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Weighting with Life Cycle Assessment and Cradle to Cradle: A Methodology for Global Sustainability Design

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Abstract: Sustainable product design uses methodologies focused on eco-effectiveness and eco-efficiency for the proposal of innovative technological solutions and for the control of environmental impacts during the product life cycle. One of the main drawbacks of such techniques is their qualitative nature, associated with a decision-making process that is sometimes arbitrary, or with unverifiable data; this means that several complementary tools are currently being used to reduce the error in the results obtained. This situation makes the unification of procedures necessary. In this context, this research develops a methodology for the sustainable design of industrial products that integrates life cycle assessment (in its environmental, economic and social application) and cradle-to-cradle techniques. For this purpose, a new assessment process is proposed, based on damage, developing LCA+C2C endpoint indicators. The methodology is subsequently verified in a case study of products for sustainable mobility (city trike electric). The results show that an integrated LCA+C2C assessment can help to propose more balanced sustainable strategies and would be a suitable method to measure tradeoffs between economic, social and environmental results, for practical purposes and future redesigns. The unified method provides a procedure to design a solution with a trade-off between eco-efficient and eco-effective criteria; it also simplifies the design phases, facilitates the interpretation of the results and provides a quantitative scope to the cradle-to-cradle framework.

Keywords: life cycle assessment; cradle to cradle; industrial product; project management; endpoint indicators; circular economy



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1. Introduction

The business strategies of any sector of activity reflect the current interest in managing the product portfolio, from the point of view of sustainable development [1]. Early design phases are critical to approach the product life cycle optimally. A global sustainable solution demands a variety of requirements. Firstly, environmental criteria that respect the natural cycles of the biosphere and allow the exhaustive control of environmental impacts (consumption of energy and material resources, environmental degradation, biodiversity loss, etc.) are needed. Secondly, it is necessary to take into account the social and economic repercussions of products, considering the impact on health, well-being, quality of life and even on culture and other anthropological areas. Finally, more far-reaching criteria can be considered in order to reverse the damage (with the regeneration of deteriorated ecosystems) caused by industrial activities during the last century. This variety of requirements has determined a change in model in the management of industrial design projects, as well as in the methodologies and tools available [2]. For each of the stages of the product life cycle, there are guides, analysis models, design guidelines and solutions, focused on improving economic, environmental and social performance (3E). If their scopes are analyzed, these can be classified into two main approaches that currently coexist [3,4]: eco-efficiency and eco-effectiveness strategies.

Eco-efficient solutions can minimize the negative impact by improving the efficiency of results. The procedure focuses on an effects assessment based on combining maximum

value with minimum resource use and minimum pollution [4]. Methods of impact analysis [5–7] utilize different formats: checklists, experts’ judgement, flowcharts, multi-criteria analysis or simulation models. As examples, the following stand out: cumulative environmental impacts [8], life cycle assessment (LCA) [7,9], eco-costs [10], material and substance flow analysis [11], environmental and material flow cost accounting [12] and environmental risk assessment [13]. The evaluation identifies those activities and processes in the product life cycle that generate the greatest environmental load; then, a prioritization of actions is established through the control of polluting substances in two phases: (1) reduction of midpoint impacts (changes in natural environmental aspects, such as global warming or acidification) and (2) reduction of endpoints (damage effects on ecosystem elements: human being, ecosystem and resources). This model is the most widely used at present; it is operational and allows economically and technically viable solutions. However, it offers short-term solutions that do not eliminate the problem. Furthermore, the strategy of minimizing impacts does not promote the proposal of cleaner alternatives; in other words, the solutions manage to reduce the consumption of resources and energy, emissions or waste, but do not reach zero impact.

On the other hand, eco-effective solutions [14–17] are proposed from the perspectives of damage restoration, removal and repair actions, closure of cycles and dematerialization [3,5,18–20]. Eco-effectiveness is a proactive approach that proposes the identification of the processes with negative impacts, to replace them with new solutions; it identifies the causes of the problem in order to eradicate it completely. It uses strategies supported by eco-innovation: clean alternative solutions, balanced in the social, economic and environmental dimensions, which also generate zero impact or even a positive impact (damage restoration). The tools associated with this approach are more limited. In general, these are conceptual design guides and strategy proposals; if any assessment tool is included, these are usually qualitative or semi-quantitative. The frameworks Industrial Ecology [19], Cradle to Cradle (C2C) [18], Blue Economy [21], Circular Economy [22], Cleaner Production [23] and Biomimicry [24] include eco-effectiveness strategies in their approaches in addition to improving the eco-efficiency of systems. Specifically, proposals that support these frameworks can be found [5,25] for different sectors, such as manufacturing [26], construction [27,28], business sites [29], waste management [30], raw material management [16] and reverse logistics [31]. There are also some proposals for complementary assessment methods, although these are scarce [32]. Figure 1 presents a comparison of the two approaches.

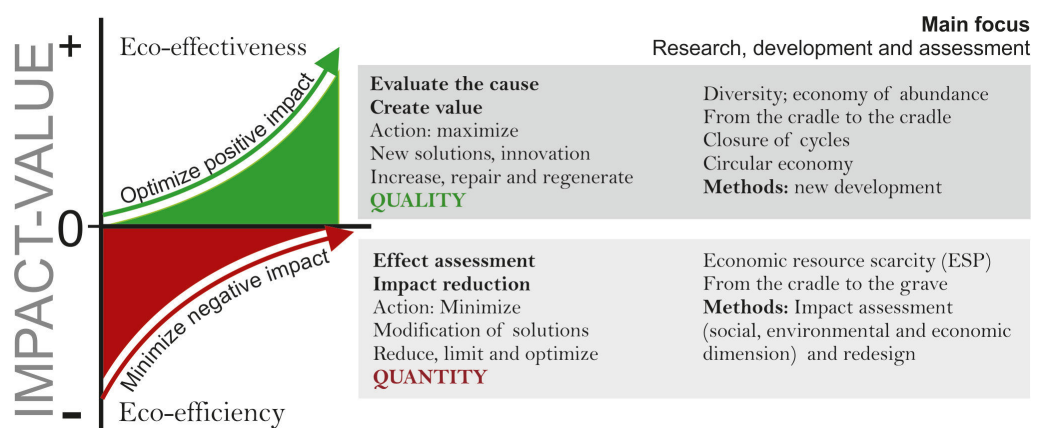


Figure 1. Eco-effectiveness perspective versus eco-efficiency perspective.

Over the last few decades, some studies have analyzed the advantages and disadvantages of each perspective (eco-efficiency and eco-effectiveness). Although an eco-efficient approach must be a priority [33], the real implementation of these solutions currently implies difficulties from the point of view of technical and economic viability [34,35]. In many cases, it is not possible to replace the conventional solution with an eco-efficient one.

Optimized products, processes and technologies cannot be eliminated radically, so the only way to control the impact is eco-efficiency. At other times, the eco-effective solution is either unknown or simply a conceptual idea, or it is viable in the long term [36]. Finally, the qualitative nature of eco-effective methods and tools makes the decision-making process arbitrary or means that it is performed with unverifiable data [37].

This situation has promoted the effort to integrate the two approaches in order to achieve balanced design solutions using eco-efficient requirements (viability of implementation in the short term with minimum environmental impact) and eco-effective requirements (including the definition of a Continuous Improvement Plan to achieve zero impact, substitution of technology and creation of positive impact) [17,38]. In general, this integration is carried out by identifying the most significant methods or strategies used individually in the two approaches, to find a balance of results. There are a few examples: product design and manufacturing processes [4,37–40], e-commerce [36], agriculture [41], energy life cycle [42] or buildings and construction [43–47]. In the specific case of industrial product projects, the two methodologies that are usually integrated are life cycle assessment (LCA) and cradle-to-cradle (C2C) techniques [4,47].

With different orientations and procedures, the application of the eco-design and impact assessment of products generates a set of results that are not comparable, but which must be contrasted in order to materialize the design solution [4,48,49]. In general, the disadvantage of integrating these two methods lies in their main differences:

1. Procedures with different stages;
2. Non-matching, or simply non-comparable, impact categories;
3. Results with different scope: quantitative (LCA) and qualitative (C2C);
4. Interpretation and presentation of impact results in different ranges of values (positive, zero and negative impacts).

These differences have meant that, to date, an integrated approach has not been achieved. Generally, design processes use “toolboxes”, or a combination of several complementary techniques, to reduce the error of the results obtained. Unification into one procedure will reduce the complexity of the design process.

In this context, this research develops a framework for the design of industrial products with a global sustainability scope, from the point of view of eco-efficiency and eco-effectiveness. A methodology that integrates the LCA and C2C techniques is proposed, simplifying the design phases, facilitating the interpretation of the results and providing a quantitative approach to C2C. The paper is structured as follows: Section 2 describes the framework, including the tasks carried out for the development of the LCA+C2C integration, the new endpoint categories and the process of weighting with LCA+C2C indicators, and Section 3 verifies the methodology applied in a case study on products for sustainable mobility. Finally, the main conclusions are set out in Section 4.

2. Materials and Methods

This section describes the framework for global sustainability with LCA+C2C integration and its context of application. For its development, the following steps were carried out and are explained in the subsections below:

1. Analysis and comparison of LCA and C2C methods (Section 2.1);
2. Development of the new damage-oriented integrated assessment process (Section 2.2);
3. Design of information flow and data classification system for the LCA+C2C assessment (Section 2.3);
4. Definition of the procedure to apply the LCA+C2C integrated design and assessment methodology (Section 2.4).

2.1. LCA and C2C for Product Design

A comparison of the LCA and C2C methods was carried out, analyzing the scope, procedure, impact categories and presentation of results, in order to find the most appropriate way to integrate the categories used in LCA (all of them in the environmental and social

dimensions) and C2C (material health, material reutilization, renewable energy and carbon management, water stewardship and social fairness).

Firstly, LCA is a quantitative and systematic assessment tool that determines the environmental, social and economic impact that a product or system generates throughout its life cycle, from the extraction of raw materials to the end of life [50,51]. Although this method does not provide a design guide, or strategies for improving environmental or social performance, the results of impact and damage generated can be used to progress eco-efficiency: to identify opportunities for improvement, compare different alternatives and provide truthful and representative information for the decision-making process, or dissemination to the community [52].

On the other hand, cradle to cradle (C2C) is a paradigm oriented towards eco-effectiveness [18] and a circular economy [53]. C2C defines a set of design principles as a guide for innovation and continuous improvement, considering environmental and social aspects, from the point of view of zero and positive impact (damage regeneration). Currently, results are qualitative and obtained through weightings of simplified categories. Furthermore, the implementation of solutions requires major social and infrastructure changes, some of which are not currently feasible, such as, for example, achieving a closed cycle of matter exchange, total waste recovery or the use of 100% renewable energy. In the available assessment process, one of the main drawbacks is the lack of relationship between the design principles (water equals food; 100% renewable solar energy; celebrating diversity) and categories of analysis (material health, material reutilization, renewable energy and carbon management, water stewardship and social fairness). Therefore, it is not possible to verify whether a design meets these principles or not. An estimation is achieved with the certification system offered by the company [54], with which the level of sustainable scope of the product is calculated (Basic, Bronze, Silver, Gold or Platinum), but without providing the direct measurement of these principles. Even so, the design strategies are representative and provide eco-innovative solutions to advance sustainable and eco-effective products.

Table 1 shows the simplified comparative study between LCA and C2C; the main characteristics of each method are collected. This evaluation was carried out to enable the integration of the two approaches [4,48,49,55–59].

Table 1. Comparison of LCA and C2C (advantages in black; disadvantages in blue).

Parameter	LCA	C2C
Objective	Eco-efficiency	Eco-effectiveness
Strategy	Minimization and cleanness	Maximization and regeneration.
Knowledge	Open, developed by the global scientific community. Application by experts in environmental analysis.	Restricted and licensed for use. No specialized training required. Some design guides available [60–69]
Normative and guidelines	Environment: ISO 14040 and ISO 14044 [9,70] Social: UNEP and SETAC Guidelines [71] Economic: ISO 15686-5 [72] (only building and construction)	Does not exist [54,73,74]
Certification	More accepted: some certifications require LCA, for example, ISO 14025: 2006 [52,75]	Certification in 5 levels: Basic, Bronze, Silver, Gold or Platinum. Private [54]
Scope	Assessment. Indirectly, in design and optimization technology.	Design and assessment
Assessment dimensions	Environmental and economic criteria, (quantitative). Social criteria (qualitative or semiquantitative); independent procedures.	Environmental and social in a single procedure. Qualitative.

Table 1. Cont.

Parameter	LCA	C2C
Assessment categories	Based on effects. Two groups: midpoint or effect indicators (>18 categories with low uncertainty but difficult to interpret) and endpoint or final damage (3 categories easy to understand but with uncertainty). [76] Does not include analysis of externalities or environmental risk.	Based on causes. Proposes 3 design principles. Five simplified evaluation categories. No direct relationship between principles and categories. 5 categories easy to understand but with uncertainty.
Life cycle inventory	Exhaustive. Impact assessment based on outputs. Complexity in data collection.	Impact assessment based on inputs. Simplified inventory.
Result Interpretation step	Characterization in equivalent units, the comparison of impacts is not intuitive: normalization or weighting necessary. The proposal for improvements will depend on the experience of the expert. It does not propose design strategies.	The interpretation is simple. It does not allow comparison of solutions: redesigns are not verifiable. Different improvement strategies, design guides and proposals for zero-impact solutions and value regeneration are available.
Assessment process	Quantitative in four detailed phases: analysis of destination, exposure, effect and damage. The identification of causes is complex.	Qualitative in four conceptual phases: define, increase, support and optimize. It does not follow an ordered sequence. It does not define the effect (damage).
Tools and software	Complete databases, a variety of analysis methods and software. Availability of free software.	Knowledge base and databases not available. Design results controlled by expert (owners).

2.2. Definition of the New Assessment Process

As Table 1 shows, one of the main drawbacks to integrating the LCA and C2C methods lies in the evaluation process, including notable differences between assessment categories and indicators, the scope and level of accuracy of results. To resolve this, an evaluation process was designed that includes new endpoint impact categories (based on damage); these are compatible between the two methods and were the result of integrating: (1) the causes analyzed by C2C (materials, energy, water and humans) [54] and (2) the effects, analyzed in LCA (18 midpoint and 3 endpoint indicators) [76]. The methods and process used are explained in detail below.

2.3. Analysis of the C2C and LCA Assessment Categories

The ReCiPe methodology was used for the selection of 18 midpoint categories in E-LCA [76,77] and the subcategories proposed in the standard guide for S-LCA [71,78]. As for C2C, in the original method, the 5 categories (material health, material reutilization, renewable energy and carbon management, water stewardship and social fairness) are simplified and do not provide enough information to be related to the midpoint indicators, so, in this research, these were completed with representative and measurable indicators (example in Figure 2). This process of category comparison identified the existence of aspects evaluated by C2C and not taken into account by E-LCA or S-LCA (and vice versa). Therefore, it was decided to create new impact categories. The categories created are damage-oriented and are characterized by LCA+C2C endpoint indicators. It must be clarified that these new categories do not coincide with those defined in the classic Eco-indicator 99 methodology (damage to human health, ecosystem and resources availability) [79].

LCA Categories		C2C - Material Health																
		Human Health							Environmental Health									
		Carcinogenic effect	Endocrine disruption	Mutation capacity	Reproductive .../...	Oral toxicity	Dermatological tox.	Toxic inhalation	Neurotoxicity	Damage to skin.../...	Respiratory tract	Aquatic toxicity	Fish toxicity	A. invertebrate tox.	Algae toxicity	Terrestrial toxicity	Persistence	Bioaccumulation
GW	Malnutrition		X		X													
	Cardiovascular diseases					X	X											
	Respiratory problems								X	X								
	Diseases transmitted .../...				X				X									.../...
	Floods										X	X	X	X				X
	Droughts															X		X
	Damage to mammals .../...										X	X	X	X	X			
OD	Skin cancer	X		X														
	Visual diseases								X									
A	Damage to flora										X				X	X	X	
	.../...																	
E	Damage to aquatic flora										X	X	X	X		X	X	
	.../...																	
.../...																		

Figure 2. Relationship process between C2C and LCA categories.

2.4. Definition of LCA+C2C Endpoint Indicators

Once the similarities between the categories of both methodologies were identified, the related relationships were classified and quantified to create the LCA+C2C endpoint indicators. Relationships were evaluated at two levels: (1) direct, if there was direct dependence between the input (C2C) and output (LCA) indicators, considering a direct dependency relationship to be when both methodologies evaluate the same aspect, although these identify the criteria with different names; and (2) indirect, if there was indirect dependence between the input (C2C) and output (LCA) indicators, considering indirect dependence to be when the evaluated aspects present common characteristics, but the indicator is not coincident.

2.5. Calculation of LCA+C2C Endpoint Indicators

Having defined the relationships between the LCA and C2C categories, the α_{ijk} (LCA+C2C endpoint indicators) were calculated. These quantify the influence of the causes (inputs) on the effects (impacts generated). As only the LCA method offers quantitative results, a weighting process was established for the different types of direct and indirect relationship. In this way, the level of intervention of a resource (input) in a midpoint category (output) is known, i.e., the intervention that a resource has in generating an impact. This value is useful, since it will be possible to identify which input generates more impact, with a direct or indirect relationship in a midpoint impact, and, by reducing or eliminating this input group, the environmental performance of the system can be improved at the environmental or social level.

Figure 2 illustrates the procedure carried out. It includes the study of dependency relationships between C2C and LCA categories and the type of relationship (direct or indirect). It can be seen that measurable and verifiable impact indicators were selected for the C2C categories, allowing comparison with the corresponding midpoint category. This

process was carried out for the 18 midpoint categories, the 31 subcategories of S-LCA and the 5 C2C categories.

2.6. Definition of New Integrated LCA+C2C Categories

The new integrated LCA+C2C categories were classified into three analysis groups to facilitate the interpretation and use of the results:

- (a) **Group I or cause–effect categories:** A set of categories that provide information regarding the impacts generated by the system individually, associated with:
- Inputs: Set J of consumed and used resources to which land (L), materials (M), energy (E), water (W), human (H) and information (I) belong. This group provides impact data related to the causes. This set is defined as: $J_k = \{1,2,3,4,5,6\} = \{L,M,E,W,H,I\} = \{\text{Land, Materials, Energy, Water, Human, Information}\}$.
 - Outputs: Set I_{jk} of midpoint impacts caused by products, by-products or substances generated in a life cycle process. These impacts are caused on resources defined in set J (land, materials, energy, water, human and information) and are quantified through endpoint impact categories (K).
- (b) **Group II or quality categories (Q_K):** A set of four LCA+C2C endpoint indicators of integrated environmental and social assessment, which provide information on the level of “care” to the *protected areas* (K). Four endpoint categories are defined, divided into society and ecosystem:
- Human health (Q_{HH});
 - Security and well-being (Q_{SH});
 - Biotic system (flora and fauna) (Q_{BS});
 - Abiotic system (hydrosphere, hydrosphere and lithosphere) (Q_{AS}).

Evaluation based on these indicators makes it possible to directly control impacts through the causes that originate them, i.e., by modifying inputs (or resources), it is possible to reduce the effects or otherwise increase the quality of the results. These categories have a distribution of both environmental and social indicators. The results are compiled in the Quality Effects Inventory (QEI). With expressions (1) to (5), the result of each Q_K category is calculated. Table 2 contains the necessary information for the calculation.

$$Q_K = \sum_{j \in J_k} R_{jK} \quad (1)$$

$$R_{jK} = \sum_{i \in I_{jk}} \alpha_{ijk} \cdot N_i = \sum_{i \in I_{jk}} w_{ijk} \quad (2)$$

$$N_K = \sum_{i \in K} N_i = \sum_{i \in K} \frac{C_i}{n_i} \quad (3)$$

$$W_R = 1 - \frac{R_{jK}}{N_K} \quad (4)$$

$$W_K = 1 - \frac{Q_K}{N_K} \quad (5)$$

For the grouping and calculation of results, the following data sets are defined:

- Set J_k or *inputs* (resources) as: $J_k = \{1,2,3,4,5,6\} = \{L,M,E,W,H,I\} = \{\text{Land, Materials, Energy, Water, Human, Information}\}$;
- Set I_{jk} or *outputs* (midpoint) as: $I_{jk} = \{C_i\}_{i=1}^n \forall i \in J_k$;
- Set K of “damages” in protected areas (LCA+C2C endpoint) as: $K = \{1,2,3,4\} = \{HH, SH, BS, AS\} = \{\text{Human Health, Human Safety, Biotitic System, Abiotic System}\}$.

The following are necessary as **starting data**:

- i is the impact category;

- C_i is the characterized impact of the impact category I ;
- N_i is the normalized results of impact category i —it permits results on the same scale and shows the contribution to the overall environmental problem;
- n_i is the normalization reference—the normalization factor for the category i in the reference system (for example, CML, Recipe H or ILCD).

Finally, the **results obtained** from the LCA+C2C endpoint weighting are defined as:

- Q_K is the LCA+C2C endpoint impact for each K (HH, SH, BS and AS) category. It measures the level of interference of each resource in the LCA+C2C endpoint categories, i.e., the loss of value by the cause–effect relationship. It is the result of the global cause–effect weighting. The unit of measurement coincides with N_K and depends on the reference method used.
- N_K is the total normalized impact value for a Q_K category. The unit of measurement depends on the reference method used.
- α_{ijk} is the weighting factor in the LCA+C2C endpoint method; it is dimensionless.
- w_{ijk} is the weighting result for an LCA+C2C endpoint category. The unit of measurement is LiC eq.
- R_{jK} is the endpoint impact generated by each type of resource (land, materials, energy, water, human and information). It is the result of the partial weighting derived from the inputs. The unit of measurement coincides with N_K and depends on the reference method used.
- W_R is the index of the quality of inputs (resources used)—the limits are $0 \leq W_R \leq 1$, where 1 is the total quality of the resource (or zero impact). The unit of measurement is LiC eq.
- W_K is the index of the quality level of the protected elements (human, biotic ecosystem and abiotic ecosystem)—the limits are $0 \leq W_K \leq 1$, where 1 is the total quality (or zero impact on the protected element). The unit of measurement is LiC eq.

Table 2. Data, relationships and indicators for impact category calculation.

J_K Causes	I_{jk} Effects	K Damage (Protected Areas)			
Resources (R_{jk})	Midpoint Category	C_i [unit]/ N_i [unit]	Type	α_{ijk}	LCA+C2C Endpoint Category (Q_K)
Materials (M)	Global warming	Kg CO ₂ eq/unit	En	0.19	Q_{HH} Anthropo-sphere, care for human health
	Ozone depletion	Kg CFC-11 eq/unit	En	0.08	
	Human toxicity	Kg 1.4-DB eq/unit	En	0.39	
	Particulate matter formation	Kg PM10 eq/unit	En	0.08	
	Photochemical oxidation potential (SMOG)	Kg C ₂ H ₄ eq/unit	En	0.14	
	Ionizing radiation	Kg U ₂₃₅ eq/unit	En	0.12	
Energy (E)	Global warming	kg CO ₂ eq/unit	En	0.50	Q_{HH} Anthropo-sphere, care for human health
	Particulate matter formation	Kg PM10 eq/unit	En	0.25	
	Photochemical oxidation potential (SMOG)	Kg C ₂ H ₄ eq/unit	En	0.25	
Human (H)	Human ecotoxicity	kg 1.4-DB eq/unit	En	1.00	

Table 2. Cont.

J _k Causes	I _{jk} Effects	K Damage (Protected Areas)			
Resources (R _{jk})	Midpoint Category	C _i [unit]/N _i [unit]	Type	α_{ijk}	LCA+C2C Endpoint Category (Q _k)
Human (H)	Health and safety (all stakeholders)	Color/[1, 6]	S	0.36	Q _{HS} Anthropo-sphere, care for human safety and well-being
	Fair salary and hours of work	Color/[1, 6]	S	0.18	
	Equal opportunities, discrimination and association	Color/[1, 6]	S	0.18	
	Social benefits and social security	Color/[1, 6]	S	0.09	
	Child labor and forced labor	Color/[1, 6]	S	0.18	
Land (L)	Access to resources (material and non-material)	Color/[1, 6]	S	0.25	
	Problems related to society: delocalization and migration, armed conflicts and rights	Color/[1, 6]	S	0.38	
	Contribution to economic and technological development	Color/[1, 6]	S	0.38	
Information (I)	Cultural heritage	Color/[1, 6]	S	0.08	
	Community engagement and public commitments	Color/[1, 6]	S	0.17	
	Feedback mechanism and consumer privacy	Color/[1, 6]	S	0.17	
	Transparency and corruption	Color/[1, 6]	S	0.17	
	End of life and social responsibility	Color/[1, 6]	S	0.25	
Materials (M)	Fresh water and marine aquatic ecotoxicity	Color/[1, 6]	S	0.17	
	Fair competition and intellectual property rights	Color/[1, 6]	S	0.17	
	Global warming	Kg CO ₂ eq/unit	En	0.34	Q _{BS} Biosphere, care for ecosystem (biotic)
	Acidification	Kg SO ₂ eq/unit	En	0.13	
	Fresh water and marine aquatic ecotoxicity	Kg 1.4-DB eq/unit	En	0.19	
Terrestrial ecotoxicity	Kg 1.4-DB eq/unit	En	0.08		
Eutrophication	Kg PO ₄ eq/unit	En	0.26		
Energy (E)	Global warming	kg CO ₂ eq/unit	En	1.00	
	Acidification	kg SO ₂ eq/unit	En	0.33	
Water (W)	Fresh water and marine aquatic ecotoxicity	kg 1.4-DB eq/unit	En	0.33	
	Eutrophication	kg PO ₄ eq/year	En	0.33	
Land (L)	Land use/transformation	m ² /year	En	1.00	
Energy (E)	Mineral resource depletion	Kg Sb eq/year	En	0.60	Q _{AS} Biosphere, ecosystem (abiotic)
	Cumulative energy demand	MJ eq/year	En	0.40	
Water (W)	Water use/depletion	m ³ /year	En	1.00	

C_i: characterization; N_i: normalization; α_{ijk} : weighting factor LCA+C2C; En: environmental parameter; S: social parameter.

- (c) **Group III or improvement categories:** Set of global sustainable performance indicators. These analyze and establish the strategies for the Continuous Improvement Plan (CIP), which includes the product redesign proposals. This group provides a single life cycle assessment score as an index of the environmental, economic and social footprint. The results are compiled in the Future Effects Inventory (FEI).

In order to analyze the product's CIP in one period, and to be able to propose the modification strategies in the next redesign, all the FEI macro-indicators must be analyzed with expressions (6) and (7). Specifically, IP% provides the improvement ratio between two product generations; it evaluates the CIP in two consecutive periods. On the other hand, IP_T analyzes the trend of change in successive product generations, or, in other words, the evolution of the product's sustainable performance from the initial implementation (launch

date) to the current period. These two indices make it possible to determine the overall efficiency of the CIP.

$$IP_{\%} = \frac{FEI(t_e) - FEI(t_e - 1)}{FEI(t_e)} \quad (6)$$

$$IP_T = \frac{FEI(t_e) - FEI(t_0)}{R - 1} \quad (7)$$

where:

- $IP_{R\%}$, the ratio of product improvement in two consecutive periods.
- IP_T , the changing trend in the complete evolution of the product (between generations or variants). If $IP_T > 0$, the product evolves correctly; if $IP_T < 0$, the strategies defined are not the correct ones, so it will be necessary to change the CIP.
- $FEI(t_e)$, the FEI indicator to be evaluated in the current period.
- $FEI(t_e - 1)$, the FEI indicator to be evaluated in the previous period.
- $FEI(t_0)$, the first FEI indicator obtained for the product, i.e., the first period coinciding with the date of market launch (first design).
- R , number of redesigns in which a strategy has been applied to improve environmental, social or economic performance.

The FEI macro-indicators are classified into three groups that organize the results of eco-efficiency and eco-effectiveness; any of these are candidates to be evaluated with $IP_{\%}$ and IP_T indices. These are described below: (1) efficiency; (2) consistency; (3) sufficiency.

- Efficiency (Ey): This corresponds to the best environmental and social performance result of the product obtained. This provides information on the improvement achieved between the different product versions (expression (8)) and the changing trend for the LCA+C2C endpoint categories (Q_k) (expression (9)). The use of this macro-indicator will minimize the impacts of the system, reducing the causes of the problem.

$$E_{R\%} = \frac{Q_k(t_e) - Q_k(t_e - 1)}{Q_k(t_e - 1)} \quad (8)$$

$$E_T = \frac{Q_k(t_e) - Q_k(t_0)}{R - 1} \quad (9)$$

- Consistency (Cy) or Effectiveness: This macro-indicator evaluates the cyclicity of the system and is composed of three complementary and proportional parameters. These can be expressed in Kg or %. CC (Cyclicality) quantifies the cycle-closing capacity of the system; ER (Energy Recovery) determines the energy recovery of the product with valorization strategies; and LCV (Loss of Cyclical Value) indicates the loss of resources, due to mismanagement of the end of life. These are calculated with expressions (10), (11) and (12). These indicators will also be subject to periodic evaluation with expressions (6) and (7).

$$CC = ReU + ReM + ReC \quad (10)$$

$$ER = RV \quad (11)$$

$$LCV = 1 - CC \quad (12)$$

where ReU are the reused system outputs (kg, %), ReM are the remanufactured system outputs (kg, %), ReC are the recycled system outputs (kg, %) and RV are the energy revalued system outputs (kg, %).

- Sufficiency (S): This is a metric of positive impact or creation of value. This implies that, apart from reaching zero-impact strategies, the solution must include plans for regeneration after previously caused damage, i.e., strategies to contribute to the planet's recovery. It is quantified from the C2C Global Score ($C2C_{GS}$) and economic indicators.

Firstly, regarding the C2C Global Score ($C2C_{GS}$), the input data for the calculation are the results obtained in the C2C certification for each category. These are weighted according to the certification milestone (Basic, Bronze, Silver, Gold or Platinum) using expression (13).

$$C2C_{GS} = \frac{1}{5} \cdot \sum_{i=1}^n (B_i \cdot 0.1 + Br_i \cdot 0.25 + Sv_i \cdot 0.5 + G_i \cdot 0.75 + P_i \cdot 1) \quad (13)$$

where:

- i , each category analyzed in the C2C certification. $C2C_i = \{1,2,3,4,5\} = \{\text{material health, material recovery, energy, water, social}\}$.
- B_i , score obtained in each category i at the basic level; Br_i , score of each category i in the bronze level; Sv_i , score of each category i in the silver level; G_i , score of each category i in the gold level; and P_i , score of each category i in the platinum level.
- Considering $0 \leq C2C_{GS} \leq 1$. With the limits: $[0, 0.75]$ negative impact creation, $(0.75, 1)$ zero impact and $[1]$ positive impact creation.

Secondly, regarding the direct and indirect economic indicators, the Continuous Improvement Plan (CIP) must be analyzed from an economic point of view. Direct economic criteria (system costs) and indirect economic criteria (costs resulting from the impact of the system) are used. Therefore, firstly, the product life cycle is evaluated with life cycle costing [80] to determine the economic viability, and, secondly, the eco-costs [10] are calculated to analyze the quality of the solution proposed in a monetary unit, i.e., the need for investment to reverse the negative impacts caused by the system. The calculations require the following information: costs of all stages of the life cycle, eco-costs and the value of the eco-cost–value ratio (EVR) [81].

2.7. Design of Information Flow and Data Classification System

The development of the new assessment categories and their classification determined the need to design a flow of information and data, grouped into three inventories of results: (1) Cause Effects Inventory (CEI), (2) Quality Effects Inventory (QEI) and (3) Future Effects Inventory (FEI). Thus, the assessment process is carried out at three sub-stages: micro-, meso- and macro-assessment levels (see Figure 3). In these three stages, the sets of results are obtained, covering both eco-efficiency indicators (CEI and QEI) and eco-effectiveness indicators (QEI and FEI).

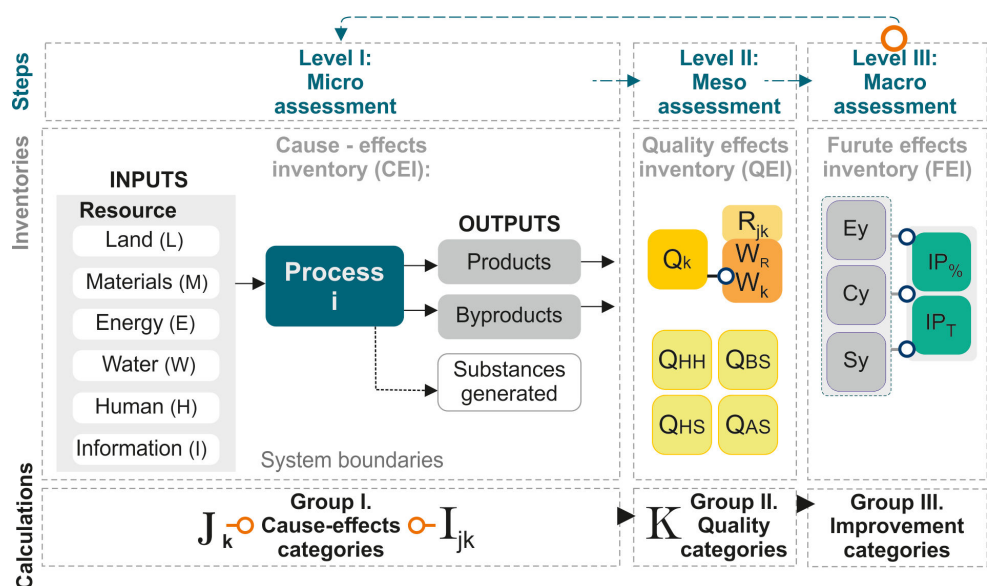


Figure 3. Classification of categories and information flow.

2.8. Methodology for Global Sustainability Design

Due to the existence of a standardized impact assessment process for LCA, it was decided to maintain the stages defined in ISO 14040 [9]. For the four steps, additional tasks and proposed modifications of the integrated method were defined. These are summarized in Figure 4.

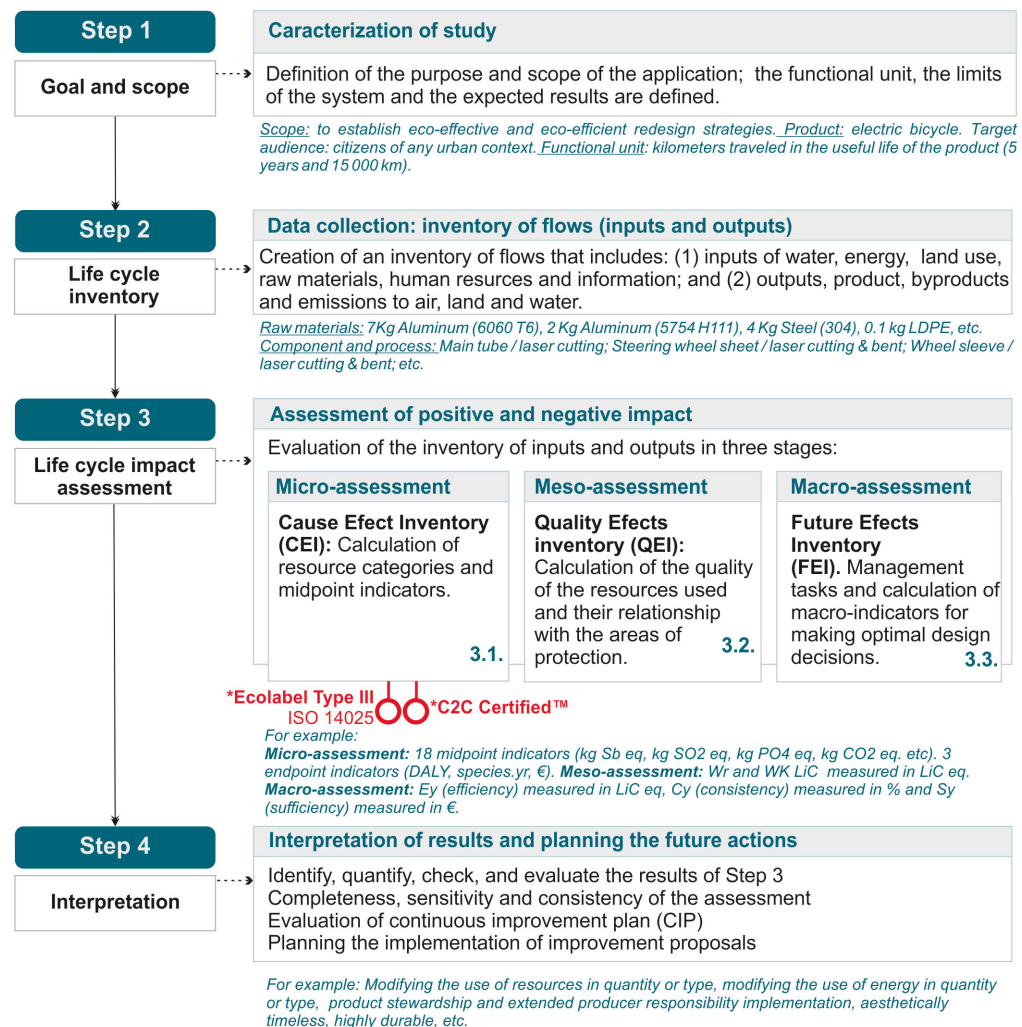


Figure 4. Phases of application of the proposed methodology.

The application of the methodology generates a final report that includes:

- **Life Cycle Inventory (LCI)** [9]
- **Cause Effect Inventory (CEI):** Results on eco-efficiency, with quantified environmental and social analysis, with S-LCA midpoint and social categories. Eco-effectiveness design data reflected in the valuation of the resources used (health, material reutilization, renewable energy and carbon management, water stewardship, social fairness and information). At the interpretation stage, these data help to identify strategies for minimizing and controlling environmental and social impacts.
- **Quality Effects Inventory (QEI):** Integrated results of the level of intervention of the causes in the generation of damage. These are obtained from the new weighting with LCA+C2C endpoint indicators, measured in LiC eq. In the interpretation stage, these data help to determine the quality level of the solution and to propose specific improvements in the input groups.
- **Future Effects Inventory (FEI):** Results of sustainable global performance with macro-indicators of efficiency, consistency and sufficiency. At the interpretation stage, this

information is relevant to the design and implementation of the Continuous Improvement Plan (CPI) of the product. The results are useful in selecting life cycle management strategies; defining strategies for product redesign, taking into account economic, environmental and social requirements; and establishing new improvement objectives and planning their implementation, thanks to obtaining a quantified value of the improvements between two consecutive time periods, and the tendency to change since the implementation of the CIP.

- **Certification reports.** Obtaining the necessary documents to certify the product with Ecolabel Type III (ISO 14025) [75] with the development of the Environmental Product Declaration (EPD) [52] and C2C certified in stage 3.1.

3. Results and Discussion

This section applies the methodology proposed in the design and evaluation of a sustainable mobility product. To validate the method, it was necessary to select a system that integrates various aspects into its life cycle: (1) in the sustainable dimensions—economic, environmental, social; (2) at the system boundaries (variety of inputs and outputs, in use of energy, materials, processes and equipment) and (3) with eco-efficient design strategies (for example, use of alternative energies) and eco-effective practices (cyclicality and resolution of social needs). For this reason, an eco-vehicle (city trike electric) was selected as a sustainable transport alternative. The following sections summarize the procedure and the most representative results.

3.1. Step 1: Goal and Scope

At this stage, the problem is characterized and the *objective and scope* of the LCA+C2C integrated analysis is defined. In this case, the objective includes: (1) to determine the global impact of the product (environmental, social and economic); (2) to establish eco-effective and eco-efficient redesign strategies to improve overall product performance and (3) to certify the product with Ecolabel Type III and C2C certification. The product is an electric bicycle and the target audience includes citizens of any urban context; the functional unit was established in the kilometers traveled in the useful life of the product (5 years and 15,000 km) and the limits of the system were delimited in the stages of manufacture, use and end of life.

3.2. Step 2: Life Cycle Inventory (LCI)

In the second phase, the LCI is carried out by compiling the set of inputs and outputs of the product life cycle. These data correspond to the “group I categories” shown in Figure 3 (flow of information and methodology data). This inventory must include at least the data necessary to calculate the impact categories (environmental and social) shown in Table 2. Table 3 shows a summary of the data for the case study.

3.3. Step 3: Life Cycle Impact Assessment

In step 3, the integrated assessment is carried out with the objective of determining the overall performance of the product (see Figure 3, “categories group II and III”). As mentioned in previous sections, the analysis has three levels: micro-, meso- and macro- assessment.

3.3.1. Step 3.1: Micro-Assessment

The micro level includes the Environmental Life Cycle Assessment (E-LCA) and Social Life Cycle Assessment (S-LCA; [59]) used to quantitatively assess the midpoint impacts. Calculation of characterization (Ci) and normalization (Ni) [9] is necessary to obtain (in the next step) the integrated weighting using the LCA+C2C endpoint. In this case, the Simapro [82] software was used for E-LCA, and Green Delta [83] for S-LCA. The results may be found in Table 4, column LCA.

Table 3. Summarized Life Cycle Inventory (LCI).

Level	Parameter	Result
Raw material	Material	Quantity (kg)
	Aluminum (6060 T6)	7.41
	Aluminum (5754 H111)	2.04
	Steel (304)	4.27
	LDPE	0.1
Product data
Components	Name/Process	Quantity (number)
	Main tube/laser cutting	1
	Steering wheel sheet/laser cutting and bent	2
	Wheel sleeve/laser cutting and bent	2
	Brake caliper support/laser cutting and bent	2
Social data	Supporting tube/laser cutting	1

	Workers	Workplace discrimination: No Overtime: Yes Stress: Yes ...
	Society	Local support: Yes Corruption: No ...
	Users	Ergonomic elements: Yes False advertising: No ...
Company	Manufacturing costs	1019.21
	Recycling strategy	Yes

Table 4. Results of micro assessment—CEI.

Dimension	LCA			C2C		Certification	
	Categories and Metrics	Category	Results	Certification			
	Impact category	C _i [unit]	N _i [year]	Ma. Health	Result ABC-X M/U/PC/E*	Level	
E-LCA	Abiotic dep. (kg Sb eq)	4.18	2.64 × 10 ⁻¹¹	Al 6060 T6	C/A/A/B	Basic	
	Acidification (kg SO ₂ eq)	5.62	1.74 × 10 ⁻¹¹	Al 5754 H111	C/A/A/B		
	Eutrophication (kg PO ₄ eq)	0.25	1.95 × 10 ⁻¹²	Steel 304	C/A/A/B		
	Global warm. (kg CO ₂ eq)	498.97	1.36 × 10 ⁻¹¹	Cardboard	X/A/A/A		
	Freshw.tox (kg 1.4-DB eq)	38.19	3.08 × 10 ⁻¹⁴	LDPE	X/A/A/X		
		
S-LCA	Impact category	Factor	N _i (points)	Ma. Reutilization	Origin	Destination	Level
	Child labor and forced labor		1	Al 6060 T6	0%	7.41%	Bronze %R (42.06)
	Health and safety (all stakeholders)		2	Al 5754 H111	0%	2.04%	
	Social benefit and social security		3	Steel 304	0%	4.27%	
	EoL and social responsibility		3	C. Cardboard	0%	0%	
	Economic and tech. develop.		1	
	Feedback mechanism and CP		4	Total	0.427	83.70	
...		
				Renewable energy		Level	

Table 4. Cont.

Dimension	LCA			C2C		
	Categories and Metrics			Category	Results	Certification
Ec-LCA	Impact category	€/unit	N _i (€)	renewable energy < 5% **		Bronze
	LCC	-	1200	Water stewardship		Level
	Global warm. (kg CO ₂ eq)	0.116	69.63	no audit for water management **		Basic
	Acidification (kg SO ₂ eq)	7.55	39.75	Social fairness		Level
	Eutrophication (kg PO ₄ eq)	3.60	0.93	Social issues relating to suppliers not evaluated; no positive impact strategy **		
	Summer smog (kg C ₂ H ₄ eq)	10.38	2.36			
	... / / ...			

Legend: * M/U/PC/E: Manufacturing/Use/Post-Consumption/EoL; ** This factor blocks the next level.

On the other hand, the product is evaluated with C2C, obtaining the qualitative level of the five categories (material health, material reutilization, renewable energy and carbon management, water stewardship and social fairness). The results may be found in Table 4, column C2C.

At this stage, independently documenting the information from the analyses is recommended, as the reports can be used later to obtain the Ecolabel Type III (EPD) [75] and C2C certification [84].

3.3.2. Step 3.2: Meso-Assessment

This step evaluates the quality of the resources used in the life cycle (inputs) and their relation with the impacts generated (outputs). The objective is to carry out the LCA+C2C endpoint weighting to obtain a quantification of the intervention of each resource (raw material, energy, water, land, human resource and information), in the generation of impact caused by the system. With the information in Section 3, and starting from the normalized impact data obtained in the previous stage, the following are determined:

1. **Partial impact weighting ($W_{i,j}$):** this is the impact generated by a given cause (input or resource). It is calculated with expression (2) and represents the level of interference of each resource in each of the protected areas (SH, SH, AS and BS). The results for the case study may be found in Table 5, column W_{ij} .
2. **Global impact weighting (Q_k):** this is the impact weighting in the LCA+C2C endpoint. This is calculated with expression (1) and represents the total interference level of the resources in the protected areas, measured through the LCA+C2C endpoint categories (Q_{SH} , Q_{SH} , Q_{AS} and Q_{BS}). The results for the case study may be found in Table 5, column Q_k .
3. **The quality of the inputs (W_r):** this is calculated with expression (4) and represents the quality level of the resource used (in LiC eq). The results for the case study may be found in Table 5, column W_r .
4. **The quality of the protected areas (W_k):** this is calculated with expression (5) and represents the quality level (in LiC eq) of the protection to the elements. The results for the case study may be found in Table 5, column W_k .

Table 5. Results of meso assessment—QEI.

K	N		Weighting LCA+C2C			
	N _K	J _k	W _{ijk}	Q _k	W _r LiC	W _K LiC
Q _{HH}	8.14×10^{-11}	M (J ₂)	1.01×10^{-11}	2.11×10^{-11}	0.88	0.74
		E (J ₃)	4.42×10^{-12}		0.95	
		H (J ₅)	6.53×10^{-12}		0.92	
Q _{SH}	30	H (J ₅)	2.07	5.94	0.93	0.80
		L (J ₁)	1.26		0.96	
		I (J ₆)	2.61		0.91	

Table 5. Cont.

N		Weighting LCA+C2C				
K	N _K	J _k	W _{ijk}	Q _k	W _r LiC	W _k LiC
Q _{BS}	1.71 × 10 ⁻¹⁰	M (J ₂)	1.62 × 10 ⁻¹¹	4.83 × 10 ⁻¹¹	0.91	0.28
		E (J ₃)	5.84 × 10 ⁻¹²		0.97	
		W (J ₄)	2.61 × 10 ⁻¹¹		0.85	
		L (J ₁)	1.57 × 10 ⁻¹³		0.99	
Q _{AS}	1.14 × 10 ⁴	E (J ₃)	4.56 × 10 ³	4.56 × 10 ³	0.60	0.40
		W (J ₄)	OBS		OBS	

Legend: OBS: outside of system boundaries; C: characterization; N: normalization; W: weighting; R_j: causes (resources); K: C2C+LCA categories; Q: endpoint LCA+C2C results; P: period; IP: improvement plant indicators; CEI: Cause Effects Inventory; QEI: Quality Effects Inventory; FEI: Future Effects Inventory.

Results are shown in Table 5. The overall interpretation is as follows: the less intervention there is between input (resource) and output (impact), the greater the quality of the resource, and therefore, the less environmental impact the product or system generates in its life cycle.

3.3.3. Step 3.3: Macro-Assessment

This step provides a set of macro-indicators that facilitate the results interpretation phase and the project management activities of design and product development. The macro-indicators of efficiency (E_y), sufficiency (S_y) and consistency (C_y) provide relevant information for the proposal of eco-effective and eco-efficient strategies. These serve to set the objectives of continuous improvement, in the redesign roadmaps, with which to obtain more sustainable versions of the product. Therefore, these support the strategic decision-making process for the Continuous Improvement Plan (see Table 4, column Step 3.3), with information about the product's evolution, i.e., between consecutive periods (IP%) or, since their launch (IP_T), analyzing the trend of change. Thanks to the macro-indicators, a "historical values sheet" is obtained. The results can be found in Table 6, including:

1. **Efficiency:** starting from the LCA+C2C endpoint impact data for the Q_{HH}, Q_{HS}, Q_{AS} and Q_{BS} categories and using expressions (8) and (9), the maximum performance of the product reached so far, the evaluation of the improvement between periods and the change trend since the product launch are obtained. See Table 4, E_y cells.
2. **Consistency:** using expressions (10), (11) and (12), the cyclicity of the system and the metabolic pathways are evaluated (C2C principle "waste equals food"). See Table 4, C_y cells. Likewise, subjecting these indicators to expressions (6) and (7) will obtain an assessment of the improvements achieved.
3. **Sufficiency:** expression (13) evaluates the eco-effectiveness of the product or the value created (C2C principle "celebrate biodiversity"); see Table 4, S_y cells. In addition, an economic analysis of the product life cycle with LCC is carried out, including the evaluation of direct and indirect cost impacts, using eco-costs and the EVR indicator [10]. The calculation of the improvement between periods, and the change trend, is carried out, as in the previous cases.

Table 6. Results of macro assessment—FEI.

FEI	Indicator	Historical Values (Pi)			Result (IP)	
		P0	P1	P2	IP%	IP _T
Ey	W _K	(t ₀)	(t ₁)	(t _e)	E%	E _T
	HH (LiC)	0.53	0.63	0.74	0.15	0.11
	HS (LiC)	0.64	0.72	0.89	0.19	0.13
	BS (LiC)	0.22	0.25	0.28	0.11	0.03
	AS (LiC)	0.3	0.4	0.40	0	0.05
Cy	Index	(t ₀)	(t ₁)	(t _e)	C%	CT
	CC (%)	0	0.4	0.6	0.33	0.30
	ER (%)	0.6	0.1	0.1	0	−0.2
	LCV (%) *	1	0.6	0.4	−0.5	−0.3
Sy	Index	(t ₀)	(t ₁)	(t _e)	S%	S _T
	C2C _{GS}	0.13	0.16	0.24	0.33	0.06
	LCC (€)	140	123.8	1200	0.90	530
	Eco-cost €	160	155	112.7	−0.3	−23.6
	Value (€) *	2000	1850	1600	−0.1	−200
	EVR*	0.08	0.08	0.082	−0.1	−0.01

* An improvement in this index supposes a result with a negative value.

3.4. Step 4: Interpretation

The last step includes the interpretation of results and the establishment of product redesign strategies for the continuous improvement plan; the consistency of the analysis is also verified. In this case study, the interpretation is simplified, given that the objective is to illustrate the use of the results provided by the methodology. An example will be given for one of the impact categories, a process that can be extrapolated to the rest of the LCA+C2C endpoint indicators.

Firstly, the techniques of the MICRO stage interpretation coincide with those carried out in conventional LCA and C2C. As the objective is to facilitate the interpretation process using the integrated LCA+C2C analysis, it is considered optional at this level. This analysis of the results will serve (at the meso level) as additional and detailed information for consultation in the life cycle impact improvement process, once the priorities for action on the causes are known.

Secondly, the MESO interpretation process is divided into two parts, the analysis of causes and definition of action strategies, according to the cause–effect interaction.

In the case of the sustainable mobility vehicle, the results indicate the need to prioritize action on the inputs (causes) in the following order:

1. Action in Q_{BS} (0.28 LiC eq) modifying the use of resources in quantity or type, in the following order: Water (0.85 LiC eq); Materials (0.91 LiC eq); Energy (0.85 LiC eq); Land (0.90 LiC eq).
2. Action in Q_{AS} (0.40 LiC eq) modifying the use of energy in quantity or type.
3. Action in Q_{HH} (0.74 LiC eq) modifying the use of resources in quantity or type, in the following order: Materials (0.88 LiC eq); Human (0.92 LiC eq); Energy (0.95 LiC eq).
4. Action in Q_{HS} (0.80 LiC eq) modifying the use of resources in quantity or type, in the following order: Information (0.91 LiC eq); Human (0.93 LiC eq); Land (0.96 LiC eq).

As with the micro level, the relationships of each resource (cause) with its impact are identified, and in the ICV, the type of input is known; it will therefore be easy to define improvement strategies. In this case, for example, the strategies according to outputs (impact and protected areas) should be prioritized in the following order for the Q_{HH} category:

1. The Q_{HH} category is mainly influenced by the quality of the materials used; in order to reduce the effects (impacts) on human health, action should first be taken on the materials.
2. As in the C2C analysis, the materials are evaluated individually; this action should be focused on those that have been classified with typology X (ABC-X assessment): corrugated cardboard, LDPE and paper. The elimination/modification of these materials will be considered.
3. These strategies, linked to the materials, contribute to reducing the following impacts: ionizing radiation (5×10^{-5} DALY), global warming (498.97 Kg CO₂ eq), human toxicity (387.68), SMOG (2781×10^{-13} kg 1.4-DB eq), ozone depletion (38×10^{-5} kg CFC-11 eq) and particulate matter formation (0.024 kg PM₁₀ eq).
4. Similarly, the other categories, Q_{SH} , Q_{BS} and Q_{AS} , are interpreted.

Finally, the process of the macro-stage interpretation will be useful to review and update the Continuous Improvement Plan (CIP) of the product. This involves the proposal of redesigns and strategies, focused on improving the environmental, economic and social performance of the product in successive milestones, marked as periods of improvement. For example, by analyzing the macro-indicator of efficiency (E_y), and considering the Q_{HH} category, an $E_{R\%}$ value of 0.15 is obtained, i.e., there is a 15% improvement in performance between the current variant and that of the previous period. In addition, an E_T value of 0.11 is obtained, this being the tendency of change in the improvement plan, throughout all the periods of the evolution of the product, since its launch. As it is greater than 0, the improvement plan is adequate for this impact category. These results indicate that the objective in the next redesign will be to improve the efficiency values, by focusing on the strategies according to the hierarchy of causes, indicated in the previous paragraph. Regarding the macro-indicator of consistency (C_y), cyclicity has a value of 0.6 (an adequate but improvable value, since it must reach 100% cyclicity, or a value of 1). This result implies the existence of practices that reduce the eco-effectiveness of the system, such as energy recovery (0.1) and landfill waste (0.4). Considering the LCV index, a loss of 40% is obtained; therefore, data will have to be improved in the following period as a redesign milestone. Finally, the macro-indicator of sufficiency (S_y) determines, among other requirements, that it will be necessary to reduce the impacts on the product life cycle as, indirectly, these imply a cost increase of EUR 112.7 (value of eco-costs) over EUR 1200 (direct costs of the life cycle of the product).

Once the results have been analyzed, improvements focused on the meso-level should be proposed. It is worth highlighting the existence of resources and databases, where strategies linked to environmental, social and economic impact, C2C principles and other eco-efficient and eco-effective methods are collected, such as, for example, [85–88]. These strategies will be proposed and planned for implementation in the next period of evolution of the product and will be evaluated once it is finished.

4. Conclusions

Recent trends in sustainable practices and a greater knowledge of the environmental, economic and social impacts generated during the manufacture, use and end of life of products have led to a change in the consumption patterns and behavior of the population, with a more active commitment to and participation in the care and recovery of the planet [89]. Users are increasingly demanding products that protect the environment and society and are willing to pay more as long as these products are manufactured in a sustainable manner [90].

This change in consumption habits forces organizations to orient their corporate objectives towards global sustainability or 3E (economic, environmental and social), integrating strategies of eco-design, clean production, extended producer responsibility (EPR) or circular economy into the product portfolio management [91].

In the design project, this results in using ecodesign practices, effective evaluation methods and tools during the product planning stage. Early design phases are critical in

order to optimally address the product life cycle: an overall sustainable solution demands a variety of requirements. Firstly, environmental criteria that respect the natural cycles of the biosphere and allow for comprehensive control of the environmental impact are needed. Secondly, it is necessary to take into account the social and economic repercussions of the product, considering its impact on health, well-being, quality of life and even on culture and other anthropological spheres. Finally, more far-reaching criteria can be considered to reverse the damage caused to the ecosystem and society through regeneration and recovery actions.

This variety of requirements demands a change in model in the management of industrial design projects, where the development decisions of a new product (or the redesign of marketed models) have a positive impact on all phases of the life cycle (extraction of materials, manufacturing, use and end of life). This requires that the design process must be supported by an orderly and systematic methodology of management, evaluation and implementation of solutions with a balance between economic, social and environmental benefits.

To achieve this objective, new, useful frameworks have been developed (such as cleaner production, industrial ecology, green manufacturing, cradle to cradle, blue economy, circular economy, among others) that include a variety of techniques and tools. These new trends are an important complement to design engineering and can bring advances in product life cycle management, improving the traditional frameworks and methodologies of sustainable design.

In this research, the integration of the life cycle assessment (LCA) and cradle-to-cradle (C2C) techniques in a single procedure is carried out from the development of the LCA+C2C endpoint weighting method. The methodology is subsequently verified in a case study of products for sustainable mobility in Spain (city trike electric). The results show that an integrated LCA and C2C evaluation can help in proposing more balanced sustainable strategies. In addition, the method would be a suitable method to measure trade-offs between economic, social and environmental results, for practical purposes and future redesigns. The future line of work to be considered is the development of software (database and calculation tool) that meets the computational needs (automated evaluation to reduce analysis time and cost with LCA + C2C endpoints). Currently, the risks linked to this type of research are related to obtaining data in the social dimension. The lack of standards, regulations and quantitative assessments means that social aspects are not considered by companies.

The proposal makes it possible to reduce the complexity of the design process, simplifying the evaluation phases and facilitating the interpretation of the results, without modifying the level of detail of LCA or the eco-effective approaches of C2C. The new C2C+LCA endpoint weighting method provides an environmental, social and economic evaluation in a single procedure, with different indicators organized into levels of action in design, evaluation and management:

- Level of evaluation of the product life cycle, which includes the Environmental Life Cycle Assessment (E-LCA) and Social Life Cycle Assessment (S-LCA). Results are collected in the Cause Effect Inventory (CEI), with eco-effectiveness design data and resources used (health, material reutilization, renewable energy and carbon management, water stewardship, social fairness and information). At the interpretation stage, these data help to identify strategies for minimizing and controlling environmental and social impacts.
- Level of product design and redesign. Results are collected in the Quality Effects Inventory (QEI), which integrates data of the level of intervention of the damage causes. These are obtained from the new weighting with LCA+C2C endpoint indicators. In the interpretation stage, these data help to determine the quality level of the solution and to propose specific improvements in the input groups.
- Level of management of the product life cycle, in the Continuous Improvement Plan (CPI). Results are collected in the Future Effects Inventory (FEI), with data of

sustainable global performance with macro-indicators of efficiency, consistency and sufficiency that can aid in: (1) selecting life cycle management strategies; (2) defining strategies for product redesign, taking into account economic, environmental and social requirements; and (3) establishing new improvement objectives and planning their implementation, thanks to obtaining a quantified value of the improvements between two consecutive time periods, and the tendency to change since the implementation of the CIP.

The following benefits are achieved individually for each method (life cycle assessment and cradle to cradle). Firstly, the LCA results are completed with the identification and grouping of problem cause types (material, energy, water, land, human and information) and the calculation of cause–effect influence. This facilitates the interpretation of the results and speeds up the identification of the problem. Secondly, a quantitative process is provided to the C2C techniques. Additionally, the S-LCA data improve the level of detail and reduce the error of the C2C results in the social category, by being able to identify the set of inputs that generate direct, or indirect, social impacts (externalities). Finally, integrated assessment helps to find a balance between eco-effective and eco-efficient strategies.

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