's, but with a stronger focus on industrial design. His model complements the data collection and analysis suggested by Munari, arguing that designers need more precise research on the product they intend to create [26]. In general, Bonsiepe's approach emphasizes a more structured and scientific

methodology for design, viewing it as part of a broader system and incorporating ethical considerations. In contrast, Munari takes a more artistic, playful, and experimental approach, valuing prototyping and simplicity in design. As product development processes evolved, this aesthetic, functional, and ergonomic approach was complemented by the inclusion of technical (engineering), economic (cost-related), and production feasibility aspects.

More recently, Ulrich and Eppinger introduced a structured and process-oriented approach to managing product development, known as the “Integrated Product Development Process.” This methodology is more comprehensive and interdisciplinary than previous models. In addition to addressing aesthetic considerations, it incorporates technical and functional aspects, making it particularly useful for complex and industrial projects. It primarily focuses on management and organization, providing structured frameworks and tools (such as IPD [27] and DOE [28]) to manage information flow, define responsibilities, and track project progress [29]. The authors advocate for the continuous integration of all product development phases—from conception, design, and prototyping to production and distribution.

Although Ulrich and Eppinger’s methodology provides a solid and structured foundation for product development, Munari and Bonsiepe offer broader approaches. Regardless of whether the methodology is more artistic or technical, the concept definition and geometric detailing phases remain central to product development, establishing the foundation for subsequent stages and impacting product performance throughout its life cycle. Ulrich and Eppinger’s approach is especially valuable for complex and industrial projects due to its structured, process-oriented management, remaining a key reference in the field [29].

A sustainable product is designed with a focus on reducing environmental impact, promoting social responsibility, and ensuring resource efficiency throughout its life cycle, from production to end-of-life [10]. In the literature, several researchers highlight the importance of integrating circular design practices and tools in the early phases of sustainable product development to facilitate the transition to a circular economy [11].

The application of circular economy (CE) indicators in product development provides a range of environmental, economic, and social benefits, as it enables the monitoring of actions and modifications that influence a product’s circularity. More details on circularity indicators and their benefits in product development are presented in the Circularity Micro-indicators Section.

The design phase is a crucial step in sustainable product development and circular systems [30]. Several authors argue that decisions made before the design phase determine 70% to 80% of the product’s life cycle costs and environmental impacts [13,30,31]. Therefore, integrating circular economy principles and circular design concerns early in the product design process is essential, as product specifications are still being defined, making integration more feasible [31–33].

Circular design seeks to rethink and redesign a product’s life cycle to minimize environmental impact and promote sustainability. According to the Ellen MacArthur Foundation, approaches to enhance circular design include selecting recyclable, renewable, safe, and sustainable materials; maintaining functionality and quality across product generations to promote reuse and reconditioning; incorporating modularity; designing for easy component repair or replacement; and facilitating disassembly and material separation to enable recycling and recovery at end-of-life [34]. This approach is important for creating products with continuous use cycles, allowing repair, recycling, or reintegration at the life cycle end, thus minimizing waste.

To incorporate environmental aspects into the product development process, [15] proposed four key methodologies that influence a product’s environmental performance. These focus on (i) raising customer awareness of circularity concepts; (ii) evaluating

environmental performance; (iii) conducting life cycle assessments (LCA) during the design process; and (iv) assessing product reuse and recycling potential. Their research concludes that the most critical phases for improving sustainability and implementing sustainable product development occur early in the process, particularly during design.

Circularity Micro-Indicators

Circularity indicators are used to track, monitor, and measure progress toward circular economy goals through quantitative or qualitative assessments. Their purpose is to provide objective and credible data on the status of this transition, allowing for the evaluation and documentation of circular economy progress [20].

Circularity indicators are categorized into three levels: macro, meso, and micro. This work focuses solely on micro-level indicators, which provide detailed insights for decision-making at the level of individual products or consumption behaviors. These indicators support the implementation of policies and decisions in areas such as product policies, energy efficiency, integrated waste management, and environmental education. They also help assess the economic, environmental, and social performance of products, companies, or consumers [6,21].

Micro-level indicators focus on various aspects of the circular economy, including recycling, reuse, end-of-life management, disassembly, repair, and resource efficiency [1]. According to multiple studies, over a hundred micro circularity indicators have been identified in the literature [33,35]. Some researchers aim to refine their calculation methodologies to reduce this broad set to a more relevant subset for evaluating circularity across different sectors.

Kristensen and Mosgaard [1] classified 30 of the most widely discussed indicators in the literature based on their typology, CE focus category, and sustainability dimensions. [33] expanded this classification by examining their application during product development versus later production stages, the use of internal versus external company data, and the influence of market conditions, legislation, and corporate policies on their calculation.

The application of these indicators allows companies to assess the circularity of their products and determine whether they are designing products that ensure the recovery of waste generated during production. Additionally, companies can evaluate their current recovery levels after products leave the facilities, whether in the form of a product, by-product, or waste [6]. These indicators also aid in selecting safer and more sustainable materials for product design and optimizing designs to facilitate reuse, repair, and recycling, ultimately extending material life cycles [36,37].

Product circularity analysis evaluates the environmental performance of a product throughout its entire life cycle, from raw material extraction to end-of-life. This analysis is crucial for products with significant environmental impacts, as it helps maximize resource efficiency and minimize environmental damage [38].

As the circular economy gains prominence, companies must prepare for this transition by assessing their circular performance and associated risks and opportunities. To remain competitive and responsible, businesses require a universal and consistent method for measuring circularity. The calculation of circularity micro-indicators is a relevant practice for organizations committed to sustainability.

The use of circularity indicators helps companies meet sustainability requirements and enhance their market position by demonstrating a commitment to circularity. Additionally, adopting circular practices can lead to cost reductions, as material reuse and waste minimization contribute to significant efficiency gains [1].

Incorporating circularity indicators into the product development phase can be instrumental in designing more sustainable products. By applying these indicators, companies can assess and improve product sustainability, promote sustainable production and consumption practices, and evaluate a product's life cycle from an environmental and social perspective [39].

According to the previously discussed product development methodologies, the process begins with concept definition, where the product is identified and all life cycle stages—from raw material extraction to end-of-life treatment—are analyzed [14]. In the subsequent design phase, raw materials are selected and circular design concepts are integrated to enhance durability, ease of repair and replacement, and product reuse.

Based on our previous study [40], in which the 30 most widely discussed micro-level circularity indicators in the literature were analyzed, we selected those whose applicability was most meaningful for plastic products used in the automotive industry, taking into account the parameters required for their calculation and their relevance to the sector. From this analysis, and in collaboration with industrial partners, the indicators selected for this study were those considered most pertinent to the current priorities of the automotive industry and for which data availability and feasibility within the case study were ensured.

The practical application of Kristensen and Mosgaard's [1] circularity micro-indicators is still limited, especially in the automotive sector. This is in line with [41], who documented the evolution of circular business strategies over seven years in a large washing machine manufacturer, highlighting practical challenges and industry-driven adaptations.

Although studies such as Saidani et al.'s [11] highlight the importance of these indicators in the early design phases, few studies explore direct collaboration with the industry for their selection and implementation [9,42]. Most studies focus on aspects related to recycling and end-of-life [23,43] paying less attention to disassembly, lifespan extension, and resource efficiency, which are essential for an effective circular economy [33,44]. This methodological approach is aligned with the frameworks proposed by [1,11], who emphasize the importance of integrating micro-level indicators in early product design phases. Compared to these studies, our approach stands out by incorporating direct feedback from industrial partners to select indicators based on both data availability and strategic relevance to the automotive sector. However, unlike more comprehensive LCA-based assessments (e.g., [45]), our method may not capture all life cycle impacts in detail, focusing instead on early-stage decision support.

3. Materials and Methods

Applying micro-indicators during the product development phase enables the team to identify opportunities to enhance circularity. These indicators provide valuable insights for decision-makers, helping to optimize design for disassembly, reuse, and recycling. To assess the impact of proposed modifications, hypothetical scenarios were created to identify areas for improvement.

The methodology builds upon the product development process outlined by Ulrich and Eppinger, incorporating sustainability and circularity considerations alongside traditional inputs such as marketing and technical specifications. Figure 1 illustrates the procedural framework used in different development phases, emphasizing collaboration with sustainability experts and the integration of circularity micro-indicators.

During the concept development phase, the development team and sustainability experts collaborate to assess key product characteristics, customer requirements, and testing protocols. This step helps identify critical areas where improvements can enhance circularity. As the design progresses into the preliminary phase, circularity-enhancing measures such as raw material standardization, increased recycled content, and more sustainable

assembly and finishing alternatives are considered. Scenario analysis is then conducted to evaluate alternative designs, determining the most beneficial modifications. This analysis guides material selection, finishing techniques, and viable end-of-life management strategies. Finally, in the pilot production phase, interactions with sustainability experts ensure that circularity levels are properly assessed, providing the company with the necessary data to communicate the product's circularity performance to customers.

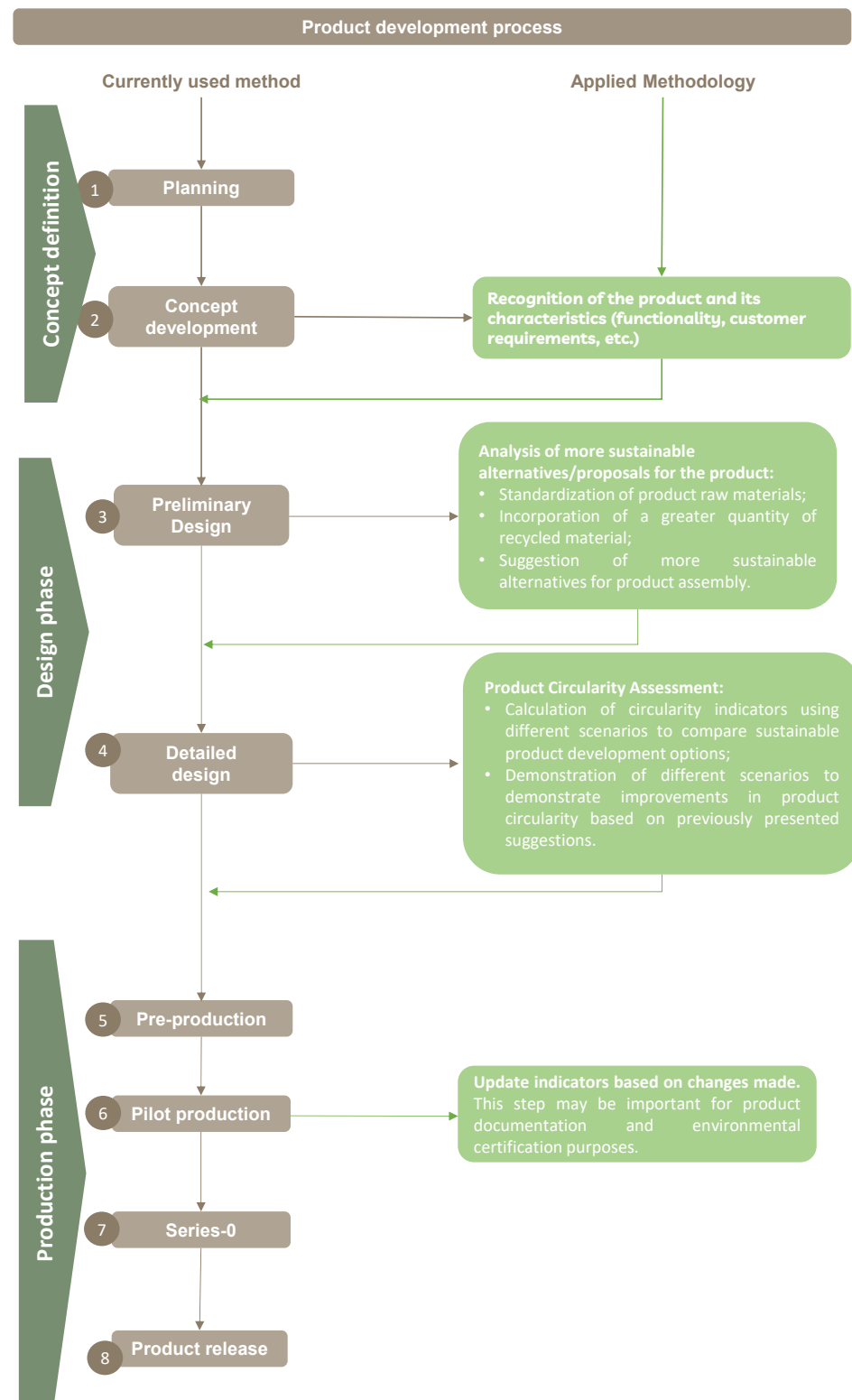


Figure 1. Methodology for sustainable and circular product development process.

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4. Results

This work involves incorporating circular design principles and circularity into the product development process to create a sustainable and circular product. To achieve this, a proposal was developed to adjust and redesign the existing product development process, as advocated for by Ulrich and Eppinger. This proposal introduces the consideration of circularity and sustainability aspects alongside traditional inputs such as functional requirements, technical specifications, and test results. The implementation of circular economy principles and the calculation of circularity micro-indicators, detailed in Section 4.1, serve as fundamental elements of this methodology.

To implement the proposed methodology, a development team was monitored to assess how their existing procedures could be adjusted to achieve a circular product. This study was conducted in collaboration with a company specializing in plastic product transformation, primarily for the automotive sector. Classified as a Tier II supplier, the company manufactures complex parts and sub-assemblies for Tier I companies, including components such as consoles, on-board computers, car radios, and dashboards.

The research specifically followed a team responsible for the development of a central console, which supports objects, utensils, and provides charging capabilities via USB and induction. The product development team consisted of three polymer engineering specialists responsible for overseeing the project for up to three months post-production, focusing on Computer-Aided Design (CAD) modifications and testing. The development process commenced after receiving specifications outlining all component requirements and test criteria.

As an aesthetic component, the console must comply with stringent OEM standards that dictate both visible and non-visible surface requirements. The development team is responsible for verifying the feasibility of the part in relation to molding, injection processes, assembly, painting, and mechanical specifications.

The entire product development process is documented in Section 4.2, including all modifications and tests conducted. Subsequently, the application of circularity micro-indicators, as discussed in Chapter 5, was used to evaluate how the development team's decisions influenced the product's circularity.

4.1. Product Case Study Development Process

The product under study is a central console comprising four welded components, designed to be integrated into the central area of a car's interior. This component meets OEM requirements, providing storage functionality and wireless and USB charging capabilities while maintaining a seamless aesthetic with minimal visible joints.

The development team analyzed the OEM-defined concept and requirements, balancing aesthetic and functional demands with technical constraints. The initial prototype consisted of four injected and welded components, as illustrated in Figure 2A.

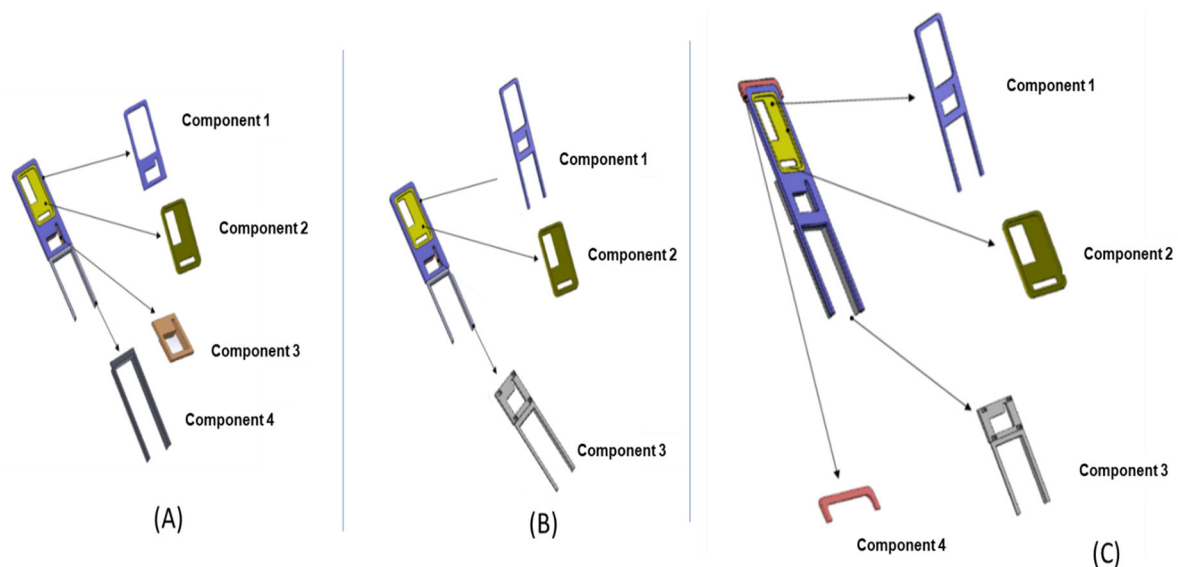


Figure 2. Product case study prototype development: (A) prototype 1, (B) prototype 2, and (C) final Prototype.

Because component four lacked the mechanical resistance required by the OEM, modifications were necessary to ensure it would not break during use. In the second prototype, developed to enhance mechanical support—particularly in the most fragile areas—a structure similar to that of component four was integrated into components one and three, as shown in Figure 2B. Component three was welded to the back of component one, while component four became a decorative element welded to the top of component one. These changes not only improved the product's mechanical resistance but also fulfilled the OEM's requirement for a cleaner production environment, as components one and three were manufactured in a single process.

Since component three serves a structural function and requires enhanced mechanical properties, a third prototype was proposed, incorporating glass fiber (GF) reinforcement. This fibrous reinforcement provides rigidity and structural integrity, making the plastic component more resistant to bending and breaking. The assembly remained as defined in prototype 2.

After several iterations, the final prototype was established, as shown in Figure 2C. All components underwent technical design modifications to preserve the confidentiality of the product. Component one includes an opening for the insertion of an electrical structure and is welded to structural component three, which provides reinforcement and support. Component two serves as the structural base for the wireless and USB electronic device charger and is covered by a rubber mat secured with two steel springs for mobile phone support. Component four is a decorative ring welded to component one.

The various stages of product design development, from prototype one to the final prototype (Sections 4.1.1 and 4.1.2), along with the tests conducted to confirm compliance with all OEM requirements and specifications, are detailed below.

4.1.1. Raw Material Selection

Raw material selection is a crucial stage in circular product development, as it directly affects recyclability and sustainability. In this study, the raw materials used were determined by the OEM, and material selection was not the direct responsibility of the development team, except when specific functional characteristics were required, such as painting or reinforcing mechanical resistance. Therefore, to enhance circularity, the development team focused on standardizing the materials used in the product and selecting raw materials for components one, three, and four, as they required painting.

At the company where this study was conducted, only components made from PC/ABS (Polycarbonate/Acrylonitrile Butadiene Styrene) can be painted. Consequently, components one, three, and four were manufactured from this material. However, to meet mechanical resistance, insulation, and structural requirements, component three was reinforced with 10% glass fiber. Component two, which includes a rubber mat, did not require painting and was therefore produced using ABS. Additionally, as PC/ABS is more expensive than ABS, its use was limited to painted components.

Regarding the incorporation of recycled materials, the OEM mandated that all product components contain at least 20% post-consumer recycled material, meeting the DIN EN ISO 14021 standard. This material could not be sourced from food systems and had to be supplied by Ravago Polymers, a polymer refining company that processes petroleum-derived raw materials from various industries to obtain polymeric materials with specific properties.

While the raw materials selected for the product were relatively homogeneous, the reinforcement of component three with GF presented challenges for recyclability. Glass fiber is highly abrasive and requires specialized granulators and recycling equipment. Furthermore, although long glass fibers provide good mechanical properties to plastic materials, they fragment during recycling, reducing the mechanical properties of the resulting recycled material.

Table 1 summarizes the raw materials for each component, as well as the percentage of recycled material that each component will incorporate. These data are necessary for the application of circularity indicators.

Table 1. Raw materials selected for each component of the product under study.

Description	Raw Material	% Recycled Material	Weight (kg)
Component 1	PC/ABS	20%	0.205
Component 2	ABS	20%	0.168
Component 3	PC/ABS + 10% GF	20%	0.102
Component 4	PC/ABS	20%	0.046

4.1.2. Component Assembly

The four components of the product were assembled using ultrasonic welding in a sandwich-like configuration, as illustrated in Figure 2. Ultrasonic welding is a technique that joins plastic parts by converting electrical energy into high-frequency mechanical vibrations. The components are fixed in precise alignment and an ultrasonic probe applies vibrations to the welding ribs, generating frictional heat that melts and fuses the materials, forming a strong and durable bond.

While ultrasonic welding is widely used in the automotive industry for its speed, strength, and durability, it poses challenges when joining materials with different compositions. In this case, component three (PC/ABS + 10% GF) was welded to component one (PC/ABS), making recycling difficult at the end of the product's life.

To address this issue, alternative assembly methods, such as quick couplers or rivets, were considered to facilitate material separation at the end of the product's life. However, this approach was ruled out because the components required precise alignment for proper integration of the electronic component. Any misalignment would prevent the electronic component from being correctly positioned.

The development team also explored the possibility of increasing the thickness of component one and adding structural ribs to eliminate the need for component three. This solution would have allowed all components to be manufactured from compatible materials—PC/ABS for components one and four, and ABS for component two—thereby improving recyclability. Additionally, all components could still be welded while maintaining stability and electronic device integration.

However, after further analysis, the development team concluded that increasing thickness and adding ribs would compromise structural stability. The resulting part would be excessively rigid, with unsupported areas exposed to extreme temperatures during use. Furthermore, adding reinforcement structures could introduce aesthetic defects. Since component one serves a primarily aesthetic function, this approach was rejected.

To maintain structural integrity while preserving aesthetics, the reinforcement structure initially added to component one was instead transferred to component three, with the exception of the welding ribs. This ensured that component three functioned purely as a technical support component, improving stability without compromising aesthetics.

4.2. Introduction of Micro-Indicators in the Product Development Process Case Study

The decisions made during product development were analyzed using circularity micro-indicators to evaluate their impact on the product's circularity. Given that the product is an automotive component, the most relevant indicators were those assessing recycled material incorporation, resource efficiency, and end-of-life management [40]. Some indicators require complex calculations or are impractical during product development, particularly in the automotive industry, where modifications require OEM approval.

To assess the influence of key decisions on circularity, the study focused on three factors: raw material selection (particularly the introduction of GF), the incorporation of recycled materials, and component assembly methods.

A review of circularity micro-indicators in the literature, combined with prior research [35,40], led to the selection of four key indicators: the Material Reuse Score (MRS), Recycling Desirability Index (RDI), Material Circularity Indicator (MCI), and Circularity Design Guidelines (CDG).

The MRS [46], RDI [47], and MCI [48] indicators rely on quantitative analysis, providing numerical values to measure the product's circularity performance and track its alignment with circular economy principles. The CDG [49] indicator is based on qualitative

analysis, assessing the product's circularity through a structured questionnaire. A detailed explanation of these indicators, along with the formulas used, is available in Appendix A.

To calculate these indicators, data on raw material composition, processing techniques, and finishing technologies were collected. Scenarios considered and rejected during product development were analyzed using these indicators to determine the impact of each decision on the product's circularity.

Despite these efforts, the study was conducted within a rigid industry where design and conceptual changes require OEM approval. As a result, the development team was not always able to implement the most optimal circularity solutions.

5. Discussion

This section addresses the output obtained from each CE micro-indicator previously selected for application in the case study (based on the criteria presented in Section 4.2). In addition to presenting in detail the analysis carried out for each indicator, we discuss the results and extract guidance and guidelines that were presented to the development team during the development process of the product under study.

5.1. Material Reutilization Score

The MRS indicator was first calculated for the base scenario, reflecting the projected characteristics of the final prototype. Each component incorporated approximately 20% recycled material. However, as the product consists of four welded components, including one reinforced with GF and two metal springs, it was deemed 0% recyclable in this scenario.

In real conditions, this product is typically integrated into a vehicle and not separated from end-of-life vehicle (ELV) waste. It is commonly shredded along with other ELV components and sent to landfill or incineration. When considered independently, the presence of GF-reinforced components welded to others makes traditional mechanical recycling infeasible. Additionally, the two steel springs would need to be removed for recycling.

To assess the impact of proposed design modifications on circularity, the MRS indicator was also calculated for two alternative scenarios, following the methodology of [40]. The parameters and corresponding results are presented in Table 2, while Appendix A provides the detailed step-by-step calculations, including the application of Equation (A1) and the input data for each scenario.

Table 2. Scenarios for calculating the MRS indicator.

	Base Scenario	Scenario 1	Scenario 2
	- Welded and assembled; - Incorporated 20% recycled material; - Component 3 containing GF; - Contains 2 metal springs that are not removed; 0% recyclable material.	- Assembled by snap fits; - Incorporated 20% recycled material; - Only component 3 is sent to landfill; 80% recyclable material.	- Incorporated 20% recycled material; - Component 3 not containing GF; - Welded and assembled, but metal springs can be removed; 100% recyclable material.
MRS Score (Level)	7% (Basic)	60% (Silver)	73% (Gold)

The analysis indicates that the final prototype achieves only a basic level of material reutilization. Although the OEM prioritizes sustainable materials during production, little emphasis is placed on recovering materials at the end of the product's life. Consequently, the incorporation of 20% recycled material did not significantly enhance product circularity.

In contrast, scenario 1, where the GF-reinforced component is not welded to the rest of the product, increases the material reutilization score by 53% compared to the base scenario, achieving the Silver level. Scenario 2, which eliminates GF entirely and enables full product recyclability even with welded components, results in a further 13% increase in the MRS, elevating it to the Gold level.

The significant improvement in MRS across scenarios demonstrates that simple design changes, such as avoiding welding of the fiberglass-reinforced component, facilitate material recovery and reuse, increasing product circularity. The complete elimination of fiberglass in scenario 2 further increases MRS, enabling full recycling and strengthening the circular economy without compromising functionality.

These improvements reflect both design and ease of disassembly and material selection, posing both challenges and opportunities for manufacturers. Investing in more circular products may require higher upfront costs, but it brings long-term environmental and economic benefits, in addition to ensuring regulatory compliance and sustainable value. Therefore, increasing MRS and MCI should be seen as an important indicator of a product's true circularity potential.

5.2. Recycling Desirability Index

By applying the RDI, the aim was to evaluate the simplicity of separating the materials incorporated into the final prototype (D_s), their level of safety (D_{MSI}), and the technological maturity of the recycling process to treat each one of these materials at their end-of-life (D_{TRL}), this being our base scenario. Furthermore, we also intended to study the impact that the proposal of not incorporating GF in component 3 would have on the simplicity, safety, and product recycling technological maturity, i.e., scenario 1.

To calculate the RDI, we again follow the approach carried out by [40]. The governing equation for the RDI, along with the equations used to determine each of its component indices, is presented in Equations (A2)–(A6) in Appendix B. The safety indexes of the materials (S_i) that make up the product were based on information previously collected about the material safety index of different plastic types presented in [47]. The classifications of material security index (MSI) for each material involved in the product are presented in Table A2 in Appendix B.

Regarding the technological maturity of the recycling process (D_{TRL}) factor, it is necessary to analyze the technological maturity of the recycling processes (R_i) used to manage the materials that compound the product at the end of its life. This analysis is performed by assigning an R_i factor, according to a scale of 1 to 9, to the maturity of the recycling technology used. The list of criteria for each level of this scale is represented in [47], and the Technological Readiness Levels (TRLs) attributed to each material that composes the product and their justifications are described in Table A3 in Appendix B.

The complete step-by-step calculation of the RDI for each scenario, including the application of the formulas, intermediate results, and the integration of the factors S_i and R_i , is documented in Appendix B, while the final RDI results are summarized in Table 3.

Table 3. Results of the calculation of RDI indicator for the different scenarios.

	D_s	D_{MSI}	D_{TRL}	RDI
Base Scenario (with 10%GF)	0.87	0.55	0.98	2.40
Scenario 1 (With 0%GF)	0.92	0.54	1	2.46

With these results, it was possible to conclude that it is more desirable to recycle the product if it does not contain glass fiber in its composition. This is proven by the increase in the D_s factor, which indicates that it is simpler to separate the materials from the product if it does not contain GF, as there will be greater uniformity of raw materials in the product, and also by the slight decrease in the DMSI factor which, as it does not incorporate GF, makes the product less hazardous to handle during its recycling process.

Therefore, it is concluded that the proposal of not using GF to reinforce component 3 would be the most favorable in terms of circularity. Due to the welding of all components, it is impossible to separate them for recycling, with component 3 being a factor that compromises the recycling of the remaining components of the product. Comparing the value obtained with other similar product case studies presented in the literature [47] allows us to conclude that the product under study is highly desirable for recycling, even containing GF in its composition. However, the product requires further effort (in terms of design, number of components, selection of more sustainable materials, and assembly process) to increase the level of circularity.

5.3. Material Circularity Indicator

The calculation of MCI served to demonstrate to the development team which proposals launched throughout the product development process would be the most advantageous for circularity. On the other hand, we also demonstrated that by taking some measures, such as increasing the incorporation of recycled content, adopting different waste routing, or implementing a reuse or collection system for return to the producer, the circularity of the product could improve significantly. The base scenario corresponds to the final prototype. Additionally, four more scenarios were studied, as described in Table 4.

Table 4. Data description for each scenario and the results of the MCI indicator calculation.

	Base Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
	- Welded and assembled; - Incorporated 20% recycled material; - Component 3 containing GF; 100% of the product is disposal.	- Welded and assembled; - Incorporated 20% recycled material; - Component 3 containing GF; 100% of the product is incinerated.	- Welded and assembled; - Incorporated 25% recycled material; - Component 3 containing GF; 100% of the product is incinerated.	- Welded and assembled; - Incorporated 20% recycled material; - Component 3 is incinerated; 80% of the product is recycled.	- Welded and assembled; - Incorporated 25% recycled material; - Component 3 not containing GF; 100% of the product is recycled.
MCI	0.192	0.641	0.664	0.637	0.664

Since the product is still under development, it is possible to explore different scenarios to facilitate understanding and the elaboration of strategies to be applied. Although the easiest components to remove are the plating and external components, plastic components are also conceptually possible to remove and disassemble to return to the producing company, provided these products are properly planned, respecting the principles of circular design so that their removal from the vehicle and subsequent recycling are possible.

The necessary data for calculating the MCI indicator for the different scenarios are provided in Table A2 in Appendix B. The detailed calculations and step-by-step procedures, as well as the equations used for the MCI calculation, are also included in Appendix B, following the methodology described in [40,48].

When analyzing the circularity defined by the MCI (Table 4) for the base scenario, it is concluded that the product developed has very low circularity (around 19%), placing it very

close to a linear economic approach. This result stems from the fact that the components that make up the product are produced with a minimal percentage of recycled material while still being highly dependent on non-renewable and fossil-based materials. Furthermore, these products are not collected for recycling or energy recovery at the end of their life, meaning that all the material that composes the product is consumed at the end of its useful life.

With the possibility of sending the product for energy recovery at the end of its life (Scenario 1), there was an increase of approximately 45% in material circularity compared to the base scenario. In the remaining scenarios, it is concluded that the possibility of increasing the incorporation of recycled material into the product and promoting the separation of components to enable full product recycling—sending components without GF for recycling and incinerating the component with GF—would not significantly improve material circularity compared to the integral energy recovery of the product.

The MCI analysis shows that the product's circularity in the baseline scenario is very low, at approximately 19%, reflecting the strong reliance on non-renewable materials and the lack of end-of-life recovery strategies. Scenario 1, which includes energy recovery, shows a significant increase of approximately 45% in the MCI, indicating that this measure can substantially improve resource efficiency and reduce landfill disposal. However, the scenarios that propose greater incorporation of recycled material and separation for selective recycling do not generate significant improvements beyond this point, due to the complexity of the materials and processes involved.

These results highlight the importance of considering the entire product life cycle to increase circularity. Measures such as increasing recycled content and redesigning to facilitate disassembly are important, but they must be evaluated alongside their technical and economic feasibility. In this case, energy recovery represents the most effective alternative to improving circularity in the short term, while solutions that increase the recyclability and reuse of materials are developed in the future.

5.4. Circularity Design Guidelines

The calculation of the CDG indicator is projected to evaluate the margin for improving the product under study and identify guidelines for enhancing its design from a circular economy perspective. The methodology for calculating these indicators is presented in [49].

Appendix D contains Table A6, which provides the levels assigned to each circular design guideline for the calculation of the CDG indicator, as well as other relevant information for each guideline group. Through these guidelines, it is possible to determine which of the five circular design groups require improvement actions. The spider diagram illustrated in Figure 3 highlights the groups of guidelines that require improvements as well as the level of improvement needed.

These results conclude that the principles of the circular economy requiring the least attention are the extension of useful life and the reuse of components. A moderate need for improvement is associated with principles for reusing the product and its structure.

On the other hand, it is extremely important to improve the product design to facilitate disassembly and recycling. Regarding the type of connectors used in the product, necessary improvements involve introducing connection systems that are easy to disassemble instead of fixed connectors (such as welding between components). Regarding recycling, improvement actions should focus on standardizing the raw materials for welded components. To this end, compatible raw materials with low environmental impact must be used, ensuring the product can be fully recycled.

Overall, the results reported in these four sub-sections corroborate the trends pointed out in the literature on the application of circularity micro-indicators, highlighting clear

benefits in improving resource efficiency and optimizing design to facilitate reuse and recycling [1,11]. These indicators provide more precise support for decision-making in the early stages of product development, aligning with circular practices that promote waste reduction and extension of material life cycles [33,44]. However, it is important to recognize that the implementation of these practices may face barriers and, in some cases, rebound effects may occur, where environmental gains are partially offset by behavioral changes or unforeseen additional costs [43]. Therefore, to ensure real and sustainable benefits, it is essential that the adoption of circular practices is accompanied by flexible policies, stakeholder engagement, and a holistic analysis of the product life cycle, avoiding undesirable impacts and promoting the transition to a truly circular economy.

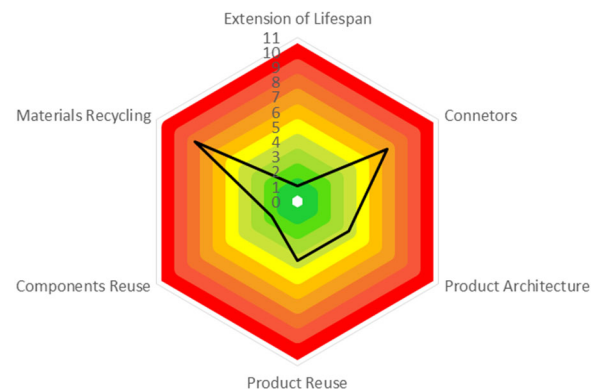


Figure 3. Margin for improvement in the design of the product under study for each of the circular economy principles. The margin of improvement represents the potential for enhancement, assessed on a scale from 1 to 9—where 1 indicates no need for improvement and 9 indicates a high need for intervention—across the fundamental areas of circular design. Its purpose is to facilitate recycling, increase material reuse, and reduce waste, thereby promoting more sustainable performance throughout the product’s life cycle and advancing its overall circularity.

6. Conclusions

Integrating circular economy principles at the early stages of product development enhances not only environmental performance but also long-term industrial competitiveness and differentiation. This study demonstrates that the adoption of circularity micro-indicators provides a practical framework to embed sustainability considerations into design decisions, particularly when supported by continuous collaboration between a dedicated sustainability expert and the development team. Such collaboration enables the real-time evaluation of design choices, fosters circular thinking, and promotes alignment with broader environmental objectives.

One of the main challenges identified is that variations in product development approaches across different companies affect the feasibility of implementing micro-indicators, coupled with a frequent reluctance among technical teams to integrate feedback from these indicators when considering alternative design options for components.

Considering the materials and current end-of-life management technologies, the need for recycling these products is high (RDI indicator), highlighting the importance of a robust recycling system. However, the developed prototype, despite containing 20% recycled material, cannot be recycled in its current design and assembly, limiting its contribution to a circular economy.

Improving circularity would require promoting end-of-life recovery, increasing recycled content, reducing incompatible material welding, and redesigning components to simplify disassembly and material separation. Nevertheless, these changes were not

adopted due to OEM requirements and resistance from the development team, who would need to rethink component design and structure.

An important contribution of this work is the establishment of an effective link between the environmental and product development departments, an often overlooked yet strategic synergy that can significantly reinforce an organization's sustainability trajectory. However, despite growing interest in circularity, much of the plastic and composite waste generated by the automotive and other manufacturing sectors continues to be landfilled. This trend highlights the need for systemic change supported by stricter regulatory enforcement and a shift in industrial mindsets toward life cycle-oriented product strategies.

Circularity micro-indicators proved to be valuable tools for evaluating resource efficiency and waste reduction potential across the product life cycle, from raw material selection to end-of-life scenarios. Nonetheless, the practical implementation of circularity assessment tools remains limited by methodological inconsistencies, partial scope coverage, and a lack of standardization across indicators.

To overcome these limitations, future research should aim to harmonize existing indicator frameworks, refine methodologies for industrial applicability, or develop new holistic circularity metrics adaptable to diverse product contexts. Such efforts are essential for operationalizing circular design in ways that are both environmentally robust and feasible for manufacturing environments.

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Abbreviations

ABS, Acrylonitrile Butadiene Styrene; CAD, Computer-Aided Design; CDG, Circularity Design Guidelines; CE, Circular Economy; ELV, End-of-Life Vehicles; GF, Glass Fiber; LCA, Life Cycle Assessment; MCI, Material Circularity Indicator; MRS, Material Reutilization Score; MSI, Material Security Index; OEM, Original Equipment Manufacturer; PC, Polycarbonate; TRL, Technological Readiness Level.

Appendix A

The MRS indicator was calculated using Equation (A1). The data used for calculating the MRS indicator for each scenario, along with the corresponding results, are presented in Table A1. The obtained values range from 0 to 100, to which a material reutilization level was assigned according to the criteria described in [46].

$$\text{MRS} = \frac{\left[\frac{\% \text{ Recycled or rapidly renewable}}{\text{product content}} \right] + 2 \left[\frac{\% \text{ of product recyclable}}{\text{or biodegradable/Compostable}} \right]}{3} \times 100 \quad (\text{A1})$$

Table A1. Scenario data used for the MRS calculation.

	Base Scenario	Scenario 1	Scenario 2
% Recycled product	20%	20%	20%
% Biodegradable/compostable product	0%	0%	0%
% Rapidly renewable product	0%	0%	0%
% of recyclable product	0%	80%	100%
MRS calculation result	7% Basic level	60% Silver level	73% Gold level

Appendix B

The RDI indicator was calculated using Equation (A2), considering three factors to prioritize the recycling of a product: the Simplicity Index of material separation (D_s), the material safety index (D_{MSI}), and technological maturity assessed through the Technology Readiness Level (D_{TRL}). This micro-indicator ranges from 0 to 3, resulting from the sum of these three factors.

$$RDI = (D_s + D_{MSI} + D_{TRL}) \quad (A2)$$

The D_s index is quantified by the opposite of the quotient of the complexity index of separation of materials (H_m) and the top scale for the complexity index of materials ($H_{Top} = 3.5$), as we can see in Equation (A3). Therefore, the H_m is calculated using Equation (A4) and considers the total mass of the product (M_{total}), the real mass in kg of the component/material (M_i), the number of materials involved in the product (M) and a constant K of value 1 to transform the values into a positive index [47].

$$D_s = 1 - \frac{H_m}{H_{Top}} \quad (A3)$$

$$H_m = K \sum_{i=1}^M \frac{M_i}{M_{Total}} \log \left(\frac{M_i}{M_{Total}} \right) \quad (A4)$$

To calculate the D_{MSI} index, a safety index (S_i) must first be assigned to each of the materials involved in the product and, further, Equation (A5) applied, where $S_{Top} = 24$ represents the maximum value of the safety index.

$$D_{MSI} = \sum_{i=1}^n \left(\frac{M_i S_i}{M_T S_{top}} \right) \quad (A5)$$

The S_i is based on the absence of damage to a country's economy due to scarcity or limited access to a specific material. [50] classified 60 unsafe materials according to eight combinations of individual factors that fall under the material risk and supply risk. For each of these risks, a score of 1–3 is assigned according to established criteria and the MSI of a material results from the sum of these risks. The material safety index (S_i) of each material is described in Table A2.

Table A2. Material safety index of each material in the product case study.

Materials	Material Risk				Supply Risk				Material Security Index
	Global Consumption	Substitutability	GWP	Total Material Requirement	Scarcity	Supply Monopoly	Political Instability	Vulnerability to Climate Change	
PC/ABS	3	1	2	1	1	2	2	1	13
ABS	3	1	2	1	1		2	1	13
PC/ABS + 10%GF	2	1	3	1	2	2	2	1	14
Stell	3	3	1	1	1	2	2	2	15

To calculate the D_{TRL} index, Equation A6 is applied, which compares the sum of the TRL of all materials and components with the maximum scale of technological updating ($R_{Top} = 9$).

$$D_{TRL} = \sum_{i=1}^n \left(\frac{M_i R_i}{M_T R_{top}} \right) \quad (A6)$$

First, the level of technological updating (R_i) is considered according to the recycling process currently in place for each material/component. The R_i was adapted from the TRL developed by the U.S. National Aeronautics and Space Administration (NASA) and contains nine levels of metrics. The TRL assigned to each material in the case study product are described in Table A3.

Table A3. Recycling Technological Readiness Level for each material involved in the composition of the product case study.

Materials	TRL	Observations
PC/ABS	9	Recycling technology available to recycle this type of material is well-matured and frequently implemented in an industrial context.
ABS		
Steel		
PC/ABS + 10%GF	8	Recycling of materials reinforced with GF still is not frequently used industrially but more often used in the laboratory.

Once each of the factors involved in the RDI indicator was individually calculated, they were added together, and the obtained results are presented in Table 3.

Appendix C

The MCI of a product considers the linear flow index of the product (LFI) and a utility function $F(x)$ which determines the influence of the usefulness of the product in relation to other similar products present on the market. Equation (A7) presents the calculation for obtaining the MCI of a product.

$$MCI * p = 1 - LFI * F(x) \quad (A7)$$

The linear flow index (LFI) measures the proportion of material that flows in a linear way, and is calculated using Equation (A8), which considers the amount of virgin raw material (V), the amount of irrecoverable material produced during recycling (W), the total mass of the product (M), the amount of waste generated during the production of recycled raw material (W_F), and the amount of waste generated in the process of recycling product components (W_C).

$$LFI = \frac{V + W}{2M + \frac{W_F - W_C}{2}} \quad (A8)$$

To calculate the amount of virgin raw material (V), Equation (A9) is used, which considers the fraction of raw material of the product derived from recycled materials (F_R), the fraction of raw material of the product derived from reuse sources (F_U) and the fraction of biological raw materials from sustainable production (F_S).

$$V = M(1 - F_R - F_U - F_S) \quad (A9)$$

The amount of irrecoverable waste (W) is calculated using Equation (A10), which defines the amount of material in a product that is landfilled or incinerated and the amount of irrecoverable material produced during recycling. The amount of irrecoverable waste of a product (W_0), which is landfilled, recovered into energy or by any other type of process where the material is no longer recoverable, is given by Equation (A11), and involves the

fraction of the mass of the product that was collected for recycling at the end of its use phase (C_R), that whose components are reused (C_U), that collected for the composting process (C_C), and that collected for energy recovery (C_E).

$$W = W_0 + \frac{W_F + W_C}{2} \quad (\text{A10})$$

$$W_0 = M(1 - C_R - C_U - C_C - C_E) \quad (\text{A11})$$

As the recycling process is not a 100% efficient process, there is also an associated amount of waste generated in this process. Therefore, the amount of waste generated during the production of recycled raw material (W_F), and the process of recycling product components (W_C), is calculated by Equations (A12) and (A13), where E_F corresponds to the efficiency of the process used to produce the recycled raw material and E_C corresponds to the efficiency of the recycling process used to recycle an end-of-life product.

$$W_C = M(1 - E_C)C_R \quad (\text{A12})$$

$$W_F = \frac{M(1 - E_F)F_R}{E_F} \quad (\text{A13})$$

The utility function ($F(x)$) has two components: one that accounts for the duration of the product's use phase and the other that accounts for the intensity of use and is calculated by Equation (A14). The component responsible for the lifetime of a product is given by $\frac{L}{L_{av}}$, where L is the shelf life of the product, on average, and L_{av} is the lifetime of similar products present in the industry. The intensity of use component is given by $\frac{U}{U_{av}}$, where U is, on average, the number of functional units achieved during the use of the product and U_{av} is, on average, the number of functional units achieved during the use of a similar product present on the market.

$$F(x) = \frac{0.9}{\left(\frac{L}{L_{av}}\right) \cdot \left(\frac{U}{U_{av}}\right)} \quad (\text{A14})$$

The data necessary for the calculation of the MCI in each scenario of case study are presented in Tables A4 and A5. These tables present the values obtained from the intermediate calculations, as well as the MCI indicator results for the different scenarios, using the equations mentioned above.

Note that only factor E_C has not been determined in the base scenario, because until this moment, recycling was not anticipated for this product, and because of this, it is impossible to determine the efficiency of this process.

Table A4. Data for MCI indicator calculations for each scenario studied.

	Base Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
M	0.525 Kg	0.525 Kg	0.525 Kg	0.525 Kg	0.525 Kg
F_R	20%	20%	25%	20%	25%
F_U	0%	0%	0%	0%	0%
F_S	0%	0%	0%	0%	0%
C_R	0%	0%	0%	80%	100%
C_U	0%	0%	0%	0%	0%
C_C	0%	0%	0%	0%	0%
C_E	0%	100%	100%	20%	0%
E_F	95%	95%	95%	95%	95%
E_C	0%	95%	95%	95%	95%
L	10 anos	10 anos	10 anos	10 anos	10 anos
L_{av}	10 anos	10 anos	10 anos	10 anos	10 anos
U/U_{av}	1	1	1	1	1

Table A5. Intermediate MCI calculation values for each case study scenario.

	Base Scenario	Scenario 1	Scenario 2	Scenario 3	Scenario 4
V	0.420	0.420	0.394 Kg	0.420	0.394 Kg
W_0	0.525	0.000	0.000	0.000	0.000
W_F	0.006	0.006	0.006	0.007	0.006
W_C	0.000	0.000	0.000	0.021	0.000
W	0.528	0.003	0.003	0.013	0.003
LFI	0.898	0.399	0.374	0.403	0.374
x	1.000	1.000	1.000	1.000	1.000
F(x)	0.900	0.900	0.900	0.900	0.900
MCI	0.192	0.641	0.664	0.637	0.664

Appendix D

The CDG indicator is a holistic tool that identifies design approaches to improve a product by evaluating the potential for enhancement and the relevance of a set of circular design guidelines. These guidelines are divided into five groups corresponding to the fundamental principles of the CE: extension of useful life, disassembly, reuse of products, reuse of components, and recycling of materials.

For each guideline, an improvement level is assigned, ranging from 1 to 3 (1 being not relevant and 3 being highly relevant for the product under study). This process is repeated for each of the five groups. The average improvement level for each group of guidelines is then calculated and multiplied by the relevance score attributed to that group. The improvement level for each circular design group therefore ranges from 0 to 9. The guidelines with the highest improvement levels should be prioritized to enhance the product's circularity.

The results of this micro-indicator are shown in a spider diagram that highlights the guideline groups requiring improvement, as well as the corresponding level of improvement. The improvement and relevance levels assigned to each guideline and group are presented in Table A6.

Table A6. Circular design guidelines necessary for calculating the CDG indicator.

Group	Circular Design Guidelines	Margin of Improvement	Relevance
Life Cycle Extension	Timeless design;	3	1
	Adaptability;	2	
	Upgrading;	1	
Disassembly	Use standardised joints;	3	3
	Use joints than can be disassembled rather than fixed joints;	3	
	Use screws with the same metrics;	1	
	Minimise type of joints;	3	
	Use easily accessible joints;	3	
	Minimise the number of joints;	3	
	Minimise the number of tools to be used;	1	
	Use standardised tools;	1	
	Adopt modular designs;	2	2
	Minimise the number of components;	3	
	Be able to quickly identify disassembly joints;	2	
	Minimise length of wires and cables;	1	
	Size components to make their handling easier;	1	
	Facilitate the accessibility of essential components (for their potential reuse/recycling);	2	
	Avoid the disassembly of parts in opposite directions;	2	
	Design to make disassembly automatic;	3	
Product Reuse	Design to avoid dirt from accumulating;	1	2
	Use materials that overcome cleaning processes;	1	
	Minimise the use of parts that require frequent repairs/replacements;	2	
	Use components with a similar life span;	3	
	Incorporate systems to monitor failing components;	3	
Components Reuse	Use standardised components;	3	1
	Minimise variations in the appliance;	1	

Table A6. Cont.

Group	Circular Design Guidelines	Margin of Improvement	Relevance
Materials Recycling	Unify materials in the components joined by fixed joints;	3	3
	Use materials with a low environmental impact (recyclable/low energy content/etc.);	3	
	Avoid using surface treatments;	3	
	Label materials;	3	
	Minimise using hazardous materials;	2	
	Minimizar o uso de materiais perigosos;	1	
	Promote monomaterial designs;	3	

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