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**Towards an Engineering Method to
Include the Three Pillars of
Sustainability and Circularity in the
Design of Mechatronic Products**

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“Nothing in life is to be feared, it is only to be understood. Now is the time to understand more, so that we may fear less.”

Maria Skłodowska-Curie

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LIST OF ABBREVIATION

Anti-lock Braking System	ABS
Active Disassembly	AD
Augmented Reality	AR
Business Model	BM
Bill of Materials	BoM
Computer-Aided Design	CAD
Cost-Benefit Analysis	CBA
Climate Change	CC
Circularity Design Guidelines	CDG
Conventional Design Processes	CDP
Construction and Demolition Waste	CDW
Circular Economy	CE
Cumulative Energy Demand	CED
Circular Economy Index	CEI
Circular Economy Indicator Prototype	CEIP
Circular Economy Performance Indicator	CEPI
Circular Economy Toolkit	CET
Disassembly Effort Index	DEI
Design for Assembly	DFA
Design for Cost	DFC
Design for Chronic Risk Reduction	DFCRR
Design for Disassembly	DFD
Design for Environment	DFE
Design for Energy Conservation	DFEC
Design for End of Life	DFEOL
Design for Flexibility	DFF
Design for Logistics	DFL
Design for Life Cycle	DFLC
Design for Manufacture	DFM
Design for Manufacture and Assembly	DFMA
Design for Mass Customization	DFMac
Design for Material Conservation	DFMC
Design for Failure Modes	DFMEA
Design for Miniaturization	DFMin
Design for Modularity	DFMod
Design for Maintainability	DFMt
Design for Procurement	DFP
Design for Packaging	DFPk
Design for Quality	DFQ
Design for Recycle	DFR
Design for Robustness	DFRb
Design for Remanufacture	DFRem

Design for Repairability	DFRep
Design for Reliability	DFRL
Design for Reverse Logistics	DFRL
Design for Reuse	DFRu
Design for Safety	DFS
Design for Supply Chain	DFSC
Design for Supportability	DFSp
Design for Social Responsibility	DFSR
Design for Six Sigma	DFSS
Design for Sustainability	DFSt
Design for Serviceability	DFSv
Design for Testability	DFTest
Design for Variety	DFV
Design for Waste Minimization and Recovery	DFWMR
Design for X	DfX
Digital Product Passport	DPP
Disassembly Sequence Planning	DSP
ease of Disassembly Metric	eDiM
Electrical and Electronic Equipment	EEE
End-of-Life Vehicles	ELV
End-of-Life	EoL
European Product Registry for Energy Labelling	EPREL
Energy-Related Product	ErP
Eco-design for Sustainable Products Regulation	ESPR
European Union	EU
Eco-cost Value Ratio	EVR
Failure Mode and Effect Analysis	FMEA
Fastener removable but not reusable	FNR
False Positive Rate	FPR
Fastener Reusable	FR
Fastener neither removable nor reusable	FU
Greenhouse Gas	GHG
Global Resource Indicator	GRI
Global Warming Potential	GWP
Human Resources	HR
Health, Safety, and Environment	HSE
Intergovernmental Panel on Climate Change	IPCC
Istituto Nazionale di Statistica	ISTAT
Information Technology	IT
Joint Research Centre	JRC
Life Cycle Assessment	LCA
Life Cycle Cost	LCC
Life Cycle Engineering	LCE
Life Cycle Inventory	LCI
Life Cycle Impact Assessment	LCIA

Life Cycle Thinking	LCT
European List of Waste	LoW
Material Circularity Indicator	MCI
Maynard Operation Sequence Technique	MOST
Material Reutilization Score	MRS
New Product Development Process	nPDP
Net Present Value	NPV
Product Based System	PBS
Personal Computer	PC
Printed Circuit Board	PCB
Product Design Process	PDP
Product-level Circularity Metric	PLCM
Product Lifecycle Management	PLM
Project Management Office	PMO
Priority Part	PP
Personal Protective Equipment	PPE
Polystyrene	PS
Product Service System	PSS
Present Value	PV
Quality Assurance	QA
Research and Development	R&D
Recyclability Benefit Rate	RBR
Recycling Desirability Index	RDI
REmanufacturing with PROduct PROfiles	REPRO ²
Recycling Indices	RI
Receiver Operating Characteristic	ROC
Restriction of Hazardous Substances	RoHS
Reuse Potential Indicator	RPI
Repair Scoring System	RSS
Sustainable Circular Index	SCI
Sustainable Circular Index	SCI
Sustainable Design Goals	SDG
Substitute It Now	SIN
Social Life Cycle Assessment	SLCA
Surplus Ore Potential	SOP
Basic tool	TC
Total Cost of Ownership	TCO
Transdisciplinary	TD
Threshold	THR
Commercially available tools	TNC
Not existing tool	TNE
Proprietary tool	TP
True Positive Rate	TPR
Theory of inventive problem solving	TRIZ
Product group-specific tool	TS

Television	TV
Unmanned Aerial Vehicle	UAV
United Nations Environment Programme	UNEP
Virtual Reality	VR
Value-based Resource Efficiency Indicator	VRE
Water Consumption Potential	WCP
Waste Electrical and Electronic Equipment	WEEE

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ABSTRACT

The escalating awareness of environmental and social responsibility, coupled with an increasing consumer demand for sustainable products, presents a profound shift in the dynamics of product design. Concurrently, movements like Zero Waste Europe, or Right to Repair have empowered consumers to advocate for a circular economy, urging the removal of barriers that inhibit product repair and promote longer product lifespans.

The confluence of heightened consumer expectations and evolving European political priorities has prompted an urgent need to address sustainability and circularity in the design of mechatronic products. A holistic approach that considers the environmental, economic, and social dimensions across the whole lifecycle of a product is essential.

This research work endeavours to develop an eco-design methodology that incorporates sustainability – encompassing its three pillars – and circularity principles into the design of mechatronic products, culminating in a comprehensive sustainability index for each analysed product. This methodology integrates environmental, economic, social, and circular indicators to guide the design for sustainability of mechatronic goods. The methodology is divided into five primary phases, ranging from product classification to life cycle engineering, sustainability index assessment, implementation of eco-design methodologies, and final report production. Each phase is meticulously designed to provide designers with actionable insights for enhancing sustainability.

The applicability of this methodology is substantiated through two compelling case studies within the mechatronic product family (i.e., household appliances). In the case of an electric oven, the methodology revealed that the social dimension presented the greatest challenge, with the methodology's stringent evaluation standards posing a hurdle. Furthermore, the environmental and economic indicators fell below acceptable thresholds. The application of the methodology resulted in a remarkable 32% enhancement in the overall sustainability of the oven. Specifically, the social aspect was ameliorated by ensuring workers' rights

and freedoms were upheld throughout the supply chain. The environmental and economic indicators also saw substantial improvements.

In the case of the cooker hood, the focus was put in the environmental aspect, followed by the economic one. Through the methodology, those dimensions were addressed, and eco-design actions were focused on improving the product's efficiency during its use. By replacing the motor and optimizing manufacturing and other eco-design actions, the cooker hood's sustainability index increased significantly by 39%. This clearly demonstrates the substantial impact that eco-design measures can have on the sustainability of mechatronic products.

Additionally, this research work proposes developing a sustainability label that would empower customers by giving them clear, understandable information about the effects of a product at every stage of its lifecycle. With the help of this label, which rates products from A to G, consumers can make well-informed choices based on social, economic, environmental, and circular factors.

The research further identifies areas for future work, including the integration of detailed data from Digital Product Passport (DPP) to enhance data reliability, the potential application of Machine Learning to streamline Life Cycle Inventory (LCI) phase, exploring the methodology's extension to various product categories, and developing a software program to automate the methodology.

In conclusion, this research work addresses the comprehensive dimensions of sustainability and circularity, promoting the application of eco-design methodologies and contributing to the ongoing paradigm shift towards more environmentally responsible and sustainable product design.

1. INTRODUCTION

The increasing recognition of the social issues confronting our society, has led to a need for integrating ideas like sustainability and circularity into engineering. In a world where technologies and systems are interconnected, it has become imperative to create products that are not just efficient and functional but also sustainable and circular. Nowadays, mechatronic products have significant ties to environmental concerns. The discourse surrounding the environmental sustainability of such products extends beyond ecological considerations to encompass economic and social dimensions. The shift from a linear to a circular economy is an essential measure to safeguard the environment from product waste and pollution, generate fresh sustainable advantages for industries, shield businesses from prospective resource scarcity, and stimulate economic growth. Through deliberate policies, policymakers are proactively laying the foundation for this substantial transition, with mechatronic products emerging as the most impacted category in the market. Given the substantial uncertainties surrounding design choices during the initial design stage, it becomes imperative to introduce innovative approaches and resources that can furnish designers with a foundation for assessing the sustainability level of a specific product or process. This is especially crucial because it is widely recognized that the initial design decisions made in the Conceptual and Embodiment Design phases exert a significant influence, accounting for 70-80% of the overall product cost. In a global context of finite resources and environmental pressures, this research work focuses on the quest for innovative solutions that enable the creation of mechatronic products with minimal environmental impact, a positive contribution to society, and, simultaneously, economic efficiency to ensure their viability in the market.

The goal of this project is to offer engineers and the academic community an approach to tackle the issues of sustainability and circularity in designing products. It aims to transform how these products are imagined, created, and produced ultimately playing a role, in creating a circular future for generations to come. To accomplish this, a framework has been developed that incorporates aspects of sustainability allowing for an assessment of these products. Through the analysis of the various product impacts, the designer is guided in the application of potential eco-design actions, thereby

enhancing the product's sustainability. Furthermore, as a result, a product classification is obtained based on its relative performance concerning environmental, economic, social, and circular impacts. This aims to provide maximum information to the consumer so that their decision-making process is well-informed. The suggested approach was tested within the household appliance sector, yet its applicability can readily be expanded to encompass other product categories.

1.1. CONTEXT OF THE RESEARCH WORK

Over the past few decades, numerous investigations have indicated a growing global demand for products and services that meet sustainability criteria. Sustainability entails establishing an economic system that not only ensures a high quality of life but also regenerates the environment and its resources. Specifically, an increasing environmental consciousness has emerged within consumers, resulting in a broadly favourable perception of product green labels (Laroche, Bergeron, & Barbaro Forleo, 2001) (Compromiso RSE, 2020). This shift is a response to environmental policies and regulations that are aligning with eco-sustainability principles. Industrial enterprises and companies are inclined to manufacture products in accordance with these guidelines, thereby offering the market more sustainable product options (Swenson & Wells, 2018). In 2015, all member states of the United Nations embraced the 2030 Agenda for Sustainable Development, which stipulated 17 Sustainable Development Goals (SDGs) that constitute a pressing demand for collaborative action from all nations on a global scale (United Nations, 2015). Furthermore, within the context of the European Green Deal a set of policies and measures have been implemented by the European Union (EU). Figure 1 presents the key aspects of the Green Deal. The industrial sector holds a pivotal position as it bears a significant share of responsibility for emissions and energy consumption. Environmental and energy issues are closely intertwined; therefore, they are important considerations in engineering design. Market demands and design considerations for energy-related product (ErP) development include energy efficiency, the use of alternative renewable energy sources, and the reduction of environmental load. Substituting fossil fuels with renewable energy sources and enhancing product energy efficiency are of paramount

importance in EU policies, as the EU heavily relies on the import of fossil resources (e.g., natural gas). The current sociopolitical context makes it crucial to seek alternatives and promote the circularity of raw materials.

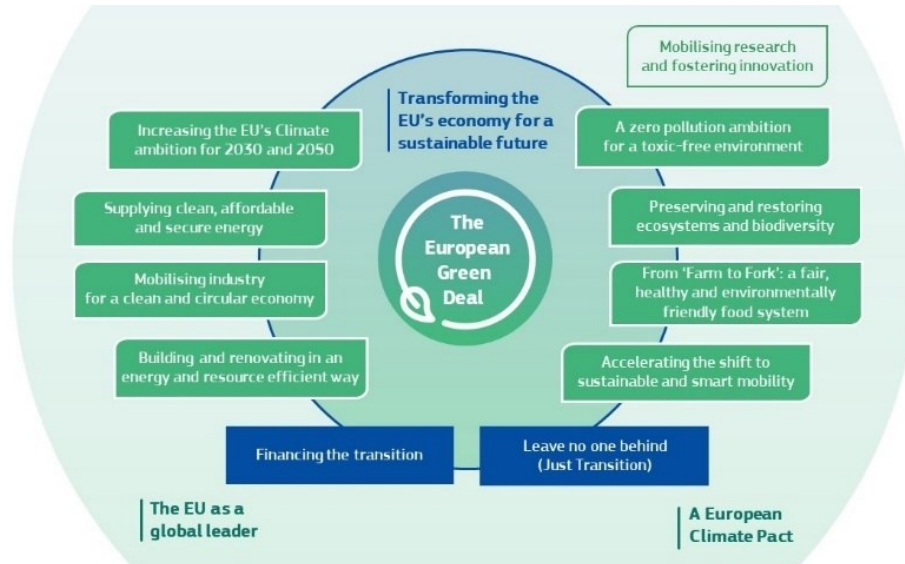


Figure 1. The European Green Deal. Image source: (European Commission, 2019a).

In this context, designing environmentally friendly products and services is one of the methods to attain sustainable development. It promotes a holistic approach aimed at preventing or mitigating impacts across the entire product lifecycle, addressing a wide range of environmental concerns (Le Pochat, Bertoluci, & Froelich, 2007). In recent years, numerous eco-design methodologies and tools have been introduced. Typically, these solutions either lean toward excessive qualitative aspects or demand an abundance of intricate input data. Moreover, they often lack effective integration into the design process workflow (Rossi, Germani, & Zamagni, 2016). Based on their function and purpose, different categories of eco-design tools can be identified: environmental impact assessment tools, guidelines and checklists, eco-design decision support tools, tools for material selection, tools for energy efficiency, tools for End-of-Life (EoL) management, or tools for sustainable supply chain management (Bovea & Pérez-Belis, 2012).

Through a restructuring of the design process that prioritizes eco-design activities, there is a potential for numerous additional enhancements in this context. This could stimulate the emergence of a new breed of design tools seamlessly integrated into the established design process, which consider

environmental factors when formulating product decisions. This research contributes to the pursuit of this goal.

1.2. TECHNICAL AND SCIENTIFIC RESEARCH OBJECTIVES

This research aims to enhance the implementation of eco-design in industries. Currently, designers have numerous factors to consider (e.g., safety, cost, quality, legal considerations, shorter lead time, embedded intelligence, etc.), so the environmental or sustainability aspect is just one among many (Brambila Macias & Sakao, 2021). Additionally, although various methods can be found in the literature, they are not always easy to implement or effective when applied in industry (Rossi, Germani, & Zamagni, 2016) (Dekoninck, et al., 2016).

The primary goal of this research is to establish a resilient eco-design methodology capable of endorsing the designer's decisions for assessing both the immediate and long-term effects across the lifecycle of mechatronic products.

The conceptual framework created in this project integrates the three dimensions of sustainability, along with circularity principles, into the mechatronic product design process. It is based on Life Cycle Engineering (LCE) and aims to enhance the sustainability of these products throughout their entire lifecycle. The proposed methodology allows for the inclusion of the desired life cycle phases (i.e., raw material extraction, manufacturing, use phase, transportation, maintenance, and End-of-Life) with the utmost flexibility. To achieve this, current approaches, methods, and practices in these areas have been reviewed and developed. Below, the various methods employed to guide the designer and achieve an increase in the sustainability of the analysed product are described:

- *Environmental Index*: it analyses the environmental impacts of the product under consideration. Comparing the outcome of the Life Cycle Assessment (LCA) for certain key environmental indicators (e.g., global warming potential, water consumption potential, surplus ore potential, cumulative energy demand) with a reference value. This reference represents the product within the analysed family that has the most negative environmental

impacts. This approach allows for obtaining a result that provides an understanding of the product's environmental sustainability within its category, while also facilitating the identification of critical issues.

- *Economic Index*: it analyses the Life Cycle Cost (LCC) of the mechatronic product, which is the total cost, comprising multiple items incurred across the different phases of its lifecycle. Like the environmental index, the product under study is compared with a reference value to assess its performance within the product-group category. In this case, the reference is a product form the same category that exhibits the worst resource consumption performance (e.g., worst energy efficiency) throughout its lifecycle.
- *Social Index*: it analyses the working conditions and the level of freedom to evaluate whether all the stakeholders and countries involved in its lifecycle adhere to them. This helps the designer to identify which phase of the lifecycle and which stakeholder within the supply chain is critical for the overall sustainability evaluation.
- *Circularity Score*: this score integrates an analysis of product reliability (i.e., disassemblability and durability analysis) and end-of-life management. Its assessment promotes understanding of how circular the analysed product is from the designer's perspective, enabling a more comprehensive product analysis.

The second goal of the developed approach is the creation of a repository for eco-design actions and best practice guidelines.

Through this objective, the aim is to establish a database that compiles design actions and strategies, as well as guidelines and best practices related to sustainability and circularity. This resource provides valuable information to professionals during the design phase on how to implement effective sustainable practices. The repository must be flexible, ensuring it can expand and remain up to date with the latest guidelines in the field of eco-design and circularity. The index assessment phase has the capability to identify sustainability criticalities, highlighting the areas where issues are present. Nevertheless, it does not offer recommendations regarding design modifications that can be applied. The establishment of redesign guidelines can aid designers in redesigning the product. These guidelines are crucial for

determining the actions required to mitigate the negative impacts of the product. The proposed improvement actions for the designer and engineer are obtained from this database. This way, theoretical knowledge is transferred into practical knowledge, which is essential when aiming to conduct transdisciplinary (TD) research (Sakao & Brambila Macias, 2018) in eco-design.

The third goal in applying the methodology is to assist the final consumer in making informed decisions, enabling them to be aware of all the impacts of that product.

This objective aims to empower consumers by providing them with detailed and transparent information about the products they purchase. It helps to educate consumers about the environmental, social, and economic impacts of products so that they can make informed decisions. This research work proposes the creation of a sustainability label, through which consumers can clearly visualize the different outcomes of the product analysis.

Finally, it is illustrated how the goals of this project align with the United Nations' 2030 Agenda, describing the SDGs to which it directly contributes and demonstrating its impact on multiple key aspects:

4 QUALITY EDUCATION



For experts and students in the field of design and engineering, the construction of a database that gathers strategies and rules for sustainability and circularity in product design can be a useful educational resource.

5 GENDER EQUALITY



By providing detailed and transparent information about products, this research empowers consumers, including women, to make informed decisions about their purchases and their impact on society. In addition, the presence of diverse perspectives is crucial for fostering innovation and creating solutions that mirror the norms, values, and aspirations of the community.

This project promotes diversity of perspectives and experiences in the industry (crucial during the development of eco-design initiatives), thereby contributing to the reduction of gender inequalities in the workplace.

8 DECENT WORK AND ECONOMIC GROWTH



Sustainability and circularity in product design can foster job creation in sectors related to eco-innovation and sustainable production. Additionally, thanks to the social index incorporated into the methodology, this project promotes the protection of fair working conditions.

9 INDUSTRY, INNOVATION AND INFRASTRUCTURE



The project promotes innovation in the design process of mechatronic products by developing a comprehensive method that incorporates sustainability and circularity into the design. This contributes to the development of sustainable infrastructure and encourages the creation of cleaner and more efficient industries.

11 SUSTAINABLE CITIES AND COMMUNITIES



Applying sustainability and circularity principles during the creation of mechatronic products leads to the development of products that are more environmentally and socially friendly. These products can contribute to the building of more sustainable cities and healthier communities.

12 RESPONSIBLE CONSUMPTION AND PRODUCTION



By promoting material efficiency and reuse, the project encourages responsible production and consumption. This reduces waste and minimizes the environmental impact of products. Furthermore, through the proposed sustainability label, it enables consumers to make well-informed decisions when purchasing products.

13 CLIMATE ACTION

This objective is directly related to the proposed project. By analysing the environmental impact of mechatronic products, critical design issues can be identified, and the proposed framework guides the designer to minimize their negative impacts (e.g., by promoting alternative materials, more efficient manufacturing processes, etc.).

17 PARTNERSHIPS FOR THE GOALS

The creation of the eco-design guidelines database as well as the collaboration between the industrial and academic sectors has been essential for the development of this methodology. Furthermore, this project highlights the need to promote government partnerships that encourage the adoption of this approach in the design of mechatronic products.

1.3. PROGRESS BEYOND THE STATE OF THE ART

There has been a growing interest in sustainability and eco-design in recent years, with an increasing number of European directives aiming to act as a catalyst for effectively incorporating these approaches into product design (Wasserbaur, Sakao, & Milios, 2022). However, upon analysing the available literature, it becomes evident that there is no flexible methodology that allows for the comprehensive analysis of all dimensions of sustainability integrated with circularity at the product level (De Pascale, Arbolino, Szopik-Depczyńska, Limosani, & Ioppolo, 2021). For some of the aspects considered in the sustainability assessment proposed (e.g., repairability), various eco-design actions for specific products can be found in the literature (e.g., cooktops, ovens, washing machines) (Boix Rodríguez & Favi, 2022) (Boix Rodríguez & Favi, 2023a), but there is a lack of a structured method to guide the redesign process (Favi C., Germani, Mandolini, & Marconi, 2016).

One of the key advancements of the proposed methodology is the integration of all these concepts into a single framework, while also adopting

a life-cycle-based approach. This enables a comprehensive assessment of product sustainability, offering feedback to designers after considering the characteristic parameters that influence environmental, economic, social, or circular performances. These aids to the designer during the redesign process come from the best practices and eco-design guidelines collected in the created repository.

One of the most popular methods for assessing environmental impacts is LCA. It enables a holistic approach to the entire product lifecycle, from raw material extraction to end-of-life (“from cradle to grave”). Simplified methods have also been developed to facilitate a quicker analysis of environmental impacts, with some of them integrated into computer-aided design (CAD) tools and Product Lifecycle Management (PLM) systems (Cappelli, Delogu, & Pierini, 2006), enabling impact assessment during the early design stages, some of them allow the designer to analyse different scenarios so the most ecofriendly one can be selected (Gaha, Benamara, & Yannou, 2018). However, while these tools can provide quantitative data on product-related environmental impacts, they do not have the capability to offer alternative solutions or recommend enhancements. In addition, the comprehensive structure for performing an LCA provides professionals with a broad spectrum of choices to conduct the analysis. This absence of restrictions in shaping LCA studies for the targeted system has resulted in diverse assumptions and findings across the existing research (Mio, Fermeglia, & Favi, 2022), making impossible to compare LCA studies performed by different practitioners. In the literature, an initial attempt to standardize the results of LCA analysis for the specific case of cooker hoods can be found, where the authors propose a technique for choosing multiple design parameters to establish a standard reference point, enabling equitable comparisons of LCA studies in the household appliances sector (Gabriel, Boix Rodríguez, Gaha, Mio, & Favi, 2023).

In this research project, this methodology is extended to be applicable to mechatronic products, and a different case study is conducted to validate its applicability. Going beyond the current state of the art by introducing a series of indices, that are essential for comparing findings across various studies and for recognizing design solutions suitable for the integration of eco-design actions within this domain, for this new product family.

When aiming to extend the product lifespan, product repair plays a crucial role in advancing the concept of a circular economy for electro-mechanical products. It involves the introduction of service loops aimed at prolonging the product's lifespan, with the goal of enabling the product's reuse, ongoing maintenance, and technical upgrades (Bocken, De Pauw, Bakker, & Van Der Grinten, 2016). Therefore, having a robust method for its evaluation is crucial. One of the challenges identified in the literature is the difficulty in determining the disassembly time (Boix Rodríguez, Gabriel, Gaha, & Favi, 2023). Currently, the eDiM database (based on the MOST method) is primarily used. However, it is not comprehensive enough to cover a wide range of mechatronic products. This study has succeeded in expanding this database, making it more suitable for use in other mechatronic products. As for end consumers, policies like energy labels have been shown to save consumers up to 285 € per year on appliance-related bills (European Commission, n.d. a). According to a study conducted by the Special Eurobarometer 492 in 2019, approximately 93% of consumers were familiar with the energy label, and about 79% took it into account when purchasing energy-efficient products (European Commission, n.d. a).

With this research project, the author aims to go further by creating a label that evaluates the product's sustainability, not just its energy efficiency or repairability (as introduced in France with the French Repairability Index). This way, information about overall sustainability (ranging from A to G) will be provided, as well as the results of various indices that compose it (i.e., environmental, economic, social, and circular). To achieve this, technical information that non-specialized audiences cannot comprehend must be transformed into indices from 0 to 1, indicating how well the product performs compared to others in its category. Additionally, it is innovative to introduce uncertainty levels associated with calculations, aiming for maximum transparency, and promoting the use of reliable and established sources of information.

1.4. THESIS OVERVIEW

The proposed research work needed a comprehensive analysis of relevant literature in the domains of eco-design and sustainability analysis, with a focus on the mechatronic field. The structured methodology comprises multiple phases that enable any user to effectively implement the approach. The real-life case studies, which include observations and remarks, provide additional support for the method's application. The thesis is structured as follows:

Section 2 (State of art) discusses the state of art in the field of sustainable product design approaches, evaluation metrics and tools, and policies to support sustainability, focusing on mechatronic products.

Section 3 (Proposed method) introduces the framework developed in this research work, exploring every aspect of the process, encompassing the underlying assumptions and the methods used to support it.

Section 4 (Case studies) presents the two case studies in which the method is applied. Two household appliances (electric oven and cooker hood) were studied to analyse their present sustainability and provide design changes to improve it. In this chapter, the results are examined and discussed.

Section 5 (Future works for methodology validation) outlines a detailed plan for validating the proposed methodology in the future. Four lines of validation are envisioned: product validation, validation with companies, validation with stakeholders, and validation with standardization bodies.

Section 6 (Conclusion) concludes the thesis, summarizing the overall work and proposing further research activities.

2. STATE OF ART

In the following paragraphs, an overview of the literature related to the product development process and design for sustainability approaches is presented. Then, current research on evaluation metrics and tools for sustainable design is introduced. Finally, a discussion about the European policies is provided, with a focus on the mechatronic sector.

2.1. INTRODUCTION TO DESIGN FOR SUSTAINABILITY AND MECHATRONICS

The notion of sustainability was initially articulated in 1987 in the Brundtland Report, which articulated that the primary objective of sustainable development is to *“meet the needs of the present generation without compromising the ability of future generations to meet their own needs”* (World Commission on Environment and Development (WCED), 1987). Subsequently, within academic discourse and corporate domains, numerous interpretations have been put forth, alluding to a business approach that is characterized by greater humanity, enhanced ethics, and increased transparency (Van Marrewijk, 2003).

Recently, a more expansive interpretation has emerged, suggesting that it encompasses three primary dimensions: one related to the environment or ecology, another associated with social aspects, and a third focused on economic considerations. The interconnection of these pillars is established within the framework of sustainable equilibrium, often referred to as the *Triple Bottom Line* concept, as introduced by Elkington (Elkington, 1994). This framework illustrates the intrinsic interdependence and correlation among the three fundamental pillars of sustainability, emphasizing the necessity for their balanced relationship (see Figure 2) (Tomislav, 2018).

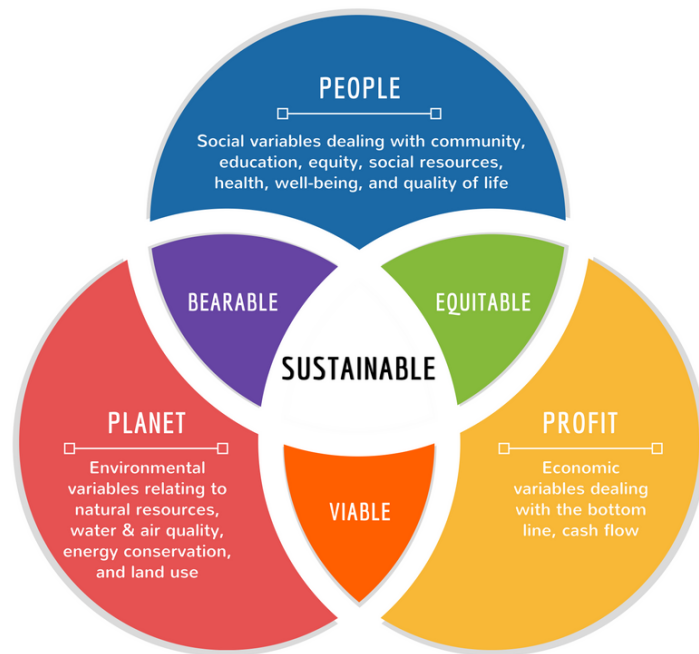


Figure 2. Triple bottom line concept of sustainable development. Image source: (Classen, 2021).

It has been proven difficult to achieve sustainability by emphasizing *ecological, economic, and social/cultural* dimensions, and a fourth dimension – *good governance* – was included in the UN’s Sustainable Development Goals (SDGs) (United Nations, 2012) (Leadership Council of the SDSN, 2014). These SDGs are a set of 17 goals adopted by the United Nations in 2015 as a universal call to action to end poverty, protect the planet, and ensure that all people enjoy peace and prosperity by 2030 (United Nations, 2015). Figure 3 shows how each goal has specific targets to be achieved. Based on the SDGs report from 2023, it has been observed that the consequences of the climate crisis, the conflict in Ukraine, a fragile global economy, and the enduring repercussions of the COVID-19 pandemic have unveiled vulnerabilities and impeded advancements toward achieving the Goals (United Nations, 2023). Five critical areas requiring immediate attention were identified:

- Leaders of nations and governing bodies ought to reaffirm their dedication to seven years of intensified, continuous, and groundbreaking efforts, on both domestic and global fronts, to fulfil the commitment to achieving the SDGs.
- Governments ought to promote specific, comprehensive, and purposeful policies and initiatives for the eradication of poverty,

the mitigation of inequality, and the cessation of environmental degradation. Emphasis should be placed on advancing the empowerment of women and girls, as well as supporting the most marginalized individuals.

- Governments ought to enhance the capabilities of both national and subnational entities, as well as bolster accountability within public institutions, to expedite the realization of the SDGs.
- The global community must reaffirm its commitment during the SDG Summit to fulfil the Addis Ababa Action Agenda and to garner the necessary resources and investments to empower developing nations in attaining the SDGs, especially those confronting unique challenges and heightened vulnerability.
- Member nations ought to support the ongoing enhancement of the United Nations development system while reinforcing the capabilities of the multilateral framework to confront emerging issues and rectify deficiencies within the international structure pertaining to SDGs that have become apparent since 2015.



Figure 3. Sustainable Development Goals. Image source: (United Nations, n.d.).

The 2030 Agenda for Sustainable Development offers a comprehensive action plan, and engineers have assumed a leading role in fulfilling the Sustainable Development Goals. They leverage their scientific expertise and practical experience to transform inventive concepts into sustainability initiatives that benefit society as a whole (UNESCO & ICEE, 2021).

When it comes to mechatronic products, it is important to understand that they do not represent a single technological domain; instead, they integrate various branches of engineering, such as mechanical, electronic, systems, and software engineering. This has led to an increase in products and systems complexity in recent years, from household appliances to automobiles (Bradley & Russell, 2010). Addressing interconnections has consistently held significance within mechatronic products, but this significance has grown further in light of the continually expanding scope and evolving demands associated with these products (Törngren, Qamar, Biehl, Loiret, & El-Khoury, 2014). Mechatronics play a significant role in the realization of sustainable products and systems. Concerning advancements in mechatronics and the design procedure, strategies like Eco-Design cover a broad array of concerns that will influence the overall mechatronic concept, especially with regard to achieving sustainability objectives that involve balancing trade-offs among system components. Therefore, the incorporation of a manufacturing process that may result in slightly higher waste levels can facilitate initiatives in other aspects of the product lifecycle, ultimately contributing to an overall reduction in waste generation. Due to the nature of these products, the main areas where they can have a negative impact from a sustainability perspective are related to, for example, the consumption of natural resources. Valuable minerals are used during the production of electronic components, and manufacturing processes can be energy intensive. During their lifecycle, efforts should be made to make them as energy efficient as possible, minimising potential environmental and economic impacts associated with their use. Furthermore, due to their complexity, handling them at the end of their lifecycle can be challenging and may require specific recycling processes. As many of them become electronic waste, improper end-of-life management can lead to various environmental impacts and pose health hazards to individuals.

In the following sections, the current state of the art regarding the different approaches for design for sustainability is described, along with the available metrics and tools and the existing European-level policies aimed at promoting sustainability in the sector of mechatronic products.

2.2. SUSTAINABLE PRODUCT DESIGN APPROACHES

As previously stated, sustainable product design aims to create products that exhibit social responsibility, economic viability, and environmental friendliness. First, the traditional product design process is presented, and then sustainability-oriented approaches will be explored. In this section, a general overview of these methods is offered and subsequently delve into the specific tools used for their implementation.

2.2.1. Conventional Product Design

The conventional design process has been analysed in detail in Gagnon's review (Gagnon, Leduc, & Savard, 2012), where it describes the specificities of all the Conventional Design Processes (CDP) found in the literature. All the CDPs reviewed can be connected to the systematic approach proposed by Pahl et al., sharing the various phases required for product design. Those stages comprising the Product Design Process (PDP) have been clearly defined and summarized in the by Pahl et al. (Pahl, Beitz, Feldhusen, & Grote, 2007). Figure 4 summarizes the steps in the planning and design process. The four phases that can be identified are described below:

- **Planning and Task Clarification:** it seeks to generate fresh ideas and concepts while gathering essential requirement information. The design task can take various forms when presented to the design departments, including a development order, a defined request, or a solicitation based on suggestions and critiques from sales, research, testing, and other sources. During this stage, engineers and designers must pinpoint the requirements that will shape the solution, making thorough documentation a priority. Various tools, such as the Quality Function Deployment matrix, may be employed to facilitate this process. The outcome of this phase is a comprehensive list of requirements. This document will serve as a fundamental reference point for any product development endeavour.
- **Conceptual Design:** this stage entails establishing the fundamental solution path by elaborating on a solution principle. Designers and engineers employ various tools, including mood boards, to inspire and provide context for the design while

generating the initial product concept. Ideas are generated through individual brainstorming sessions and group discussions. Typically, this design stage includes activities such as sketching, drawing, creating mock-ups, or constructing models to evaluate basic technical feasibility and assess proposed production methods, among other considerations (Ulrich & Eppinger, 2015).

- **Embodiment Design:** it involves advancing the product design beyond its initial concepts. During this stage, designers explore rival products, gaining insights into their strengths and weaknesses from both manufacturing and assembly perspectives. Concepts are materialized through the creation of 2D sketches, CAD models, layout drawings, schematics, and mock-ups. These mock-ups and/or prototypes serve to evaluate technical principles such as user requirements, component configuration, and manufacturing capabilities, as well as to visualize layouts (Ulrich & Eppinger, 2015). Additionally, this stage includes calculations related to performance, as well as decisions regarding materials and finishes. For instance, a critical technical analysis carried out during this phase involves optimizing cost-effectiveness.
- **Detail Design:** in this phase, designers and engineers apply their expertise in manufacturing and materials to optimize designs for efficient and cost-effective production. They also address factors such as safety and usability. The resulting working drawings, which include details about material choices, tolerances, and manufacturing processes, are then given to the production team as part of the product development phase. Subsequently, the product moves into the manufacturing stage, during which design engineers collaborate closely with the production team.

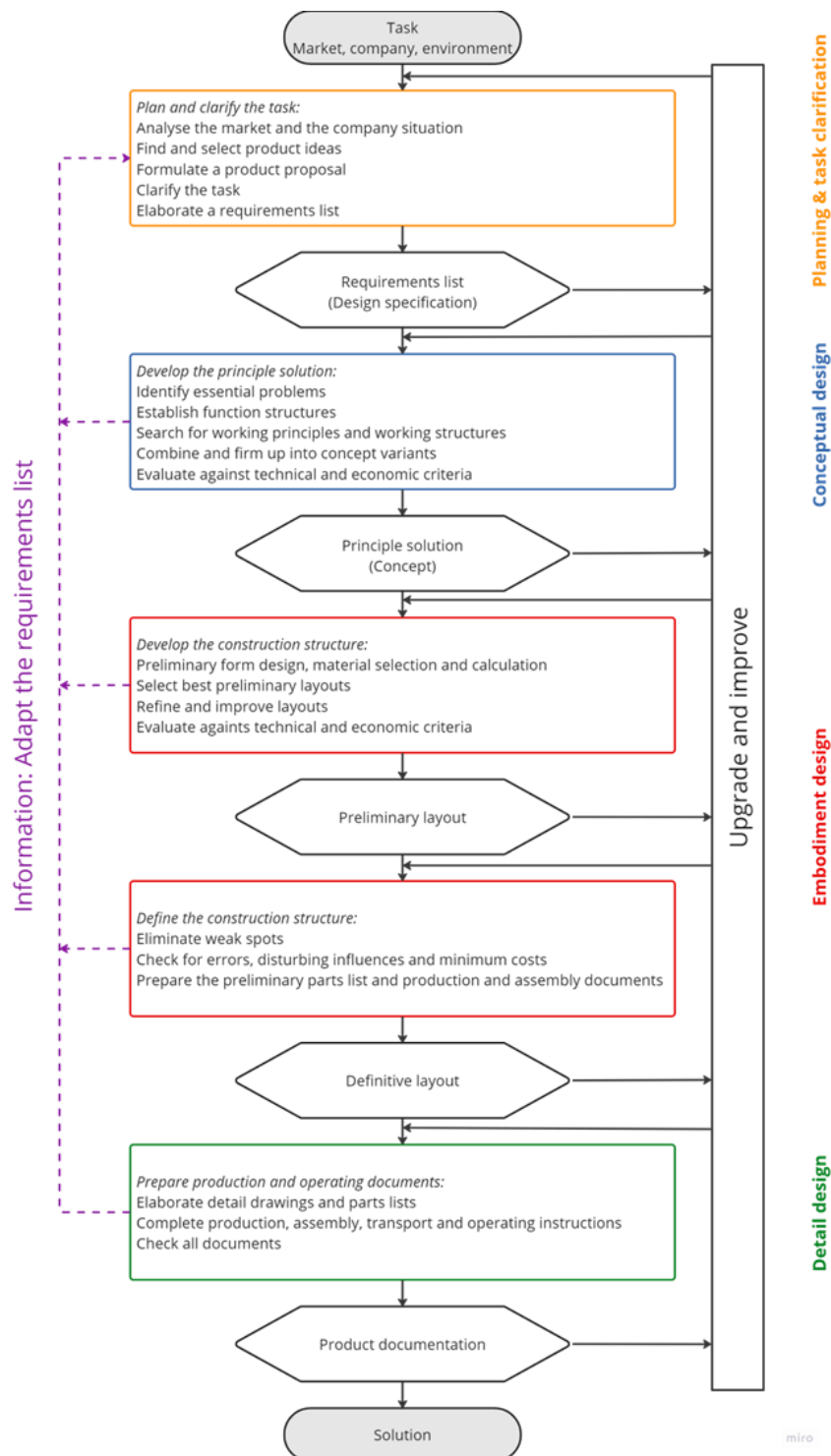


Figure 4. Product Development Process design phases (Pahl, Beitz, Feldhusen, & Grote, 2007).

However, the PDP proposed by Pahl et al. does not consider the interaction between departments and designer engineers. That is why in the literature, Boothroyd has proposed the New Product Development Process (nPDP) (Boothroyd, Dewhurst, & Knight, 2011). With this new approach, potential interactions are included from the initial design phase to help optimize this process. This approach is known as Concurrent Design and is defined by carrying out design tasks concurrently whenever feasible, as opposed to the conventional approach of sequential product development (Albin & Crefeld III, 1994). Benefits such as improved product quality and meeting customer requirements at the lowest possible cost are key advantages (Sohlenius, 1992) (Tseng & Abdalla, 2006). Nonetheless, managing nPDP can be challenging due to the increased number of stakeholders simultaneously involved (Jun, Park, & Suh, 2006). To enhance the efficiency of the nPDP, various strategies have been devised, collectively referred to as Design for X (DfX) methods (Huang, Lee, & Mak, 1999). Here, the “x” is replaced with the specific optimization focus (e.g., Design for Repair, Design for Disassembly, etc.). DfX methodologies prioritize the enhancement of the product property associated with “x”, often overlooking other aspects of the product’s lifecycle (Kuo, Huang, & Zhang, 2001). The review conducted by Benabdellah et al. provides an overview of the various techniques found in the literature for DfX (Benabdellah, Bouhaddou, Benghabrit, & Benghabrit, 2019). Table 1 summarizes them.

Table 1. Overview of DfX techniques (Benabdellah, Bouhaddou, Benghabrit, & Benghabrit, 2019).

Area	Scope	Design for	Design considerations
Economy	Product	Assembly (DFA)	Design to reduce the number of parts, tasks, and motions; design to reduce the difficulty of processes.
		Manufacture (DFM)	Design to eliminate expensive manufacturing processes and materials.
		Manufacture and Assembly (DFMA)	Design to address both DFM and DFA.
		Variety (DFV)	Design to reduce design effort and time to market and to reduce the impact of variations in life cycle costs.
		Six sigma (DFSS)	Design to reduce variation and defects; design to meet customers’ requirements.
		Safety (DFS)	Design to reduce risks of injury and to integrate hazard and risks of humans, materials, etc.

		Testability (DFTest)	Design to reduce failure modes.
		Maintainability (DFMt)	Design to simplify repairs process; design to reduce repair time and to improve fault isolation.
		Robustness (DFRb)	Design to decrease production costs.
		Failure modes (DFMEA)	Design to reduce failure rate.
		Supportability (DFSp)	Design to improve installation, user training, maintenance, customer support and product upgrades.
		Flexibility (DFF)	Design to consider changes in customer need/want; design to enable product reconfiguration.
		Modularity (DFMod)	Design to have loosely coupled interfaces enabling module variation in products.
		Miniaturization (DFMin)	Design to reduce production costs and to reduce barriers to innovation.
		Serviceability (DFSv)	Design for compatibility with service and for streamlined service process, component and storage.
	System	Supply chain (DFSC)	Design to address the performance of both logistics and reverse logistics benefits.
		Logistics (DFL)	Design to decrease packaging and to reduce product size for storage and transportation.
		Mass customization (DFMac)	Design to enable commonality and reusability between products parts and process.
		Procurement (DFP)	Design to enable parts commonality and to leverage existing supplier relationship.
	Both	Quality (DFQ)	Design to eliminate defects in production processes and to meet customers' requirements.
		Life cycle (DFLC)	Design to reduce life cycle cost.
		Cost (DFC)	Design to reduce cost.
Ecology	Product	Recycle (DFR)	Design to increase recyclable material inputs and outputs and to minimize material variety.
		Reuse (DFRu)	Design to standardize components and to enhance the durability of reuse targeted components.
		End of Life (DFEOL)	Design to ensure easy access to fasteners and joints and to lower destructiveness and selectiveness of disassembly process.
		Remanufacture (DFRem)	Design to enable disassembly, assembly, cleaning, testing, repair, and replacement.

		Reliability (DFRL)	Design to use proven components and to identify and eliminate critical failure modes.
		Sustainability (DFSt)	Design to consider the three dimensions of sustainability: economy, ecology and equity.
		Environment (DFE)	Systematic consideration of environmental safety and health.
		Chronic risk reduction (DFCRR)	Design to reduce hazardous material and emissions or waste.
		Energy conservation (DFEC)	Design to reduce energy consumption and to ensure rapid warm up and power down.
		Material conservation (DFMC)	Design to reduce product dimensions and to utilize renewable, abundant, and recyclable resources.
		Waste minimization and recovery (DFWMR)	Design to reduce waste; design to increase use of biodegradable materials.
Ecology and economy	Product	Reverse logistics (DFRL)	Design to enable customers to support preventing returns.
		Disassembly (DFD)	Design to reduce environmental impact, to simplify repair time and to improve fault isolation.
		Packaging (DFPk)	Design to reduce production costs, design to reduce environmental impact.
Equity	Product	Social responsibility (DFSR)	Design to enable linkages with society, design to consider non-traditional markets, design to eliminate social problems.

2.2.2. Design for Disassembly

The Design for Disassembly is a sustainable product design approach that aims to optimize the disassembly process, creating products that are easy to disassemble into single components. Disassembly methods have emerged as a crucial concern during the End-of-Life stage of products (Osti, Ceruti, Liverani, & Caligiana, 2017). An effective disassembly approach can enhance the overall product life cycle by simplifying maintenance and repair procedures during the use phase. Furthermore, it plays a pivotal role in encouraging product recycling at the EoL stage by facilitating the recovery and reuse of components and materials (Go, Wahab, Rahman, & Ramli, 2010). Favi et al. explained that usually DFD encompasses various design responsibilities, including the choice of materials, component design, defining product architecture, and the appropriate selection and utilization of connections and fastening mechanisms (Favi, Marconi, Germani, &

Mandolini, 2019). To achieve effective integration of DFD techniques, designers should take into account a set of recommended principles (Go, Wahab, Rahman, & Ramli, 2010) as well as the rules presented in Table 2 (Bogue, 2007):

- Product architecture, component design, fastening methods, and material selection.
- EoL disposition for each component (e.g., recycling, reuse, landfill).
- Income generated from each component based on its EoL disposition.
- Labour expenses associated with the disassembly process.
- Disposal costs for residual waste generated at each stage of the disassembly process.
- The net profit derived from each individual disassembly stage.
- Impact of each single step in the disassembly process.

Table 2. DFD design rules (Bogue, 2007).

Factors affecting the disassembly process	Guides to improve disassembly
Product structure	<ul style="list-style-type: none"> • Create a modular design. • Minimise the component count. • Optimise component standardisation. • Minimise product variants.
Materials	<ul style="list-style-type: none"> • Minimise the use of different materials. • Use recyclable materials. • Eliminate toxic or hazardous materials.
Fasteners, joint and connections	<ul style="list-style-type: none"> • Minimise the number of joints and connection. • Make joints visible and accessible, eliminate hidden joints. • Use joints that are easy to disassembly. • Mark non-obvious joints. • Use fasteners rather than adhesives.
Characteristics of components for disassembly	<ul style="list-style-type: none"> • Good accessibility. • Low weight. • Robust, minimise fragile parts. • Non-hazardous. • Preferably unpainted.
Disassembly conditions	<ul style="list-style-type: none"> • Design for automated disassembly. • Eliminate the need for specialised disassembly procedures. • DFD with simple and standard tools.

DFD provides various disassembly techniques that can greatly simplify the disassembly process. Abuzied et al. presented a review of those techniques, dividing it into two categories: (i) disassembly embedded design, and (ii) active disassembly (AD) (Abuzied, Senbel, Awad, & Abbas, 2020). The first one entails the integration of a disassembly mechanism directly into the product's design. This integrated mechanism can be activated to start the disassembly process through various means, such as thermal, electrical, mechanical, or electromagnetic stimuli (Soh, Ong, & Nee, 2016). While the active disassembly involves the separation of assemblies through the utilization of intelligent materials or product structures that can be triggered by one or more external stimuli (Willems, Dewulf, & Duflou, 2005). The review demonstrated that there is a growing demand for a disassembly method that enables cost-effective, non-destructive separation of products at the end of their life cycle, and this demand can be met through the use of AD. The disassembly sequence planning (DSP) is a critical process used to evaluate the accessibility of components or sub-assemblies and to analyse the disassembly paths. It provides a quantitative assessment of a product's ease of disassembly (Smith, Hsu, & Smith, 2016). DSP can be regarded as the initial phase for disassembly analysis and consequently serves as the primary step in shaping a DFD methodology. Numerous research endeavours are dedicated to creating algorithms and methodologies for identifying the optimal disassembly sequence for specific components within industrial products (Ong & Wong, 1999) (Gungor & Gupta, 2001) (Zhang & Zhang, 2010) (Kheder, Trigui, & Aifaoui, 2015). After the literature analysis done on DSP by Favi et al., a gap in approaches dedicated to addressing the challenges of estimating and minimising disassembly time can be found. Initial investigations have introduced preliminary studies focused on estimating disassembly time, with the goal of incorporating it as a target in the optimization problem within DSP (Favi, Marconi, Germani, & Mandolini, 2019). In recent years, more importance has been placed on DFD, even though these methods have existed for years (Dewhurst, 1993). This is due to increased market competition with more competitive pricing and the rapid creation of products, as well as certain policies that compel the improvement of the environmental impact of products, such as Waste Electrical and Electronic Equipment (WEEE), the restriction of hazardous substances (RoHS), or the End-of-Life Vehicles (ELV) (Frizziero, Liverani, Caligiana, Donnici, & Chinaglia, 2019). Many

studies combined the DFD with Augmented Reality (AR), where the AR can be used to create a virtual model of the product that can be used to visualize the disassembly process and identify the optimal disassembly sequence. These techniques can also optimise the maintenance process by providing efficient and effective disassembly instructions (Frizziero, Liverani, Caligiana, Donnici, & Chinaglia, 2019) (Frizziero, Donnici, & Freddi, 2022) (Frizziero, Leon Cardena, Freddi, Grassoni, & Liverani, 2023). The benefits of using DFD approaches are confirmed by different research case studies within the mechatronic products. For example, Bogue, which suggest that using these methods can lead to economic benefits and produce products that are more profitable. Using as a case study the Kodak's "Funsaver" that was designed following the DFD methods and allowed to recycle or remanufacture between the 77% to 90% of the parts (Bogue, 2007). Or the application of DFD to a volumetric pump, proving that assessing the DSP can significantly reduce both resource consumption and the direct and indirect costs associated with dismantling (Frizziero, Leon Cardena, Freddi, Grassoni, & Liverani, 2023).

2.2.3. Design for Repairability

The Design for Repairability (DFRep) or Design for Maintainability (DFMt) are a sustainable design approaches that focus on creating products that are easier to repair when they break. DFRep aims at increasing the lifespan of the product by optimizing the repair and maintenance process. This way, instead of having to dispose of the entire product, only the damaged component is discarded, reducing the overall amount of waste generated. DFRep also benefits consumers by saving them from having to purchase new products (Cordella, Alfieri, & Sanfelix Forner, 2019). Usually, repairs occur when a product or a component thereof ceases to function as intended or when the product's performance deteriorates due to wear or damage (British Standards Document, 2009). Bracquené et al. defines the steps that are included in the repair cycle: (i) Product identification, (ii) Failure diagnostic, (iii) Disassembly & reassembly, (iv) Spare part replacement, and (v) Restoring to working condition (Bracquené, et al., 2018). Different initiatives to evaluate the repairability of products can be found in the literature. Those methods can be classified as: (i) Qualitative, (ii) Semi-quantitative, and (iii) Quantitative.

Qualitative assessment methods

This kind of methods typically comprise several criteria that must be met to qualify for a label. Below, some examples are described:

- **Blue Angel label:** This label is created by the German government and is awarded to products that meet the high standards set for each product category (German Federal Government, n.d.). The requirements are determined by the Federal Environment Agency, and not all of them are related to repairability; only for the product categories of mobile phones, PC, TV, vacuum, and coffee machines are criteria related to DFRep identified (e.g., durability tests, ease of disassembly, priority parts, spare parts supply, warranty).
- **Nordic Swan ecolabel:** Alongside the Blue Angel, this label from the Nordic countries (i.e., Denmark, Finland, Iceland, Norway, and Sweden) is one of the oldest eco-labels in the world (Nordic Council of Ministers, n.d.). It follows the same philosophy as the previous one. In this case, mechatronic products that include criteria related to repairability (e.g., instruction on maintenance, ease of disassembly, priority parts, spare parts supply, warranty) are the white goods, PC, imaging equipment, and TVs and projectors.
- **EU ecolabel:** it is a voluntary environmental label that seeks to promote products that minimise the environmental impacts throughout their life cycle when compared to other products in the same category (European Commission, n.d. d). It will be discussed in detail in Section 2.4. In this case, PCs, imaging equipment, and TVs included criteria related to repairability.

Semi-quantitative assessment methods

This kind of methods typically assign a weight to each criterion and then aggregate these weighted criteria to calculate a “repairability score” for the product. Below, some examples are described:

- **Austrian Technical Rules - ONR 192 102:2014 “Label of excellence for durable, repair-friendly designed electrical and electronic appliances:** this standard was published by the Austrian Standard Organization and it is focus on reduce waste

generated by discarded products and extend their useful life, improving their repairability or recyclability (Austrian Standards, 2014). It establishes a set of mandatory requirements (17 criteria for white goods and 21 for brown goods), and other optional criteria that can contribute to improve the overall score (23 for white goods and 32 for brown goods). The products are classified with a qualitative score that ranges from 5 to 10 (i.e., 5-6 is good, 7-8 is very good, and 9-10 is excellent).

- **iFixit repairability score for smartphones and computers:** the scoring system proposed by iFixit is based on the engineers' experience during the repairability of each product analysed (i.e., phones, tablets, and laptops). The qualitative score ranges from 0 to 10, with 10 being the easiest to repair. The scores are updated frequently due to technological changes, materials used, and design trends (IFIXIT, n.d.).

Quantitative assessment methods

These methods utilise measurable data to compute a repairability index or metric. Below, some examples are described:

- **eDiM:** the ease of Disassembly Metric seeks to assess the effort required for fully or partially disassembling a product or component. Using the Maynard Operation Sequence Technique (MOST) (Zandin, 2021), a database of disassembly tasks is created. The effort involved in disassembly and reassembly is quantified in terms of the expected time required for these disassembly tasks, measured in seconds. It can be applied to a wide variety of products (Vanegas, et al., 2018).
- **EN 45554:2020 - General methods for the assessment of the ability to repair, reuse and upgrade energy-related products:** this horizontal standard is focused on ErP and it includes generic criteria and methods for assessing the ability of certain parts to be removed from products for the purpose of repair, reuse or upgrade. The parameters considered by this standard are the disassembly depth, fasteners and connectors, tools needed for the disassembly, working environment, skill level of the operator, diagnostic support and interfaces, availability of spare parts, types and availability of information, return options, data management,

and password and factory reset for reuse. This standard also provides the formula to aggregate all the criteria scores in order to obtain a final score for the overall product (CEN/CENELEC, 2020b).

- **French Repairability Index:** France was the first European Union country to introduce a mandatory label specifically for product repairability. Starting in January 2021, it was implemented for mobile phones, laptops, televisions, electric lawnmowers, and front-loading washing machines. In November 2022, it was updated to include four additional categories: top-loading washing machines, dishwashers, vacuum cleaners, and pressure washers. This label aims to inform consumers about the repairability of these products. Figure 5 illustrates how a scale from 0 to 10 has been employed. The criteria considered in this index include the availability of documentation, ease of disassembly, the availability and cost of spare parts, and certain specific product features. By introducing additional parameters that take into account product reliability or robustness, this index will evolve into a product durability index by 2024 (Ministère de la Transition écologique et de la Cohésion des territoires, n.d.).



Figure 5. French Repairability Index (Ministère de la Transition écologique et de la Cohésion des territoires, n.d.).

- **Repair Scoring System:** the RSS was developed by JRC and enables the computation of a “repairability score” by evaluating product-specific criteria and various weighted parameters (Cordella, Alfieri, & Sanfelix Forner, 2019). It served as a reference for the EN 45554 standard. The parameters included in the RSS are related to the disassembly (i.e., disassembly depth, fasteners, tools, disassembly time), process (i.e., diagnosis support, spare

parts, software and firmware, safety, skill, working environment, data transfer, password reset) and commercial guarantee.

Dangal et al. examine the objectivity and completeness of several reparability scoring systems. Table 3 presents the criteria that drives reparability and the design features and principles affected.

Table 3. Overview of design features and principles empirically shown to drive reparability (Dangal, Faludi, & Balkenende, 2022).

Desing features and principles	Definition and how it relates to repair
Disassembly	The product is taken apart so that it can subsequently be reassembled and made operational (CEN/CENELEC, 2014). Required to access components for most repairs (Vanegas, et al., 2018).
Reassembly	Assembling a product to its original configuration after disassembly (Peeters, Tecchio, & Vanegas, 2018). Required to return a product to operation.
Fastener removability and reusability	Facilitation of removability of fasteners while ensuring that there is no impairment of the parts [or product] due to the process. Required for disassembly and ease of reassembly.
Fastener visibility	Whether more than 0.5 mm ² of the fastener surface area is visible when looking at fastening direction (Vanegas, et al., 2018), and visual cues (Flipsen, Huisken, Opsomer, & Depypere, 2019). Facilitates product disassembly.
Tools required	Number and type of tools necessary for repair of the product (CEN/CENELEC, 2020b).
Modularity	The product design is composed of different modules. A module can consist of one or more components. Modules can be separated from the rest of the product as self-contained, semi-autonomous chunks; and they can be recombined with other components (Bonvoisin, Halstenberg, Buchert, & Stark, 2016). Modularity improves diagnosis (Arcos, Bakker, Flipsen, & Balkenende, 2020), product disassembly, (Cordella, Sanfelix, & Alfieri, 2018) and spare part price. The degree of modularity needs to be balanced – bundling into bigger modules decreases disassembly time but makes spare parts expensive, and vice versa.
Diagnosis	Process of isolating the reason for product failure. Diagnosis is facilitated by designed signals (text, light, sound, or movement) (Poza Arcos, Bakker, Flipsen, & Balkenende, Practices of Fault Diagnosis in Household Appliances: Insights for Design, 2020). Even without these features, visible surfaces and component accessibility for inspection can also promote failure isolation (Poza Arcos, Bakker, Flipsen, & Balkenende, Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study, 2021).
Health and safety	Health and safety risks to the user during and after repair. Features minimizing safety risks also increasing confidence in product

	disassembly and reassembly (Dangal, van den Berge, Pozo Arcos, Faludi, & Balkenende, 2021).
Standard parts and interface	Enforcing “the conformance of commonly used parts and assemblies to generally accepted design standards for configuration, dimensional tolerances, performance ratings, and other functional design attributes” (Moss, 1985). Standardization beneficially affects spare part cost and availability, tooling, component identification complexity, and skill levels required, and increases the interchangeability of components during maintenance and repair (Perera, 1999).
Information accessibility	Information available to the product user and repairers. Whilst this is not directly a design element, manuals and labels are provided with the product. Guides repair process (Pozo Arcos, Bakker, Flipsen, & Balkenende, Practices of Fault Diagnosis in Household Appliances: Insights for Design, 2020) (Pozo Arcos, Bakker, Flipsen, & Balkenende, Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study, 2021).
Design simplicity/complexity	A minimal number of disassembly steps and/or disassembly time (Cordella, Sanfeliix, & Alfieri, 2018), and simplicity in understanding the interface and malfunction feedback to assist failure diagnosis (Pozo Arcos, Bakker, Flipsen, & Balkenende, Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study, 2021).
Adaptability/upgradability	Adaptability allows performance of the designed functions in a changing environment. Upgrading enhances the functionality of a product (Den Hollander, 2018). Software-related issues in the product can sometimes be repaired through updates.
Ease of handling	Features such as small size, low centre of gravity and the presence of handles all promote ease of product handling (Den Hollander, 2018). Facilitates disassembly process during product manipulation.
Interchangeability	Assuring components can be replaced in the field with no reworking required to achieve a physical fit. Allows for component testing (Pozo Arcos, Bakker, Flipsen, & Balkenende, Practices of Fault Diagnosis in Household Appliances: Insights for Design, 2020) (Pozo Arcos, Bakker, Flipsen, & Balkenende, Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study, 2021) and facilitates component replacement.
Robustness	Selecting designs that are robust. Assures products do not break during repair (Beuth publishing DIN, 2014); increases confidence during disassembly (Pozo Arcos, Bakker, Flipsen, & Balkenende, Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study, 2021).
Redundancy	Providing an excess of functionality and/or material in products or parts. Allows removal of material as part of a recovery intervention (Keoleian & Menerey, 1993). Functional redundancy assists fault location and isolation (Pozo Arcos, Bakker, Flipsen, & Balkenende, Practices of Fault Diagnosis in Household Appliances: Insights for Design, 2020).

Firmware reset	Software and the electronics-related issues can be fixed via reset. Reset functions facilitate cause-oriented diagnosis (Pozo Arcos, Bakker, Flipsen, & Balkenende, Practices of Fault Diagnosis in Household Appliances: Insights for Design, 2020).
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2.2.4. Eco-Design

The Eco-Design can be defined as “*the integration of environmental aspects into product design with the aim of improving the environmental performance of the product throughout its whole life cycle*” (European Parliament, 2009c). As can be seen, it is based on the premise of minimizing the environmental impact of products throughout their lifecycle. To achieve this, various aspects must be taken into consideration, such as increasing resource efficiency, reducing energy consumption, minimizing waste generation, or promoting recyclability. When Eco-Design is applied to the industrial sector, the aim is to incorporate these environmental considerations into the Product Development Process (PDP) (International Organization for Standardization, 2020). The implementation of the Eco-Design can be done through different methods and tools that have been developed during the years. Rossi et al. conducted a review to understand the primary barriers that hinder the practical and efficient integration within the industry. The methods found in literature can be clustered into eight groups (including qualitative, semi-quantitative, and quantitative methods) (Rossi, Germani, & Zamagni, 2016):

- **LCA tools:** the LCA will be explained in detail in Section 2.3.1. It is a framework to assess the environmental impact related to a product or a service during their whole life cycle (International Organization for Standardization, 2006b). Different commercial software tools can be used to perform this assessment (e.g., SimaPro, GaBi), as well as some OpenLCA software tools that are freely available. The main barriers of these kind of tools are the specific knowledge needed to perform the analysis, the time effort, and the need to dispose of a high quantity of quality data.
- **CAD integrated tools and methodology:** these tools allow to assess the environmental impacts during the first design phase, using the information retrieved from the CAD models. Different researches can be found in the literature where they connect a CAD system to a LCA software tool (Marosky, Dose, Fleischer, &

Ackermann, 2007) (Yang, Li, Wang, & Wang, 2012). In this case, the main limitations are the licence price, the limitation in databases and number of impact indicators, or the simplification in the product modelling.

- **Diagram tools:** they are a qualitative or semi-quantitative approach used when there is a lack of detail information, and the life cycle is available. Different matrices can be found in literature such as the MECO Matrix (Wenzel, Hauschild, & Alting, 1997), the Environmental Design Strategy Matrix (Abramovici, Quezada, & Schindler, 2014), MET Matrix (Brezet & Van Hemel), etc. For these tools it is needed an experienced operator who is able to interpret the results and work with arbitrary estimations.
- **Checklists and guidelines:** these qualitative methods are used to quickly evaluate the environmental performance of products. Numerous eco-design recommendations are available in existing literature, intended to provide designers with reference points. These guidelines are generally quite broad in scope and can be applicable to a wide range of products. However, translating these recommendations into specific design decisions can pose a challenging task. One of the main examples are the Ten Golden Rules (Luttropp & Lagerstedt, 2006). Other examples are the Ecodesign Pilot (ECODESIGN PILOT, n.d.), the tool MATto focused on material selection (Allione, De Giorgi, Lerma, & Petrucci, 2012). As for the diagram tools, the user needs to be an expert to interpret the arbitrary estimations and the general suggestion proposed by those methods.
- **Design for X approaches:** as explained in Section 2.2.1, DfX approaches were developed to optimize specific product requirements. In Table 1 can be identified those categories that fell inside the eco-design field. Due to the large amount of tools available, one of the main barriers is the selection of the most appropriate one, so it is needed to know the criticalities before starting the analysis.
- **Methods for supporting the company's eco-design implementation and generation of eco innovation:** these methods seek the implementation of the eco-design in companies, through the application of organized methods and frameworks.

EDIMS method is an example that helps overcoming the challenges about the integration of eco-design tools with traditional design processes (Le Pochat, Bertoluci, & Froelich, 2007). Or the framework proposed by Pigosso et al. which was applied to a large manufacturing company with successful results (Pigosso, Rozenfeld, & McAlloone, 2013). The staff needs to be skilled and trained on the matter to perform these methods (knowing deeply their principles).

- **Methods for implementing the entire life cycle and user centred design for sustainability:** they are focused on consider different specifications to promote multi-objective approaches. Some of them seek to improve the user behaviour (Rodríguez & Boks, 2005) (Jelsma & Knot, 2002). As for the case explained before, the main limitation is the time effort and the required experience for the staff.
- **Methods for integrating different existing tools:** the main goal is to improve the usability of the existing methods and tools, promoting their implementation in the industry. Many researchers tried to put together the LCA with the TRIZ method, in order to complement the findings of the environmental assessment with the problem-solving approach (Hua, Yang, Coulibaly, & Zhang, 2006) (Yang & Chen, 2012) (Russo, Bersano, Birolini, & Uhl, 2011).

This analysis highlights how despite the numerous strategies suggested by the academic literature, industries continue to face challenges when it comes to implementing and utilising them effectively. This gap between eco-design tools and their application increases with the insufficient awareness regarding the critical aspects of a product and the necessity for specialised understanding of sustainability issues. There are many eco-design methods and tools applied to mechatronic products, some of which have been presented before. For example, the research done by Boix Rodríguez et al., where they applied the Life Cycle Thinking (LCT) and the standard ISO 14006:2020 (International Organization for Standardization, 2020) to improve the design of a traditional heat exchanger for domestic heating systems (Boix Rodríguez, Rossi, Cappelletti, & Favi, 2023). In the review done by Merschak et al., the inclusion of uncertainties for the environmental assessment during the early phases of design is noted as a key aspect

(Merschak & Hehenberger, 2019). This information about uncertainties should be combined with the results in order to develop re-design decisions.

2.2.5. Circular Design

The circular design is a sustainable approach that has gained significant attention in recent years, as way to deal with the environmental problems caused by the linear economy (i.e., take - make - dispose). The circular design seeks to promote Circular Economy (CE), which aims to keep resources in circulation for as long as possible. Figure 6 shows the butterfly diagram proposed by Ellen MacArthur Foundation, as can be seen, there are two main cycles: the technical cycle and the biological one. The tighter the cycle the more economic value is retained. Within the technical cycle, products and materials are maintained within the system through practices like reutilization, repair, remanufacturing, and recycling. Meanwhile, in the biological cycle, the nutrients derived from biodegradable materials are reintroduced into the environment to support the regeneration of nature (ELLEN MACARTHUR FOUNDATION, 2019b).

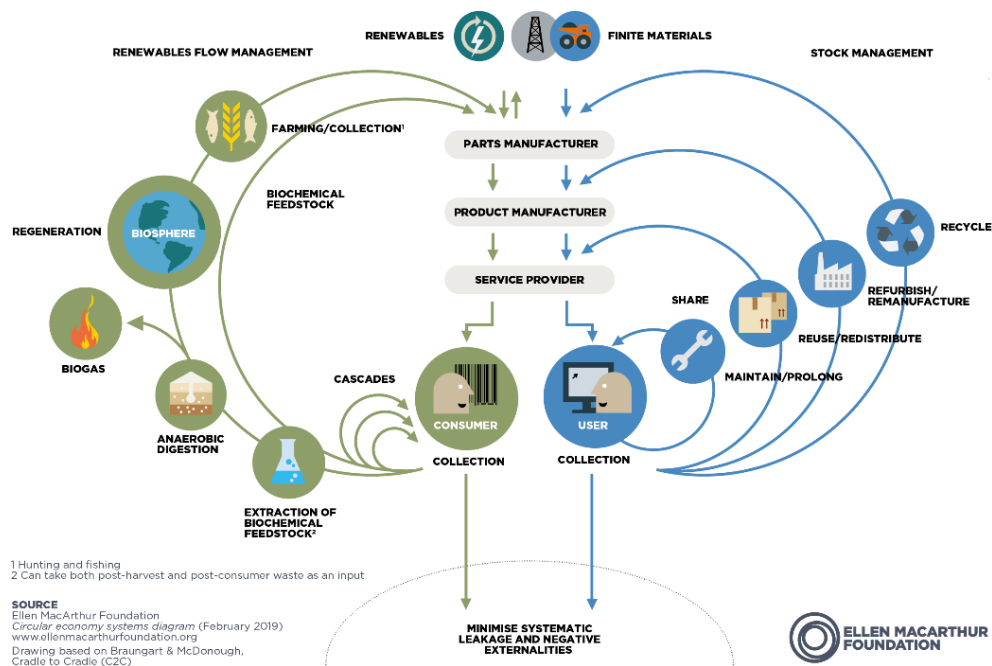


Figure 6. Butterfly diagram for the CE.

The CE is founded on three design-driven principles: (i) minimize/eliminate waste and pollution, (ii) promote the circulation of products and materials at their maximum value, and (iii) support the regeneration of nature (ELLEN MACARTHUR FOUNDATION, 2019a). During circular design, the focus is not solely on the needs of the end user, but also on the system within which the design will be placed. The part of the CE that is related to the mechatronic products is the right side of the diagram (i.e., the technical cycle). Within the larger outer loops, there exist smaller inner loops. These inner loops represent areas where significant value can be obtained, as they preserve a greater portion of the product's embedded value by maintaining its integrity. Therefore, priority should be given to cycles that manage to maintain the product mostly intact (i.e., share, maintain, reuse). Nevertheless, those cycles that destroy the product or some of its components still result in cost savings, as they prevent the need for a complete new product acquisition (Favi C. , Germani, Luzi, Mandolini, & Marconi, 2017) (ELLEN MACARTHUR FOUNDATION, 2019a). Below, the different loops of the technical cycle are briefly explained:

- **Sharing:** this option is not applicable to all products in the economy, but it allows to drastically increase the utilization of many devices. A wide range of products can be used for sharing purposes (e.g., tools, cars, houses, bikes, scooters, etc.). Projects such as the *Toronto Tool Library and Makerspace*, show how users can benefit from this sharing philosophy, accessing superior tools compared to what they might purchase individually just through the subscription to the service (ELLEN MACARTHUR FOUNDATION, 2021b).
- **Maintaining:** extending the useful life of a product is another way to maximise its value. It can be applied to products or components that suffer wear and tear. Maintenance is a key aspect to keeping devices at high performance and reduce the risk of failures.
- **Reusing:** as for the actions explained above, with the reuse, the product or component keep their original form and purpose. If the component is the one that will be reused, it is only possible when the component has a longer lifespan than the product itself (Favi, Marconi, Germani, & Mandolini, 2019).
- **Redistributing:** it offers an alternative method to prolong the usage of products and prevent them from becoming discarded.

This involves redirecting products from their original target market to a different customer, allowing the product to continue serving a valuable purpose.

- **Refurbishing:** through the refurbishment a product can return to perfect working condition, it may encompass tasks such as repairing or substituting components, revising specifications, and enhancing their aesthetic appeal. Lots of technological companies offer the option to buy used items (e.g., mobile phones, laptops, etc.) and after the refurbishment they resell it cheaper than the original price (Apple, n.d.).
- **Remanufacturing:** it occurs when products are no longer suitable for continued use in their current condition and require extensive refurbishment to enable reuse. Remanufacturing entails the reengineering of products and their components to achieve a state comparable to new, with either the same or enhanced performance levels as newly manufactured items. Typically, remanufactured products or components come with warranties that match or exceed those offered for newly manufactured equivalents.
- **Recycling:** the last cycle of the diagram seeks to keep the value of the materials used, avoiding them to become waste. Through recycling, the inherent worth of a product, which encompasses the time and energy invested in its creation, is forfeited. However, the value of the materials is preserved. Recycling involves the conversion of a product or component into its elemental materials or substances, followed by their reprocessing into fresh materials.

Regarding the circular design for mechatronic products, there are several works available in the literature, and they will be discussed in detail in Section 2.3.4, together with the different metrics and tools that can be used to address circularity.

2.3. EVALUATION METRICS AND TOOLS

To create more sustainable mechatronic products that adhere to circular principles, it is necessary to have a robust system of tools and metrics that enable the evaluation of various sustainability aspects. This section focuses on providing the current state of the literature regarding these tools during the design and evaluation of mechatronic products, considering environmental, economic, social, and circularity factors.

2.3.1. Environmental Assessment Tools

First, the methods used to assess the environmental impact of these products throughout their lifecycle are analysed. Thanks to these tools, areas that can be potentially improved are identified, typically through product comparisons within the same product family. Many of the techniques that enable this analysis have already been discussed in Section 2.2, such as DfX approaches or various eco-design application options. This section has been reserved to provide a detailed explanation of one of the internationally recognized methods to do the environmental assessment, the Life Cycle Assessment. With this comprehensive method, which have standards to explain its framework and requirements (International Organization for Standardization, 2006b) (International Organization for Standardization, 2006a), it is possible to evaluate the environmental impact of a product. Figure 7 shows the different phases of the LCA according to ISO 14040. Below, each of the phases of the LCA are described.

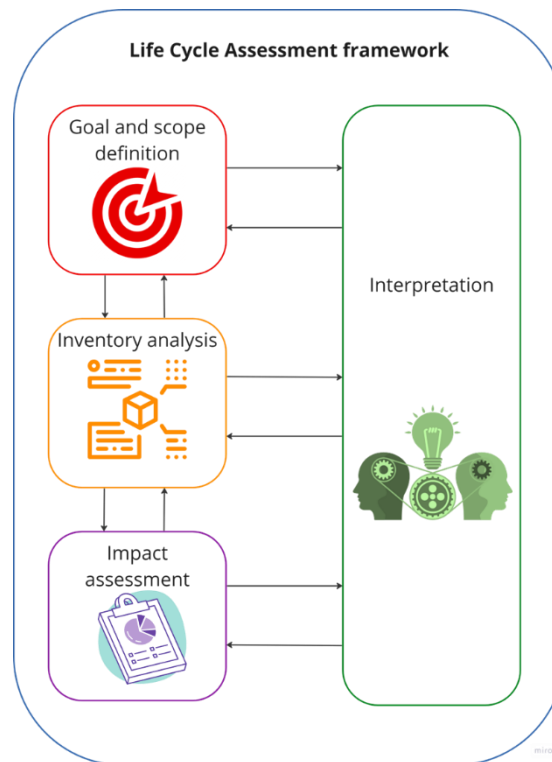


Figure 7. Stages of an LCA (International Organization for Standardization, 2006b).

- **Goal and scope definition:** this phase serves to characterize the product, process, or activity, setting the stage for the evaluation and delineating the system's scope and boundaries. Furthermore, this phase is instrumental in pinpointing the environmental impacts to be considered during the assessment.
- **Life Cycle Inventory analysis (LCI):** this process involves the compilation and quantification of various elements associated with the entire life cycle of the product being studied. The input data necessary for creating this LCI can be categorized into four main types: processes, product stages, system descriptions, and waste types. The data related to processes pertains to the resources utilized and emissions generated during the general processes essential for manufacturing materials and energy. Product stages data is specific to the processes unique to a particular product's life cycle. System description data pertains to information about groups of unit processes that describe more complex system-level activities. Waste types data concerns emissions during various waste management processes. Processes, system descriptions, and

waste types constitute general data that must be interconnected with the product stages data, which is product-specific for each item under examination.

- **Life Cycle Impact Assessment (LCIA):** the LCIA is focused on appraising the potential environmental consequences by utilizing the results obtained from LCI. Broadly speaking, this procedure encompasses the linkage of inventory data with distinct environmental impact categories and category indicators, with the goal of gaining insight into these impacts. Additionally, the LCIA phase contributes valuable information for the subsequent phase of life cycle interpretation.
- **Interpretation:** this phase combines the results of the LCI analysis and LCIA. The objective of the interpretation phase is to present outcomes that align with the predefined objectives and scope, while also drawing conclusions, addressing limitations, and offering recommendations.

As can be seen, the amount of information required to conduct an LCA is quite substantial, making it typically challenging to implement in the early stages of product design. In order to facilitate early-stage environmental assessment for designers, various methods for simplifying LCA have been developed over the years. Beemsterboer et al. conducted a review of the state of the art in these simplifications, suggesting that the different methods identified can be grouped into five simplification approaches (Beemsterboer, Baumann, & Wallbaum, 2020):

- **Exclusion:** strategies for exclusion can be directed either towards the inventory model or the considered impact categories. These strategies serve to narrow the focus of the study to those elements that directly pertain to its objectives. Documentation of exclusions can be found within the goal and scope definition, specifically under the sections related to system boundaries and the selection of impact categories.
- **Inventory data substitution:** the quality of LCA results is significantly impacted by the alignment of data availability and the defined system boundaries. In cases where primary data is lacking, practitioners of LCA need to explore alternative solutions. According to Baumann and Tillman, the data types that can be

substituted are: (i) product description, (ii) input flows (e.g., energy, raw materials), and (iii) output flows (e.g., waste and emissions) (Baumann & Tillman, 2004).

- **Qualitative expert judgment:** to assess environmental impacts, LCA studies often rely on various qualitative assumptions. These assumptions may, at times, enable a partial bypass of full quantification. Among the simplification methods discussed in the literature, one notable strategy at the qualitative end of the LCA spectrum is the utilization of matrix approaches. These matrix approaches represent an alternative simplification strategy that questions the prevailing notion of LCA as a purely quantitative assessment of a product system and its associated effects. It appears that criticisms against the adoption of matrix approaches have gained significance, particularly with the proliferation of commercial LCA databases and the availability of advanced software tools.
- **Standardisation:** standards are commonly established within a context of impartiality. The efficacy of these standards has been a subject of exploration with respect to their capacity to minimize variations in Life Cycle Assessment results resulting from subjective decisions made by analysts (Säynäjoki, Heinonen, Junnila, & Horvath, 2017). From a simplification standpoint, standards adhere to an inherent simplification principle as they aim to provide a framework and direction for methodological selections in the field of LCA.
- **Automation:** the emergence of automation as a streamlining framework within LCA has been a relatively recent advancement. Tools and software packages have been increasingly employed to put automation strategies into action. Among the most fundamental automation techniques within the realm of LCA is likely the automated computation and organization of Life Cycle Inventory and Life Cycle Impact Assessment outcomes, facilitated through the use of spreadsheets and specialized computational software. When examining contributions to automation in the literature focused on simplification, these contributions can be categorized into two primary areas: computational strategies and data integration methods.

There are many examples of singular simplification methods or their application within particular product systems are well-documented. However, an apparent dearth of comprehensive review articles specifically addressing the overarching concept of simplification has been observed. Therefore, there remains an unexplored avenue for research aimed at dissecting and organizing the implications stemming from various simplification strategies across diverse product systems and application categories. It is important to address these topics since the act of simplification diminishes the degree of agreement within the scientific community, while concurrently elevating the level of uncertainty regarding the outcomes of the environmental assessment due to reduced data input.

2.3.2. Economic Assessment Tools

The economic analysis of a product is essential to assess its viability and make informed decisions regarding its development, production, and marketing. This section describes some of the most commonly used techniques in the literature to address this aspect. Life Cycle Costing is a part of sustainability methodologies that centre on examining resource flows related to the creation and use of products and services. LCC is an economic strategy that calculates the comprehensive expenses of a product, procedure, or operation, taking into account the entire duration of its lifetime (State of Alaska - Department of Education & Early Development, 2018). In the field of mechatronic products, various studies can be found that utilize LCC for economic analysis. For instance, in the research conducted by Yaping et al., a mathematical model for the LCC of an urban rail transit vehicle is presented. In this article, the utility of this technique is explained for identifying the important criteria to consider during the purchase of these products. Typically, the decision was solely focused on the purchase price, and through LCC, it is demonstrated that all phases of its lifecycle must be taken into account to avoid making a poor financial decision (Yaping, Xingchen, Lu, Yao, & Yiwei, 2016). On the other hand, in the study conducted by Iraldo et al., the use of LCC in conjunction with LCA is proposed to compare various alternatives of household appliances. Their main objective was to explore whether prolonged longevity of energy-intensive products is favourable from both an environmental and economic standpoint. Concluding that from an economic perspective, consumers often

favour products with greater durability. However, this preference may not align with environmental considerations. The choice for more durable options becomes optimal from both economic and environmental standpoints only when the production and disposal phases significantly outweigh the environmental impact of the use phase (Iraldo, Facheris, & Nucci, 2017). Another economic technique related to LCC would be the Total Cost of Ownership (TCO), which could be defined as described as the total expenses linked to the procurement, possession, utilization, and eventual disposal of a product or service (Ellram, 1995). The primary distinction lies in the fact that the LCC takes a product-centric approach, accounting for costs associated with the creation, design, production, distribution, operation, and disposal of the product. Conversely, the TCO assumes the customer's perspective, calculating costs related to the product's search, acquisition, installation, operation, and disposal. As a result, TCO typically focuses on a shorter time horizon than the entire lifespan of the product. In the research done by Saccani et al., they conducted a review of the different models of TCO available in the literature and they proposed a new one designed to cater to a wide range of durable consumer goods purchase categories (which was a critical aspect within the literature available), this tool aids in shaping the ultimate buying choices of individual customers (Saccani, Perona, & Bacchetti, 2017). The Cost-Benefit Analysis (CBA) is a technique that can be also used to guarantee optimal resource allocation efficiency and attain the highest possible benefits in societal well-being. The CBA method involves the identification of all potential gains and losses associated with a proposed project. These gains and losses are then quantified in monetary terms and evaluated based on project selection criteria to ascertain the project's efficiency and desirability from a societal standpoint (Nas, 2016). Articles like the one by Chen et al., demonstrate how this technique can be employed as decisionmaker to achieve equilibrium between the level of resources dedicated to product disassembly and recycling, and the resulting financial returns, using a mechatronic product as case study (Chen, Navin-Chandra, & Print, 1994).

To conclude this presentation of economic approaches, the Net Present Value (NPV) method is one of the most used techniques to perform a LCC economic evaluation (Xie, Cui, & Li, 2022). With this method, the present value of future cash flows is calculated, considering how the value of money changes over time and the cost of capital. This method helps determine

whether an investment will be profitable or not. If the NPV value is positive, means it is profitable, whereas if it is negative, it indicates that it will not be profitable (Gaspars-Wieloch, 2019).

2.3.3. Social Evaluation Metrics

To conduct a comprehensive sustainability analysis, it is necessary to perform a study of the potential social impacts associated with the product. In the context of mechatronic product engineering, this assessment involves measuring and quantifying factors ranging from equity in the supply chain to the product's acceptance by the community. The UNEP (United Nations Environment Programme) proposed the technical framework to conduct a Social Life Cycle Assessment (SLCA) that share the same four phases that the LCA (i.e., goal and scope definition, inventory analysis, impact assessment, and interpretation) (UNEP, 2009). It offers a suitable framework that enables a broader range of stakeholders to participate in advancing social responsibility while evaluating the life cycle of products and services. Social impacts result from either favourable or unfavourable influences on social endpoints, for example, the welfare of stakeholders. The possible impact categories can be clustered in human rights, working conditions, health and safety, cultural heritage, governance, and socio-economic repercussions. While Table 4 summarizes the stakeholders' categories and subcategories.

Table 4. Categories and subcategories of stakeholders for SLCA (UNEP, 2009).

Stakeholder categories	Subcategories
Stakeholder "worker"	Freedom of association and collective bargaining. Child labour. Fair salary. Working hours. Forced labour. Equal opportunities/Discrimination. Health and safety. Social benefits/Social security.
Stakeholder "consumer"	Health and safety. Feedback mechanism. Consumer privacy. Transparency. EoL responsibility.
Stakeholder "local community"	Access to material resources. Access to immaterial resources.

	<ul style="list-style-type: none"> Delocalization and migration. Cultural heritage. Safe and healthy living conditions. Respect of indigenous rights. Community engagement. Local employment. Secure living conditions.
Stakeholder "society"	<ul style="list-style-type: none"> Public commitments to sustainability issues. Contribution to economic development. Prevention and mitigation of armed conflicts. Technology development. Corruption.
Value chain actors (without consumers)	<ul style="list-style-type: none"> Fair competition. Promoting social responsibility. Supplier relationships. Respect of intellectual property rights.

In the field of mechatronic products, there are not many articles available in the literature; some of them have sought to integrate issues like gender during the design process through DfX approaches (Design for Gender). This is the case with the research conducted by Holl et al., which demonstrates that by conducting an interdisciplinary study, it is possible to enhance the ergonomic and technical aspects of the laser engraving and cutting machine (Holl, Horwath, Cojocaru, Hehenberger, & Ernst, 2018). Another example of research that includes the social dimension is the Sustainable Circular Index (SCI) created by Garrido Azevedo et al. In the realm of the social dimension, they seek to minimize work-related accidents, precarious employment, absenteeism, employee turnover, and productivity loss. However, the SCI is applicable at company level, but not to product or component level (Garrido Azevedo, Godina, & de Oliveira Matias, 2017).

In the context of understanding the social dimension of sustainability, Sutherland's research has made significant contributions by investigating the role of manufacturing in affecting society (Sutherland, 2016). The research highlights the challenges in internalizing and operationalizing social sustainability in manufacturing, emphasizing the need for a multidisciplinary approach to measure and evaluate social impacts accurately. The article emphasizes the immaturity of the SLCA methodology and calls for the development of consensus, standardization, and predictive assessment tools for social impacts. The future works suggested in the article

align with ongoing research directions, including the identification of indicators throughout the supply chain, establishing associations between social and financial performance, and developing standardized approaches to consider multiple dimensions of sustainability. Incorporating insights from this research can enhance the discussion on social sustainability within the context of mechatronic product design.

2.3.4. Circularity Evaluation Metrics

To conclude the assessment of the various tools available in the literature for analysing the sustainability of a product, the metrics that can be employed to evaluate circularity are described below. As previously explained, the goal of a circular economy is to achieve a net balance between resources consumed and waste produced, equal to zero. This is why the analysis of circularity entails a study that may encompass all or only some of the sustainability pillars (i.e., environmental, economic, and social). De Pascale et al. have conducted a literature review to identify the different circularity indices available, categorizing them into three groups: (i) micro-level indicators (i.e., products, companies, consumers), (ii) meso-level indicators (i.e., eco-industrial parks), and (iii) macro-level indicators (i.e., city, region, nation, global) (Kirchherr, Reike, & Hekkert, 2017) (De Pascale, Arbolino, Szopik-Depczyńska, Limosani, & Ioppolo, 2021). Since this thesis focuses on mechatronic products, the analysis of circularity indicators will be limited to those related to micro-level. Table 5 compiles the main information regarding these 29 indices found in literature.

Table 5. CE indicators at micro-level (De Pascale, Arbolino, Szopik-Depczyńska, Limosani, & Ioppolo, 2021). N.A. = Not Applicable

#	Name	Acronym	Measurability	Application level	Presented case study	Sustainable dimensions	Reference
1	Disassembly Index	Effort DEI	0-100	Product, Component	N.A.	Environmental, Economic	(Das, Yedlarajah, & Narendra, 2000)
2	CE Toolkit	CET	1 (low), 2 (medium), 3 (high)	Product	N.A.	Environmental, Economic	(Evans & Bocken, 2013)
3	End-of-Life Index	EoL	0-10	Product, Component	Power tool.	Environmental, Economic	(Lee, Lu, & Song, 2014)
4	Recycling indicator set	N.A.	0-1	Product	Recycling of LCD televisions	Environmental, Economic	(Nelen, et al., 2014)
5	Reuse Indicator	Potential RPI	0-1	Resource, Waste	Coal combustion by-products (CCBs). CCBs are solid residues produced in electricity generation.	Environmental, Economic	(Park & Chertow, 2014)
6	CE Index	CEI	Economic value	Material, Waste streams	Recycling of a car materials	Environmental, Economic, Social	(Di Maio & Rem, 2015)
7	Material Indicator	Circularity MCI	0-1	Product, Materials, Energy	N.A.	Environmental, Economic	(ELLEN MACARTHUR FOUNDATION, 2019a)
8	Recyclability Rate	Benefit RBR	Functional unit	Product, Materials	A closed-loop recycling and an open-loop recycling, in Flanders	Environmental, Social	(Huysman, et al., 2015)

9	Eco-cost Value Ratio	EVR	Economic value	Product	An application of a business model for sustainable water recreation in Friesland	Environmental, Economic	(Scheepens, Vogtländer, & Brezet, 2016)	
10	CE Indicator Prototype	CEIP	“Least ideal” - “Most ideal”	Product	N.A.	Environmental, Economic	(Cayzer, Griffiths, & Beghetto, 2017)	
11	Synthetic Environmental Indicator	Economic	N.A.	Economic value	Product	Multifunctional building glass frontage project, in Northern Italy	Environmental, Economic	(Fregonara, Giordano, Ferrando, & Pattono, 2017)
12	Longevity Indicator	N.A.	Time units	Product, Materials	Mobile phone product system	Environmental, Social	(Franklin-Johnson, Figge, & Canning, 2016)	
13	Material Reutilization Score	MRS	From Bronze \geq 35 to Platinum 100	Product, Materials	N.A.	Environmental, Economic, Social	(Cradle to Cradle Products Innovation Institute, 2016)	
14	Recycling Indices	RI	0% - 100%	Product	To calculate the recycling performance for LED lamps and LCD/LED screens	Environmental, Economic	(van Schaik & Reuter, 2016)	
15	CE Performance Indicator	CEPI	Functional unit	Materials, Embodied Energy	Post-industrial plastic waste treatment	Environmental	(Huysman, De Schaepmeester, Ragaert, Dewulf, & De Meester, 2017)	
16	Product-level Circularity Metric	PLCM	0-1	Product, Materials	To calculate the circularity of a plastic	Economic	(Linder, Sarasini, & van Loon, 2017)	

							toy product and of used engines			
17	Value-based Efficiency Indicator	Resource	VRE	Economic value	Product, Resource-efficient sector	Materials,	Several industries evaluated and compared with a traditional mass-based approach	Dutch was and mass-	Environmental, Economic, Social	(Di Maio, Rem, Baldé, & Polder, 2017)
18	End-of-life Indices: - Reuse Index - Remanufacture Index - Recycling Index - Incineration Index (energy recovery)		- I _{EOL-Ru} - I _{EOL-Rm} - I _{EOL-Rc} - I _{EOL-Inc}	Economic value	Product, Energy		Sub-assemblies and parts of two mechatronics products	and two	Environmental, Economic	(Favi C. , Germani, Luzi, Mandolini, & Marconi, 2017)
19	Recycling Index	Desirability	RDI	Complexity scale is 3.5 The top scale for the MSI is 24 The top scale for the TRL scale is 9	top Materials		Electronic devices		Environmental, Social	(Mohamed Sultan, Lou, & Mativenga, 2017)
20	Sustainable Index	Circular	SCI	0-1	Product Energy	system,	N.A.		Environmental, Economic, Social	(Garrido Azevedo, Godina, & de Oliveira Matias, 2017)
21	Global Indicator	Resource	GRI	Recyclability: 1-10	Materials		Wind turbine		Environmental, Economic, Social	(Adibi, Lafhaj, Yehya, & Payet, 2017)

				Geopolitical stability index: 0-10				
22	Linear Flow Index for Product Families		N.A.	Modular structure of product families	Materials, Components, Product families, Waste streams	A family of prosthetic fingers	Environmental, Economic, Social	(Mesa, Esparragoza, & Maury, 2018)
23	Circularity Guidelines	Design	CDG	High, medium, low	Product	A selected group of products that are classified in the sEEE category	Environmental	(Bovea & Pérez-Belis, 2018)
24	Combination Matrix		N.A.	Low-High	Product system, Resource	Cellular phone as material and gold as resource	Environmental	(Figge, Thorpe, Givry, Canning, & Franklin-Johnson, 2018)
25	Effective Disassembly Time	Disassembly	N.A.	Minimum corrective factor: 0.91	Product	Washing machine and coffee machine	Economic	(Marconi, Germani, Mandolini, & Favi, 2019)
26	ease of Disassembly Metric	Disassembly	eDiM	Disassembly time [s]	Product, Component	Recycling facility in Belgium that processes approx. 30,000t of WEEE collected in the Country	Economic	(Vanegas, et al., 2018)
27	End-of-use Value Recovery	Product	N.A.	Pareto analysis: economic value; AHP: 0-9	Product	A hard disk drive	Economic	(Cong, Zhao, & Sutherland, 2019)

28	REmanufacturing with the aid of the PROduct PROfiles tool	REPRO ²	External and Internal criteria	Product	N.A.	Economic	(Zwolinski, Lopez-Ontiveros, & Brissaud, 2006)
29	Circularity Calculator	N.A.	% of product or part in the following cycles: remanufacturing, refurbishment, recycling	Product	N.A.	Environmental, Economic	(IDEALO&CO Explore, 2016)

As can be observed, in recent years, a wide range of indices has been developed, reflecting the growing interest in transitioning to a circular economy by both academia and industry. Nevertheless, this review demonstrates a lack of standardization in assessing and implementing the circular economy. Most of the indicators considered environmental and economic dimensions, while a few incorporated all three pillars of sustainability. Failing to consider the social aspect during the analysis could hinder its implementation, as policies aiming to achieve the circular economy are interconnected with community safety, employment opportunities, education, and environmental conservation goals, especially in regions where a significant portion of the population resides below the poverty line (Kankanamge, Yigitcanlar, Goonetilleke, & Kamruzzaman, 2019). In order to confront and effectively handle the intricacies associated with the transition to a Circular Economy, it may become imperative to streamline the extensive number of metrics, curbing flexibility in their application, while striving to establish a unified and reliable standardized measurement model, free from arbitrary elements.

2.4. EU POLICIES

National and international policies and regulations play a crucial role when aiming to integrate sustainability into the design of mechatronic products. This section has focused on reviewing and analysing some of the most pertinent European-level policies. This study is essential to grasp the context in which these products are designed, produced, and marketed. Policies related to the environment serve as a primary driver for advancing sustainable production and innovation. The interaction between policymakers and industry is not a unilateral affair; policies emerge as the product of a collaborative process. This collaborative process, involving legislators, industry representatives, and various stakeholders, significantly shapes the actual design of policy instruments, which are just one of several factors influencing innovation. The effectiveness of these policy instruments is heavily contingent on a myriad of other variables, including technological possibilities, market dynamics, and emerging opportunities. Illustrative instances of sustainable measures that encourage the “closed-loop” concept within product lifecycles encompass offering tax incentives to companies

with a minimal ecological footprint that engineer longer-lasting, readily recyclable products, and fostering collaborative platforms among value chains and industrial symbiosis. Furthermore, there are existing instances of adopting a CE approach in legislation (e.g., China, Japan, Germany, the UK, and the EU). Nevertheless, challenges and constraints persist in its assimilation and execution across various domains (Garrido Azevedo, Godina, & de Oliveira Matias, 2017). The primary goal of these directives is to compel industrial companies to enhance product sustainability and drive industrial innovations, thereby steering society towards sustainable development in both products and production processes. Achieving this objective necessitates the enhancement of environmental policies and innovation policies that are environmentally driven. Europe has set a goal to achieve climate neutrality by 2050, marking its ambition to be the world's first carbon-neutral continent. The European Union has established a comprehensive set of legally binding climate objectives that encompass various critical aspects of the economy. These objectives encompass emissions reduction targets in multiple sectors, an initiative to enhance natural carbon absorption capabilities, a revised emissions trading system aimed at limiting emissions while pricing pollution to encourage investment in eco-friendly practices, as well as social assistance programs for individuals and small enterprises (European Commission, n.d. b). In October 2023, the Commission adopted the last two components within the “Fit for 55” legislative package, demonstrating Europe’s commitment to achieving its 2030 climate goals. This comprehensive set of laws underscores Europe’s dedication to fulfilling its pledges to its citizens and global partners by taking a leading role in climate action and driving the green transition for the betterment of both its people and industries. The Energy Taxation Directive, a crucial component of the Fit for 55 Package, is still pending completion, and the Commission is encouraging Member States to expedite negotiations and reach a conclusion without delay (European Commission, 2023).

2.4.1. CE Action Plan

The new Circular Economy Action Plan, proposed by the European commission, presents a forward-looking strategy aimed at fostering a cleaner and more competitive Europe through collaborative efforts with economic stakeholders, consumers, individuals, and civil society groups. Its

goal is to expedite the necessary transformative shift outlined in the European Green Deal, all the while building upon circular economy initiatives that have been in place since 2015 (European Commission, 2015). The proposal outlines a series of interconnected strategies aimed at creating a robust and cohesive product policy structure. This structure is designed to promote sustainability in products, services, and business models, ultimately reshaping consumption habits to minimize waste generation. The implementation of this product policy framework will occur incrementally, with a particular focus on addressing critical product value chains. Additional measures will be introduced to decrease waste and to foster a thriving internal market within the EU for top-quality secondary raw materials. Concurrently, efforts will be made to enhance the EU's ability to manage and mitigate its waste (European Commission, 2020). European Union measures and legal frameworks are already in place to some degree to tackle sustainability considerations associated with products, whether through compulsory or optional means. Particularly, the Eco-design Directive (European Parliament, 2009b) effectively governs energy efficiency and certain aspects of circularity in products related to energy. The central focus of this proposed legislation is to expand the scope of the Eco-design Directive, extending its applicability beyond energy-related items. This adjustment aims to encompass a wider array of products and enhance its effectiveness in promoting circularity. the Commission will explore the possibility of defining sustainability principles and adopting suitable measures to oversee the following aspects (European Commission, 2020):

- Enhancing the durability, reusability, upgrade potential, and reparability of products while also tackling the issue of harmful substances in them, boosting their overall energy and resource efficiency.
- Facilitating the process of remanufacturing and promoting high-quality recycling.
- Enhancing the proportion of reused materials in goods, while maintaining their functionality and safety standards.
- Minimizing carbon emissions and ecological impacts.
- Preventing the use of disposable items and combating the problem of products becoming obsolete prematurely.
- Implementing a prohibition on the disposal of durable unsold products.

- Encouraging the adoption of product-as-a-service or similar models that enable manufacturers to retain product ownership and remain accountable for its performance throughout its entire lifespan.
- Harnessing the capabilities of digitalizing product information, which may involve implementing methods like digital passports, tagging, and watermarks.
- Evaluating and incentivizing products according to their distinct sustainability achievements, which may involve tying rewards to exceptional performance standards.

The Commission intends to update the Monitoring Framework for the CE (Eurostat, n.d.), incorporating European statistics wherever feasible. The new set of indicators will consider the key priorities outlined in this action plan and the connections between circularity, climate neutrality, and the zero-pollution goal. The shift towards a circular economy will entail profound and systemic changes, both within the European Union and on a global scale. This transformation may at times prove to be disruptive, necessitating a commitment to fairness. It will demand the collaboration and alignment of all stakeholders, spanning across various levels, including the EU, national, regional, local, and international.

2.4.2. Eco-design Directive

The Eco-design Directive 2009/125/EC (European Parliament, 2009b) has a well-established history of generating advantages for both businesses, consumers, and the environment. This regulation establishes a framework for determining the eco-design requirements for Energy-related Products sold in the European Union. Its focus is on enhancing energy efficiency to reduce the environmental impact of these types of products. ErP includes appliances, lighting equipment, refrigeration equipment, and heating equipment, among others. This directive anticipates the inclusion of two distinct categories of obligatory product prerequisites. The first pertains to specific requirements, which establish measurable thresholds like maximum energy consumption or minimum percentages of recycled materials. The second category involves generic requirements, which do not establish specific limits but necessitate attributes like “energy efficiency” or “recyclability”. It should be noted that adherence to the appropriate

harmonized European standard is presumed to signify compliance with these requirements. In 2021, the implementation of eco-design measures across 31 product categories resulted in a substantial reduction of EUR 120 billion in energy costs for consumers in the European Union. Additionally, these measures contributed to a 10% decrease in the annual energy consumption of the affected products (European Commission, n.d. c). The cornerstone of the Commission's strategy toward achieving greater environmental sustainability and promoting circular products is the newly proposed **Eco-design for Sustainable Products Regulation** (ESPR), released in 2022. This proposal is an extension of the current Eco-design Directive, which presently focuses solely on products related to energy. It will empower the establishment of performance and information standards for a wide range of tangible products available in the EU market, though there are certain exclusions, including items like food and feed as defined in Regulation 178/2002. Additionally, for product clusters with significant shared traits, the framework can facilitate the formulation of overarching regulations. The introduction of the *Digital Product Passport* is set to offer insights into the environmental sustainability of products. Accessible via a simple data carrier scan, it will furnish details regarding aspects like product durability, repairability, recycled content, and the availability of spare parts. This initiative aims to empower consumers and businesses in making informed purchasing decisions, streamline the repair and recycling processes, and enhance transparency concerning a product's environmental footprint throughout its lifecycle. Furthermore, the product passport is expected to assist public authorities in conducting more effective checks and inspections. ESPR, being rooted in the Eco-design Directive 2009/125/EC, is poised to eventually supplant the existing directive. In the interim, Directive 2009/125/EC will remain in effect. The Eco-design and energy labelling working plan for the years 2022-2024 is an extension of previous efforts, which have been ongoing since the inception of the initial Eco-design Directive. This comprehensive plan encompasses not only the tasks mandated by the Energy Labelling Framework Regulation (EU/2017/1369) (European Parliament, 2017) but also evaluates the advancements achieved through the European Product Registry for Energy Labelling (EPREL). Additionally, the plan addresses analogous activities related to tire labelling, which are grounded in distinct legal foundations.

In a study conducted by the Special Eurobarometer in 2019, it was found that 93% of consumers were familiar with the energy label, and 79% of them took it into account when making purchases of energy-efficient products (European Commission, n.d. a). EU regulations pertaining to energy labels and eco-design are projected to result in energy savings of around 230 million tonnes of oil equivalent (Mtoe) by 2030. As a result, consumers are expected to enjoy an average annual cost reduction of up to 285 € on their household energy expenses. Additionally, the implementation of energy efficiency measures is forecasted to generate an additional 66 € billion in revenue for European enterprises (European Commission, n.d. a). Due to advancements in energy-efficient technology, along with the diminishing consumer distinction between A++ and A+++, the EU's energy label categories are undergoing a gradual transition. They are shifting back to the more straightforward A to G scale (see Figure 8). For instance, a product currently classified as A+++ for energy efficiency might be reclassified as a class B or lower when rescaled, even if its energy consumption remains unchanged. Initially, the A class will be vacant to accommodate the development of even more energy-efficient models in the future.

How to recognise a rescaled product ?

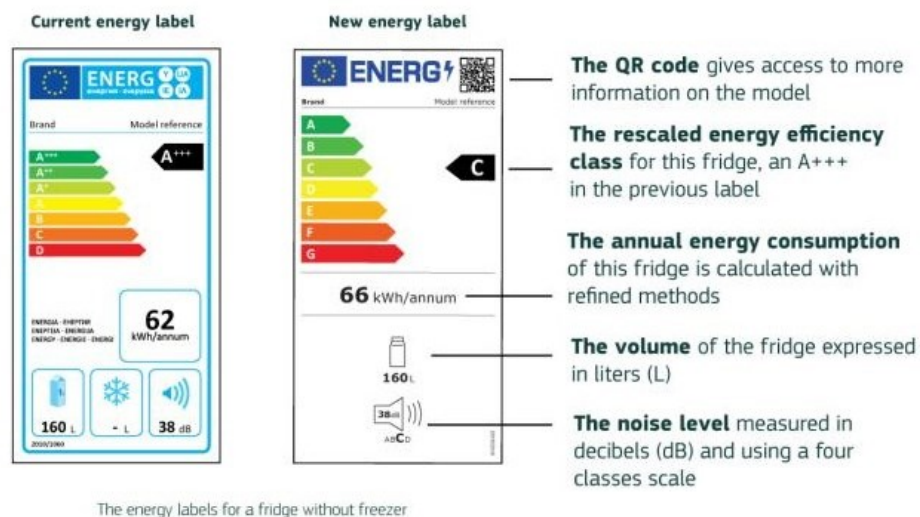


Figure 8. Current energy label vs New energy label (European Commission, n.d. a).

This approach aims to empower consumers in making more informed choices when selecting energy-efficient products, while simultaneously fostering an environment that motivates manufacturers to persist in their

efforts to advance energy-efficient technologies through research and innovation. In 2021, a rescaling process was implemented for the initial set of five product groups (fridges and freezers, dishwashers, washing machines and washer-dryers, electronic displays including televisions, and lighting), and additional product groups bearing EU energy labels are scheduled for rescaling in the forthcoming years.

2.4.3. Waste management

The European Union’s waste policy is designed to foster the development of a circular economy, focusing on the extraction of valuable resources from waste materials to the greatest extent possible. As part of this transformative process, various EU waste regulations are currently under examination for potential revisions. The central legislative instrument governing waste treatment and management within the EU is the Waste Framework Directive, which establishes a “waste hierarchy” outlining the preferred order of waste management practices (see Figure 9). Specific waste categories necessitate tailored approaches. Consequently, in addition to the overarching legal framework, the EU has implemented a multitude of regulations to address distinct waste categories (European Commission, n.d. e).



Figure 9. Waste hierarchy within the Waste Framework Directive (European Commission, n.d. e).

The *European List of Waste* (LoW) serves as a shared framework for categorizing waste throughout the European Union, facilitating effective waste management, including the handling of hazardous waste. These waste

codes play a crucial role in various activities, such as waste transportation, the issuance of installation permits (which frequently refer to specific waste codes), and the compilation of waste-related statistics. The provision of a guidance document concerning waste classification assists national authorities, local governments, and businesses (particularly in permit-related matters) in accurately understanding and implementing European Union regulations related to waste classification (European Parliament, 2018a). For different waste streams, dedicated implementation reports and directives can be found:

- **Batteries and accumulators:** batteries serve as an essential energy reservoir and play a pivotal role in advancing the journey towards climate neutrality and a more sustainable, circular economy. The global demand for batteries is on a rapid ascent, projected to increase fourteenfold by 2030, with the European Union expected to contribute 17% of this demand. The regulatory framework within the EU concerning batteries is designed to ensure their sustainability across their entire life cycle, encompassing material sourcing, collection, recycling, and repurposing. In the current energy landscape, these new regulations foster the growth of a competitive and sustainable battery industry, thereby bolstering Europe's transition to clean energy and reducing dependence on fossil fuel imports. In July, 2023, the European Parliament and the Council jointly adopted the Batteries Regulation, a pivotal step to mitigate the environmental impact of this burgeoning battery industry, in light of evolving socioeconomic conditions, technological advancements, shifting market dynamics, and diverse battery applications (European Parliament, 2023c).
- **End-of-Life vehicles:** the ELV Directive, commonly known as the Directive on end-of-life vehicles, establishes specific objectives for end-of-life vehicles and their constituent parts. Furthermore, it enforces strict restrictions on the use of hazardous materials in the production of new vehicles, particularly substances like lead, mercury, cadmium, and hexavalent chromium, unless specific exemptions apply due to a lack of suitable alternatives. The European Union has also implemented additional regulations, such as the Directive governing the approval of motor vehicle types with an emphasis on their capacity for reuse, recycling, and

recoverability. In 2021, a comprehensive evaluation of the ELV Directive was initiated, culminating in the proposal of a new regulation in 2023 (European Parliament, 2023a).

- **Mining waste:** mining waste arises as a result of the extraction and refinement of mineral resources. This category encompasses components like topsoil overburden, which is removed to access the mineral deposits, as well as waste rock and tailings that remain after the valuable mineral extraction process. European Union regulations are designed with the objective of mitigating or preventing any detrimental environmental impacts associated with the handling and disposal of mining waste (European Parliament, 2009a).
- **RoHS:** the primary objective of the RoHS Directive is to mitigate the threats that improper management of electronic and electrical waste poses to both the environment and human well-being. The directive actively advocates for the enhanced recyclability of electrical and electronic equipment (EEE), given that discarded EEE and its constituent parts have fewer harmful materials. Simultaneously, it establishes equitable conditions for manufacturers and EEE importers operating within the European market (European Parliament, 2023b).
- **Ship recycling:** the primary objective of the EU's Ship Recycling Regulation is to mitigate and forestall accidents, injuries, and adverse consequences on both human well-being and the environment that may arise from the dismantling of vessels registered under European Union member states (European Parliament, 2018f).
- **WEEE:** the quantity of waste arising from electrical and electronic equipment (commonly referred to as WEEE or e-waste) in the European Union experiences a steady growth each year. This surge in e-waste production has made it one of the swiftest expanding waste categories. It encompasses a broad spectrum of devices, such as mobile phones, computers, televisions, refrigerators, household appliances, lighting fixtures, as well as medical equipment and solar panels. The WEEE Directive mandates the proper collection and treatment of WEEE, establishing specific objectives for their collection, recovery, and

recycling. Additionally, it aids European nations in combatting the illicit exportation of waste more effectively by making it more difficult for exporters to disguise unlawful shipments of WEEE. Furthermore, it lessens the administrative workload by promoting the harmonization of national EEE registers and standardizing reporting formats (European Parliament, 2018d).

- **Construction and demolition waste:** the primary goals for this waste category encompass two key aspects. To begin with, the European Union strives to guarantee environmentally responsible management of Construction and Demolition Waste (CDW). Secondly, harnessing the complete value of CDW will actively support the shift towards a circular economy (European Parliament, 2018c).
- **Landfill waste:** in 2018, a quarter of the total municipal waste generated within the European Union ended up being disposed of in landfills. This practice can pose significant risks to both the environment and human well-being. Landfilling leads to the generation of leachate, which can contaminate groundwater, and it results in the production of methane, a potent greenhouse gas. Moreover, when recyclable waste is sent to landfills, valuable materials are needlessly lost from the European economy. The Landfill Directive has been established with the dual purpose of safeguarding human health and protecting the environment. It specifically aims to minimize or, ideally, prevent any adverse consequences stemming from landfill operations, including their impact on surface water, groundwater, soil, air quality, and human health. This is achieved through the implementation of stringent operational and technical standards (European Parliament, 2018b).
- **Packaging waste:** the Packaging Directive strives to create consistency in national regulations regarding packaging and the handling of packaging waste. Its primary objectives include ensuring robust environmental safeguards and facilitating the smooth operation of the internal market. The most recent revision of the Directive includes updated provisions aimed at reducing the generation of packaging waste while encouraging practices such as reuse, recycling, and other methods of reclaiming

packaging waste instead of simply disposing of it. Notably, all EU member states must establish producer responsibility schemes for all types of packaging by the end of 2024, and the Directive establishes precise recycling targets (European Parliament, 2018e).

- **Sewage sludge:** the Sewage Sludge Directive seeks to safeguard human, animal, plant, and environmental well-being through the establishment of prescribed limits for heavy metal content in soil and sludge. Additionally, it aims to promote greater utilization of sewage sludge in agriculture. This directive further outlines specific concentration limits for seven heavy metals in sewage sludge for agricultural purposes and in soil treated with sludge. It also prohibits the application of sewage sludge that would lead to heavy metal concentrations in soil surpassing these specified limits (European Parliament, 2022).
- **Waste shipments:** the primary objectives of European Union regulations pertaining to the transportation of waste materials encompass safeguarding the environment, minimizing hazards to human well-being. Additionally, they seek to enhance legal transparency and promote consistency in the realm of cross-border waste shipments (European Parliament, 2021).

2.5. STATE OF THE ART SUMMARY AND RESEARCH QUESTIONS

The analysis of the literature referring to sustainable engineering design for mechatronics highlights the evolving understanding of sustainability as a multidimensional concept. It has been explained how mechatronic products, known for their multi-disciplinary nature, pose unique challenges and opportunities in achieving sustainability. They are associated with natural resource consumption, energy-intensive manufacturing, and complex end-of-life management. However, it has been observed that sustainability analyses for these products focus on environmental and economic aspects of sustainability. Delving into social and ethical dimensions is essential for a more holistic perspective.

Regarding methodological engineering design approaches which include various metrics and tools, numerous strategies and indices can be found that aim to assess these parameters (qualitatively, semi-quantitatively, and

quantitatively). However, despite the wide range of options available, there continues to be a gap between these eco-design tools and their actual implementation in the industry, primarily due to their often-high complexity of those techniques. Furthermore, a lack of standardization of these indicators has also been observed.

Lastly, it has been shown that European policies are essential for encouraging the long-term growth of mechatronic devices. Eco-design and sustainability are gradually finding their way into mechatronic goods thanks to the European Union's active promotion of sustainable practices. Energy efficiency, reducing environmental effect, encouraging the development of circular economies, and protecting consumers by emphasizing high-quality and safe products are just a few of the many topics covered by these regulations. To improve the efficacy of these policies, nevertheless, it is imperative to harmonize standards that benefit producers and consumers alike, strengthen oversight and enforcement, foster innovation, and coordinate policies globally (because mechatronic products frequently have international markets).

To address the key issues related to improving sustainability in the mechatronic industry and enabling informed decision-making, the following research questions are proposed:

- **RQ1:** How can a resilient eco-design methodology be developed to enable designers to comprehensively assess the short-term and long-term effects throughout the lifecycle of mechatronic products, while integrating sustainability dimensions and circularity principles?
- **RQ2:** What methods and approaches are effective in the context of the study for evaluating the sustainability of mechatronic products in terms of environmental impact, costs, and social conditions across all phases of their lifecycle?
- **RQ3:** How can a repository of eco-design actions and best practice guidelines be established, which is flexible enough to stay current with the latest trends and guidelines in the field of eco-design and circularity?
- **RQ4:** To what extent can a sustainability label be developed to enable consumers to clearly and transparently understand the

environmental, economic, and social impacts of mechatronic products, and how can these results be presented in a manner accessible to the general public?

These research questions align with the thesis's objectives, focusing on the development of a comprehensive eco-design methodology, the establishment of a best practice repository, and empowering consumers through a sustainability label. The research seeks to address the lack of a comprehensive approach in assessing the sustainability of mechatronic products and contribute to the advancement of the eco-design and circularity field.

3. PROPOSED METHOD

This chapter aims to explain the complete methodology developed in this research work, which aims to include the three pillars of sustainability as well as circularity indicators during the design phase of mechatronic products. The proposed methodology is based on an analysis of the environmental, economic, and social characteristics of mechatronic products throughout their lifecycle. Several indicators and metrics are used to understand the product sustainability and to have a clear overview early in the design phase. The metrics used to analyse the three pillars of sustainability are LCA for environmental impact, LCC for economic assessment, and a combination of indices measuring the rights and freedoms of the population for social impact. Additionally, for the assessment of circularity, EoL management indices and a reliability score have been combined. The use of these metrics in the early design stages allows the designer to obtain a clear indication of the critical points of the product design and areas for intervention to enhance it.

3.1. OVERVIEW OF THE ENGINEERING METHOD PROPOSED METHODOLOGY

The proposed framework is a systematic approach that can be performed iteratively to optimize the sustainability score of the analysed product. The method comprises five main phases, as shown in the flowchart in Figure 10 (dotted lines), and they are summarized as follow: (i) Product classification, (ii) Life Cycle Engineering analysis, (iii) Sustainability Index assessment, (iv) Implementation of eco-design methodology, and (v) Report production. The following paragraphs describe in detail each stage of the framework proposed.

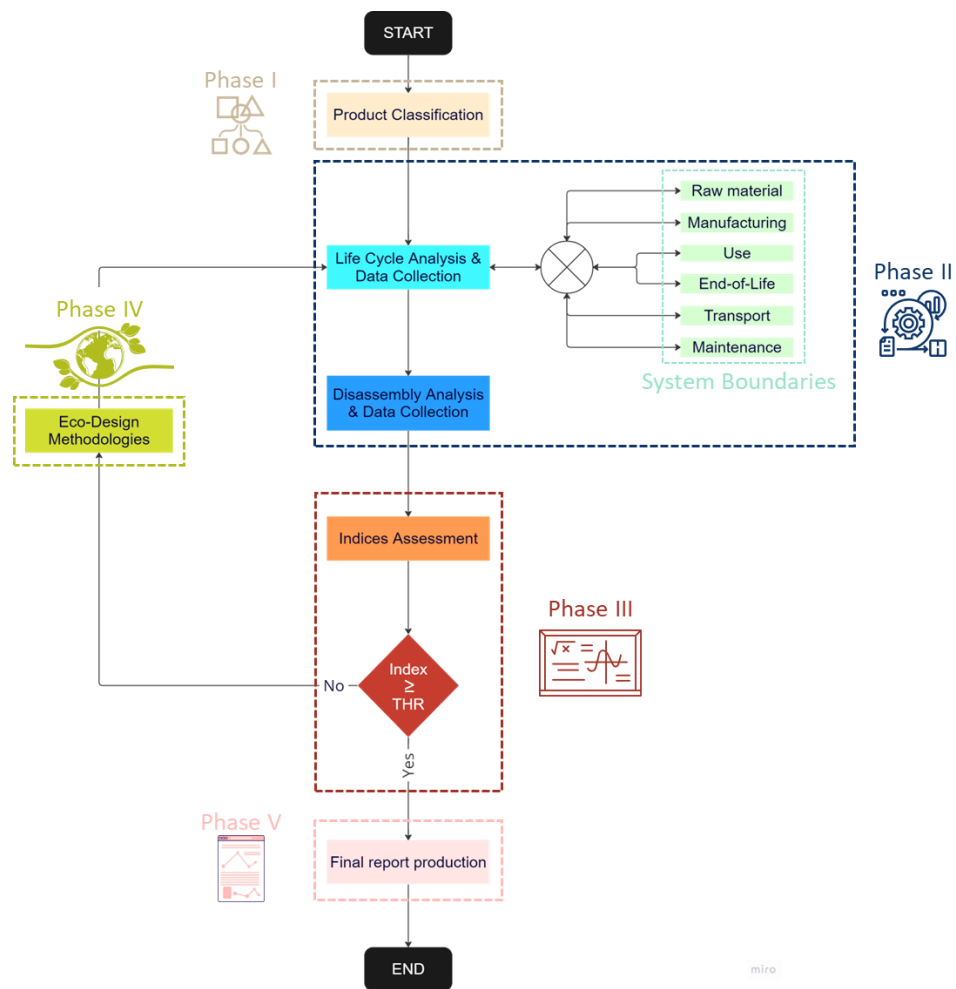


Figure 10. Overall workflow of the framework proposed.

3.2. PHASE I: PRODUCT CLASSIFICATION

In this initial phase of the methodology, the basic characteristics of the product to be analysed are defined, along with any potential requirements or constraints set by the design department (see Figure 11). The information gathered here is of great importance as it enables the optimization of the Sustainability Index calculations, taking into account the specific type of product under examination.

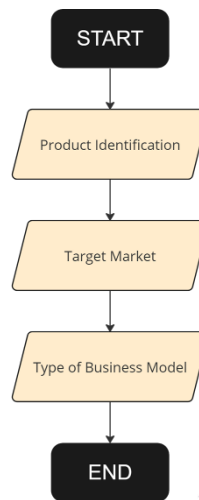


Figure 11. Workflow Phase I: Product Classification.

3.2.1. Product identification

Firstly, it is necessary to identify the category of mechatronic product the user intends to analyse. Following a general classification about mechatronics, different categories of products based on their characteristics and functions can be identified (Bishop, 2018). Below, an example list of families of mechatronic products is presented, although this methodology can be extended to all those products.

- Robotics and automation systems (e.g., industrial robotic arm used in manufacturing)
- Automotive mechatronics (e.g., the anti-lock braking system (ABS) in vehicles)
- Household appliances (e.g., washing machines)
- Consumer electronics (e.g., smart devices)
- Industrial automation (e.g., PLC-based systems)
- Aerospace and defence systems (e.g., unmanned aerial vehicle (UAV))
- Home automation (e.g., automated lighting)
- Agricultural mechatronics (e.g., drones for precision farming)
- Medical devices and biomechatronics (e.g., cardiac pacemaker to regulate heart's rhythm)
- Entertainment and gaming technologies (e.g., virtual reality (VR) headsets)

- Educational mechatronic products (e.g., electronics kits that teach circuit building)

3.2.2. Target market

When industries design an appliance, they typically define an initial target market where it will primarily be sold. While there is no certainty that the product will remain in the target country throughout its use and End-of-Life, that “target” country is used as an assumption for future calculations. Therefore, for sustainability index calculations, data related to that state will be used (e.g., energy grid mix, percentages of recycled material, etc.). Furthermore, the redesign options proposed will be tailored to that market, avoiding for example the use of prohibited materials in that region. It is also important to determine the expected quality and price of the appliance from the beginning. Thus, by classifying it as high-end, mid-range, or low-end, the optimization of the calculation of certain factors that affect the sustainability index can be simplified (e.g., economical index, materials used, etc.).

3.2.3. Type of business model

The final section for the comprehensive product description is defining the type of Business Model (BM) in which the product will be involved. The aim of this section is to clearly establish the uncertainty of the source of the information required for the calculation of all indices. Since depending on which BM is being used, the reliability of the data can vary significantly. This helps to define the uncertainty regarding the data source, thus enhancing the analysis of the sustainability index results. The following is a description of the main features to be taken into consideration in the two BM analysed: the Product Service System (PSS) and the Product Based System (PBS).

Product-Service System

When a manufacturer sells a service, the fact that the product that performs that service is durable and repairable is critical because the company pays the replacement costs. Therefore, in this case, European policies that seek to achieve circular economies are aligned with the company's objectives. When working with PSS, the level of information about the product is much higher than with PBS and this is a huge advantage

when calculating and interpreting the different sustainability indexes, being able to easily obtain eco-design actions (as guidelines) that will be used by engineers during the creation of new products.

Product-Based System

In this case, the consumer buys a product, and the manufacturer is no longer responsible for it after it is sold and the warranty period has expired, so the end user is more concerned with the product's durability and repairability. In this scenario, it is important that all information about the product's repairability is easily accessible and understandable, as it is highly likely that an external technician will perform the maintenance or replacement of parts. The level of uncertainty for the data from this scenario is higher than the one for the PSS since it will be based mostly in assumptions. In Section 3.3 the management of the uncertainty is described in detail.

3.3. PHASE II: LIFE CYCLE ENGINEERING ANALYSIS

This framework's second phase is crucial for a methodology intended to produce a sustainability index for mechatronic products. All relevant information must be gathered in order to conduct a thorough analysis of all impacts (such as technical, environmental, economic, and social) resulting from decisions made throughout the product's lifecycle. Mitigating the negative effects of product production and consumption is one of the main goals of this phase. It is broken down into three stages, which are described below, as shown in Figure 12.

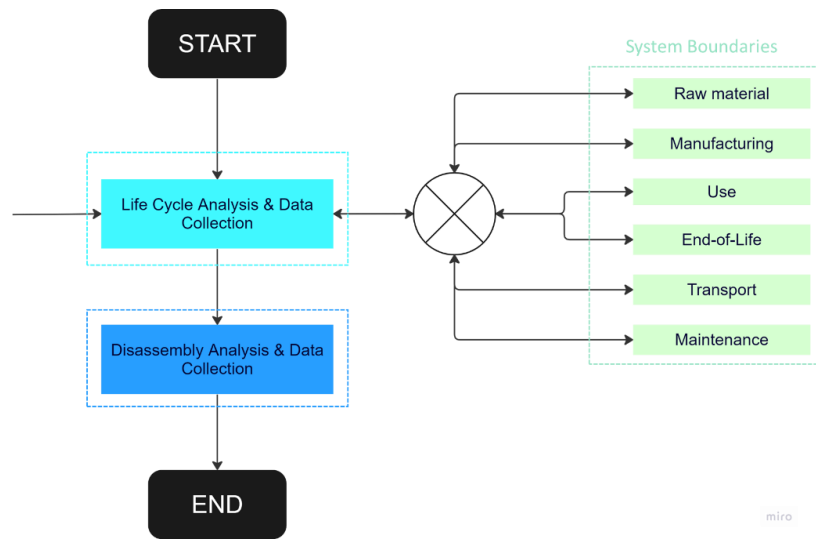


Figure 12. Workflow Phase II: Life Cycle Engineering.

3.3.1. System boundaries

Setting up the system boundaries and choosing which lifecycle phases to include or exclude early on is crucial. Only data related to these phases will thereby be gathered. This methodology, which is shown in Figure 13, enables a thorough examination of a product from cradle to grave, covering the following stages: (i) Material extraction, (ii) Manufacturing, (iii) Use, (iv) End of life, (v) Transportation (i.e., for material extraction, to distribution plant, to end-user or to EoL treatment facility), and (vi) Maintenance.

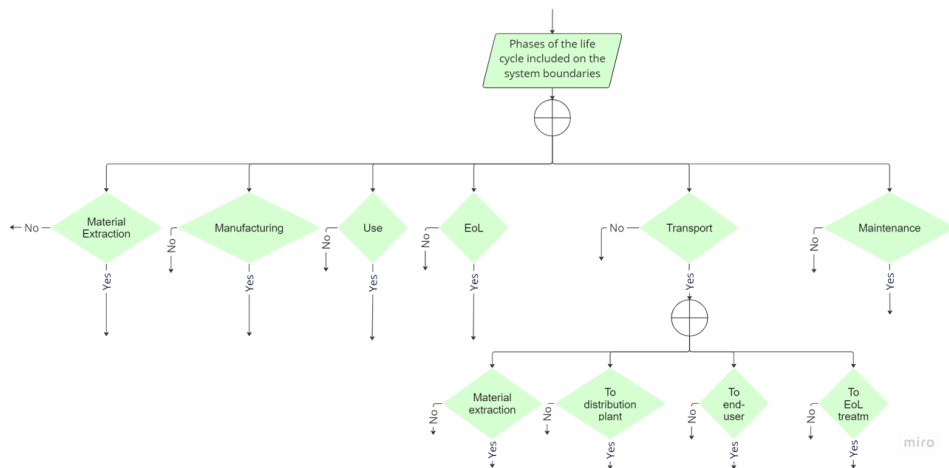


Figure 13. Flowchart for System Boundaries.

The methodology offers freedom and flexibility to the user, allowing for a simpler analysis that includes only some of these phases (those that are more relevant to the ongoing study or product group category).

3.3.2. Life Cycle Analysis

This phase of the methodology is similar to the Life Cycle Inventory (LCI) outlined in ISO 14040 and ISO 14044 (International Organization for Standardization, 2006b) (International Organization for Standardization, 2006a), as explained in detail in Section 2.3.1. It involves gathering all relevant information (i.e., information related to the system boundaries selected) and conducting necessary calculations (e.g., determining data uncertainty or associating each data point with the index affected by it) to have all the data required for the accurate calculation of the sustainability index. The first thing that needs to be defined is the *functional unit*, which can be defined as “*quantified description of the performance of the product systems*” (Weidema, Wenzel, Petersen, & Hansen, 2004). The following describes the pertinent information for each of the phases that can be considered and the approach that can be employed to obtain such information:

- **Data for raw material extraction:** data related to the material source used to produce the component (e.g., origin, material, country of extraction). A virtual approach can be used to gather this information (e.g., BoM and CAD).
- **Data for manufacturing processes:** first, it is necessary to establish whether all the components utilized in product creation are new or if some of them have been reused. When all the components are new, the plant information for producing each of them will be considered, including utilities such as water, electricity, and gas, along with the various production processes used. Conversely, if any components are reused, they must be identified, and data collection will be limited to the production plant details for those new components exclusively.

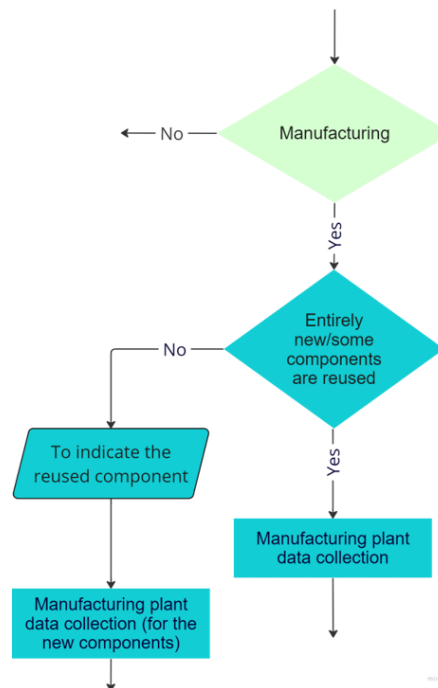


Figure 14. Data collection manufacturing phase.

- Data for use phase:** For this phase, all the potential resources that can be consumed by the product during its lifespan have to be considered, including electricity, gas, water, detergent, wood, or fuel oil. Additionally, the origin of these resources should be specified (e.g., whether electricity is sourced from the country's energy grid mix or from private renewable sources, such as solar panels). Once the resources consumed by the device are defined, it will be specified whether the product has sensors to calculate its consumption. If the device is equipped with sensors, it will enable a more accurate estimation of consumption during this phase, as designers and engineers can use average consumption values for such products in the specific country. Conversely, if the product lacks sensors, the consumption of these resources will be estimated using statistical data from the region where the product is intended to be sold.

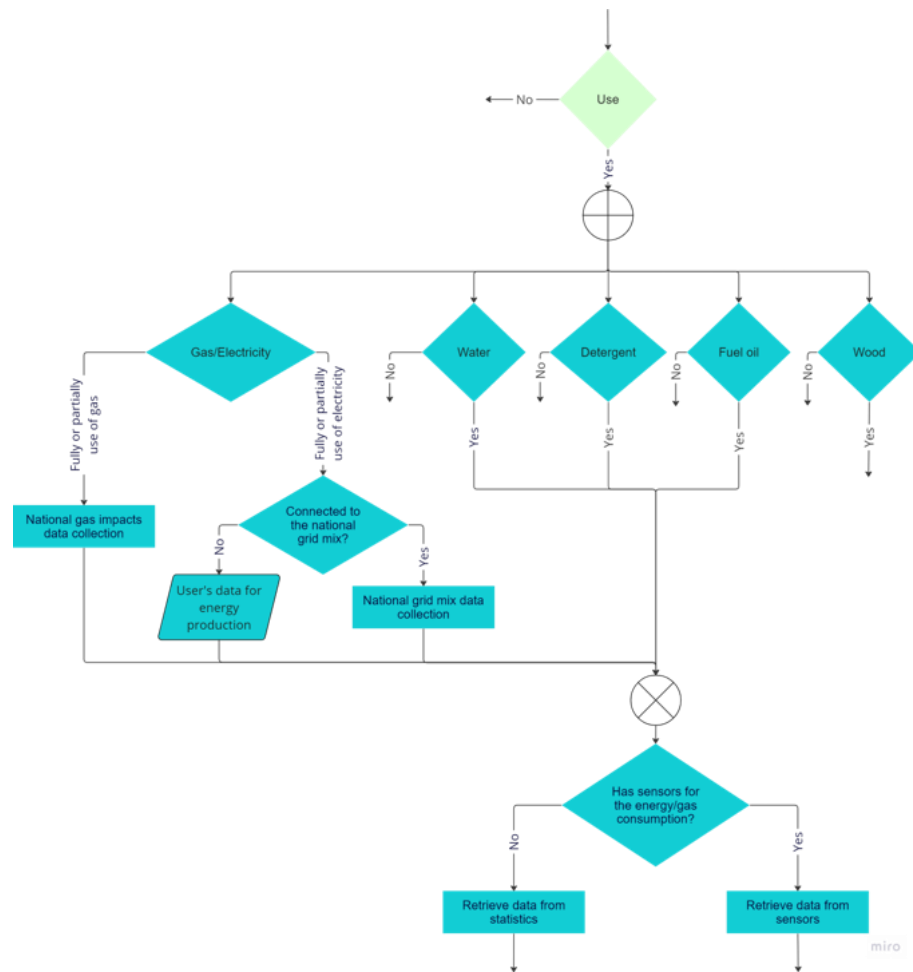


Figure 15. Data collection use phase.

- Data for EoL phase:** For end-of-life considerations, it must be specified whether all components will undergo the same treatment (e.g., landfill) or if some will have a different EoL process. Once all the treatments to be used are established, information related to these processes is collected based on statistics from the country where the product will be sold (in the absence of information, European best practice documents related to the disposal of the studied products will be used) (European Parliament, 2018a) (European Parliament, 2018c). Additionally, based on the end-of-life scenario selected in this phase, the index related to that scenario will be prioritized during the sustainability index calculation (i.e., it will carry greater weight in the calculation).

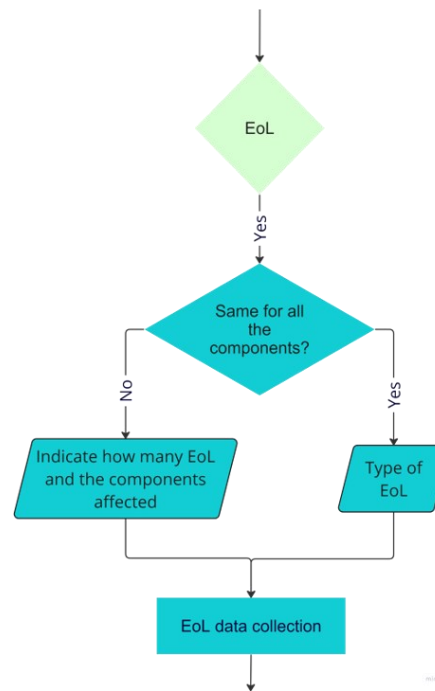


Figure 16. Data collection EoL phase.

- **Data for transportation:** In this phase, data related to the transportation of raw materials, from the manufacturing plant to the distribution plant, from the distribution plant to the end user, and for end-of-life facilities, is collected. The proposed methodology grants complete freedom to the designer/engineer to choose the most suitable estimations for the selected product (e.g., by plane, by truck, by ship, by train, etc.).

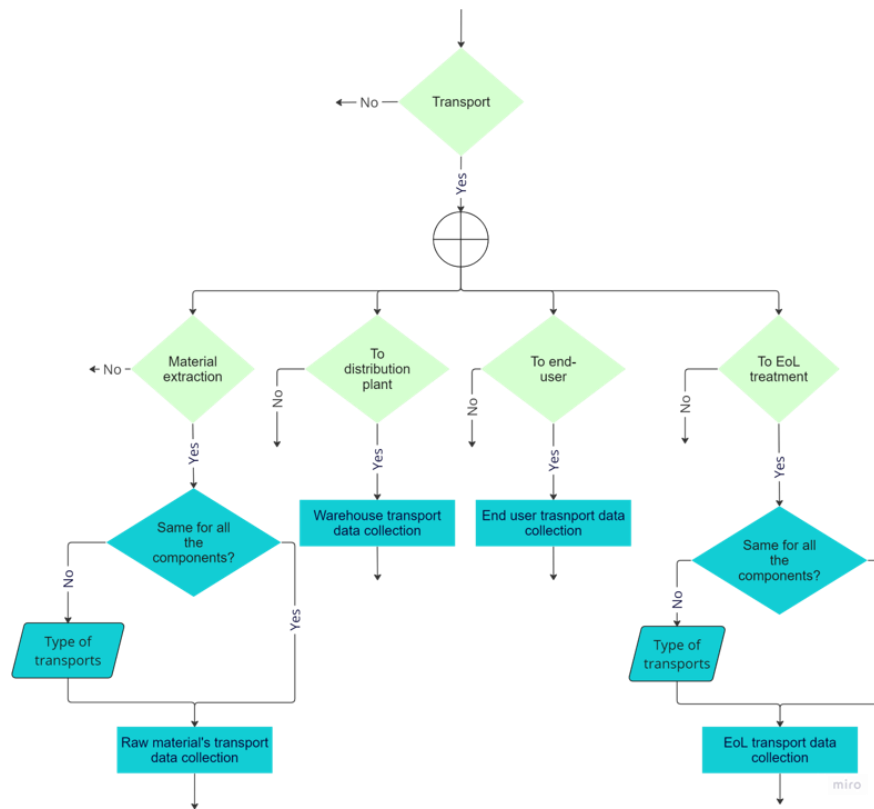


Figure 17. Data collection transport phase.

- **Data for maintenance:** This phase aims to define which components need to be replaced during the product's lifespan. In this way, the impacts related to the production of these replacement parts can be considered (i.e., those associated with material extraction and manufacturing). To identify components requiring maintenance, an initial assessment will examine whether products in the same group have sensors that can provide relevant information. If the product lacks sensors, a statistical data analysis and spare parts sales analysis will be conducted. Additionally, it is determined whether the product has programmed maintenance by the manufacturer or not.

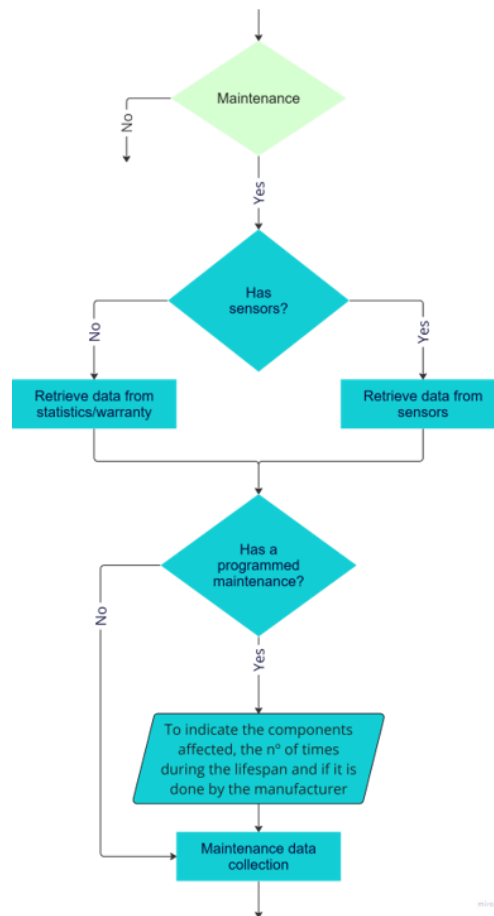


Figure 18. Data collection maintenance phase.

3.3.3. Disassemblability Analysis

As can be seen in Figure 19, the first action during the disassemblability analysis is the definition of the parts that need to be disassemble.

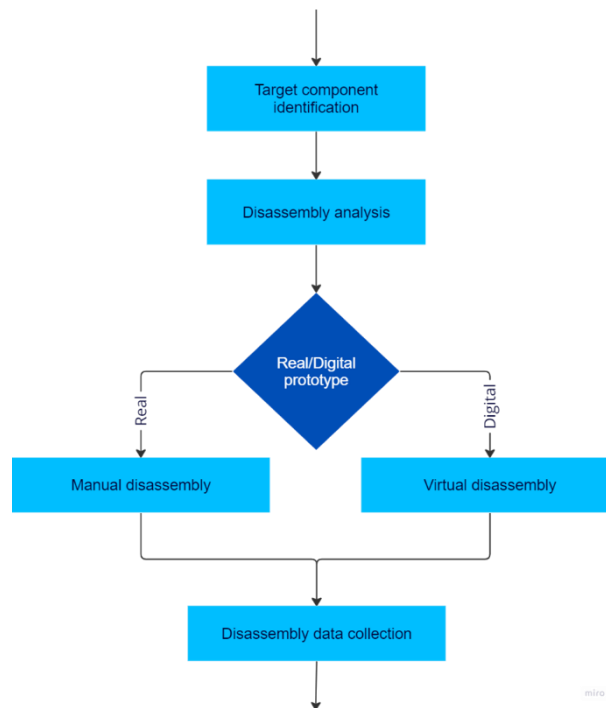


Figure 19. Disassemblability analysis flowchart.

Identification of target components

When considering mechatronic products, reference is made to complex products that may be made of a significant number of interconnected components. These components can undergo wear and tear throughout the product's lifecycle, thereby requiring replacement to restore the product's full functionality. To simplify the disassemblability analysis of such products, it is necessary to focus the study on those components of greater significance. These components are commonly referred to as "target components" or "priority parts" (PPs). Focusing on key components simplifies the analysis, as it is not necessary to evaluate all components equally, saving time and resources.

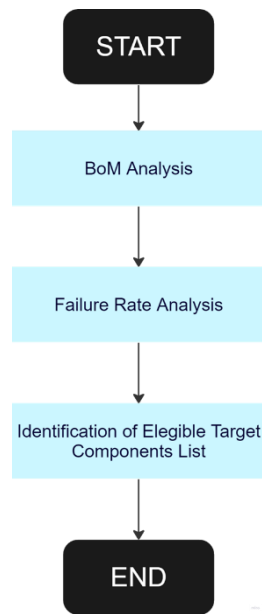


Figure 20. Workflow for the identification of target components.

To enable the comparison of products belonging to the same product group, priority parts must be determined at the level of the product group (Cordella, Alfieri, & Sanfelix Forner, 2019). When establishing the list of priority parts, the factors to consider are, first, the failure frequency, and second, the importance of this component for the product's operation. As recommended in the Cordella et al. report (Cordella, Alfieri, & Sanfelix Forner, 2019), the economic value of the spare part is not a suitable indicator for identifying the target components, as these can potentially be either cheap or expensive. Below, all the tasks required for creating the target component list are described (see Figure 20).

Bill of Materials analysis

The Bill of Materials (BoM) lists all the components that make up a product. Through its analysis, it is possible to determine which of these parts play a critical role in the overall functionality of the appliance. Any component required to perform primary or secondary functions will be considered a priority part. Report prEN 45552 defines primary functions as those that are necessary to achieve the intended use, while secondary functions are supplement or enhance the primary functions (CEN/CENELEC, 2020b). Furthermore, this analysis is also useful for

identifying components that contain regulated materials or substances, ensuring compliance with the related European regulations.

Failure rate analysis

As previously explained, the analysis of component failure frequency is a key factor in creating the target components list with respect to sustainability. To analyse this aspect, different approaches can be followed: (i) market analysis of spare parts (from which the components that statistically break the most can be extracted), (ii) literature analysis (e.g., statistical reports from national and international entities, which identify critical components for that particular product family), and (iii) Failure Mode and Effect Analysis (FMEA) from product manufacturers (e.g., components that statistically account for more than 75% of product failures). In summary, a wide range of sources can offer valuable insights, including manufacturers of products and components, repair professionals, organizations specializing in reuse and remanufacturing, consumer testing entities, insurance firms, researchers, and regulatory bodies (Cordella, Alfieri, & Sanfelix Forner, 2019).

Identification of eligible target components list

As a result of this process, a list of target components is obtained, which is common for that product group and allows for product comparison with other appliances in its category. For each part, an image and a brief description of its functionalities are also provided.

Disassembly analysis

The disassembly analysis is aimed at gathering all the information related to the repairability of the product. The horizontal standard EN 45554:2020 (CEN/CENELEC, 2020b) provides all the necessary information for assessing the repairability of an Energy-related Product. Because repairability is just one of the factors comprising this sustainability index, its implementation is designed to be straightforward during the initial stages of product design, so the Disassemblability Index (I_D), reported in the Repair Scoring System (RSS) (Bracquene, et al., 2019) will be used as an indicator. The number of steps necessary to disassemble the target component, the type and quantity of fasteners and connectors used (i.e., reusable, removable, or neither removable nor reusable), and the kind of tools required (i.e., basic

tools, product group-specific tools, other commercially available tools, proprietary tools, or not feasible with any existing tool) are all factors to consider (CEN/CENELEC, 2020b) (Cordella, Alfieri, & Sanfelix Forner, 2019). Section 3.4.4 provides a thorough explanation of each of these parameters. Two approaches are viable for obtaining the required disassembly data for the mechatronic product being examined, depending on the type of prototype accessible (see Figure 19). The first option pertains to a digital disassembly of the product, applicable when only the digital prototype of the product is available (e.g., CAD model). In this scenario, the process involves removing components one by one from the model and product structure until the target component is reached. There are certain prerequisites for the virtual prototype, including the need for each item to be defined (e.g., the inclusion of all screws and commercial components) and the establishment of assembly relations. The second approach involves physically disassembling the prototype manually. Virtual disassembly offers the advantage of being applicable in the early stages of product design without the necessity of creating a physical prototype. However, it may have lower accuracy compared to the manual disassembly of the physical product, as certain specific details could potentially be missing and only theoretically assumed (e.g., the type of tool used) (Boix Rodríguez & Favi, 2023b). Simultaneously with the disassembly process conducted on each priority part and starting from a fully assembled prototype, it is imperative to collect data (disassembly data collection) to facilitate the evaluation of the Disassemblability Index (I_D). Subsequently, a description of the setup for manual disassembly tests is provided, encompassing operator selection, necessary equipment and tools, and the outlined procedure (Boix Rodríguez & Favi, 2023b).

Operator

An experienced and trained operator will be responsible for conducting the disassembly of the appliances (with a minimum of one year of experience). To mitigate any bias during these tests, other industry experts will closely monitor the disassembly process.

Equipment and Tools

- **Mechatronic product:** a fully assembled device serves as the starting point for the disassembly analysis.

- **Toolset:** a complete set of tools, including screwdrivers, pliers, wrenches, and any specialized tools needed for disassembly.
- **Data collection tools:** digital cameras to document each step of the disassembly, computers for data gathering, notepads and pens for taking manual notes.
- **Safety gear:** goggles, gloves, and other personal protective equipment (PPE) for the operator.

Procedure

- **Preparation:** Position the product in a well-lit and controlled workspace. No matter the operator's height, ergonomics will be guaranteed by an adjustable workbench. The work surface should be set at elbow height for the operator (Eklund, 1995) (International Health Facility Guidelines, 2023). Making sure the operator has room to manoeuvre around the product is crucial. The operator will be able to access every tool.
- **Safety:** the operator ensures that safety protocols are followed throughout the process, using appropriate safety gear and handling any hazardous materials with care.
- **Disassembly:** the operator removes the components one by one until the priority part is reached. For each PP, it will be assumed that it starts from the fully assembled product.
- **Data collection:** during the disassembly, the operator records relevant data for the calculation of the Disassemblability Index.
- **Photographs:** pictures are taken during the disassembly to document the condition of the components and the type of fasteners or connectors.
- **Finalization:** once the target components defined in the priority parts list are fully disassemble, the data collection phase is concluded, and all tools and equipment are organized.
- **Data analysis:** all the data gathered (including images and notes) will be used for the subsequent analysis, and in particular for calculating the I_D .

In the Appendix I, different tables that provide an overview of all the data to be collected during the Phase II of this methodology can be found. In these tables, each parameter is identified by a unique code (ID), and three levels of parameter detail are outlined: (i) *Level 0* corresponds to the parameter's

category, (ii) *Level 1* specifies the aspect under evaluation, and (iii) *Level 2* indicates the specific part of the product to which it relates (i.e., raw material, component, or the product as a whole). In addition, the related scientific field for each parameter is specified, along with the affected indices, the information source used for data collection, and the associated level of uncertainty for each parameter. The considered scientific fields are as follows:

- Environmental impact
- Cost
- Manufacturing
- Remanufacturing/ Upgradability
- Repairability
- Reuse
- Recycling
- Remanufacturing&Repairability&Reuse&Recycling&Upgradability =EoL
- Social aspects

The sources considered for the data collection are:

- CAD
- BoM
- Product Lifecycle Management (PLM)
- Public Reports
- Scientific Literature
- Statistics
- Standards
- Embedded sensors
- Engineering Department
- Design Department
- Research & Development (R&D) Department
- Production Department
- Quality Assurance (QA) Department
- Sales & Marketing Department
- Procurement Department
- Project Management Office (PMO)
- Human Resources (HR) Department

- Finance & Accounting Department
- Information Technology (IT) Department
- Health, Safety, and Environment (HSE) Department
- Legal Department
- Customer Support Department
- Logistics and Supply Chain Department

One of the established methods for analysing uncertainty factors is the Pedigree Matrix, composed of various indicators (i.e., reliability, completeness, temporal correlation, geographical correlation, further technological correlation) (Ciroth, Muller, Weidema, & Lesage, 2016) (Chen & Lee, 2021). In this framework, with the aim of streamlining data quality analysis, the focus has been on the “reliability” factor, which describes the quality of data generation depending on their source. Based on this reliability factor, the calculation results of the indices will be weighted. Table 6 displays the potential uncertainty scores from 0 to 5 (0 represents the ideal case where the information is verified and originates internally within the company, while 5 represents the worst-case scenario where data could not be obtained directly). The weighting factor to be used for multiplying the sustainability indices ranges from 0.5 to 1, as shown in the Table 6.

Table 6. Uncertainty scores and associated weights based on data source reliability.

Score	Description	Weight
0	The data is accurate, and the information comes from inside the company	1
1	The data is accurate, but you need to request it to an external company (supplier)	0.9
2	The data is difficult to retrieve, or you cannot get it completely	0.8
3	Part of the data is not available (e.g., you know the supplier, but you do not know the origin of the material), or based on assumptions (no standards available)	0.7
4	Almost all the data is missing or based on assumptions. Only few information is available	0.6
5	The data is missing	0.5

3.4. PHASE III: SUSTAINABILITY INDEX ASSESSMENT

This chapter explains how to calculate a sustainability index. Traditional LCA methods have limitations in interpreting the results of the analysis, and designers’ primary focus is often on reducing production costs rather than considering the entire product lifecycle (Favi C. , 2013). As a result, it is critical to create a sustainable model with clear outcomes. Figure 21 depicts

all the indicators that will be included in the final sustainability score. This sustainability index, as can be seen, includes: (i) Environmental Index, (ii) Economic Index, (iii) Social Index, and (iv) Circularity Score. A comprehensive explanation of each factor that contributes to the sustainability score is provided, including the formulas used for their calculation.

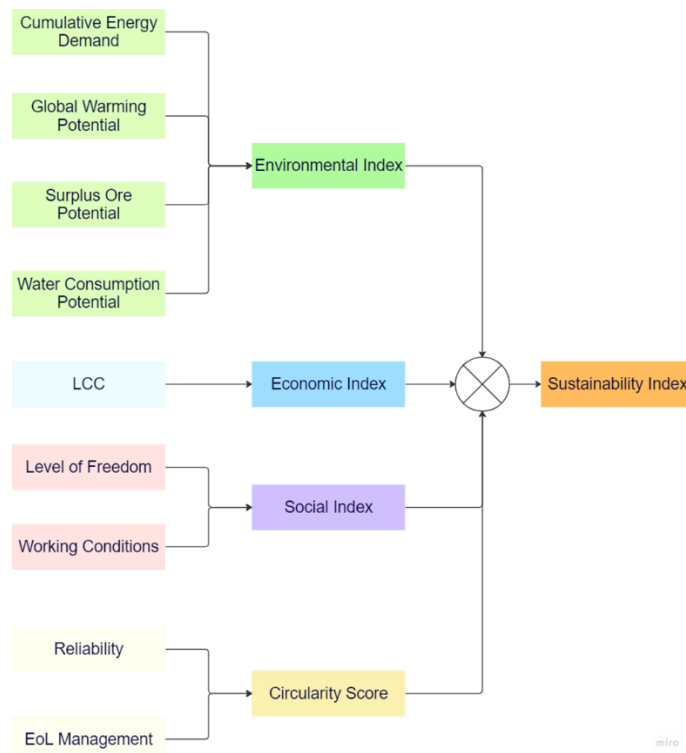


Figure 21. Flowchart for the Sustainability Index calculation.

3.4.1. Environmental Index

As shown in Figure 22, to obtain the final environmental impact value, a series of steps must be carried out, which can be grouped into two main stages: (i) Parameters Assessment, and (ii) Environmental Index Assessment. In the first stage, the results of all parameters influencing the index are calculated and processed to make them comparable with other products in the same category. In the second stage, the environmental impact value is obtained by weighting each of the considered indicators. Each stage is described in detail below.

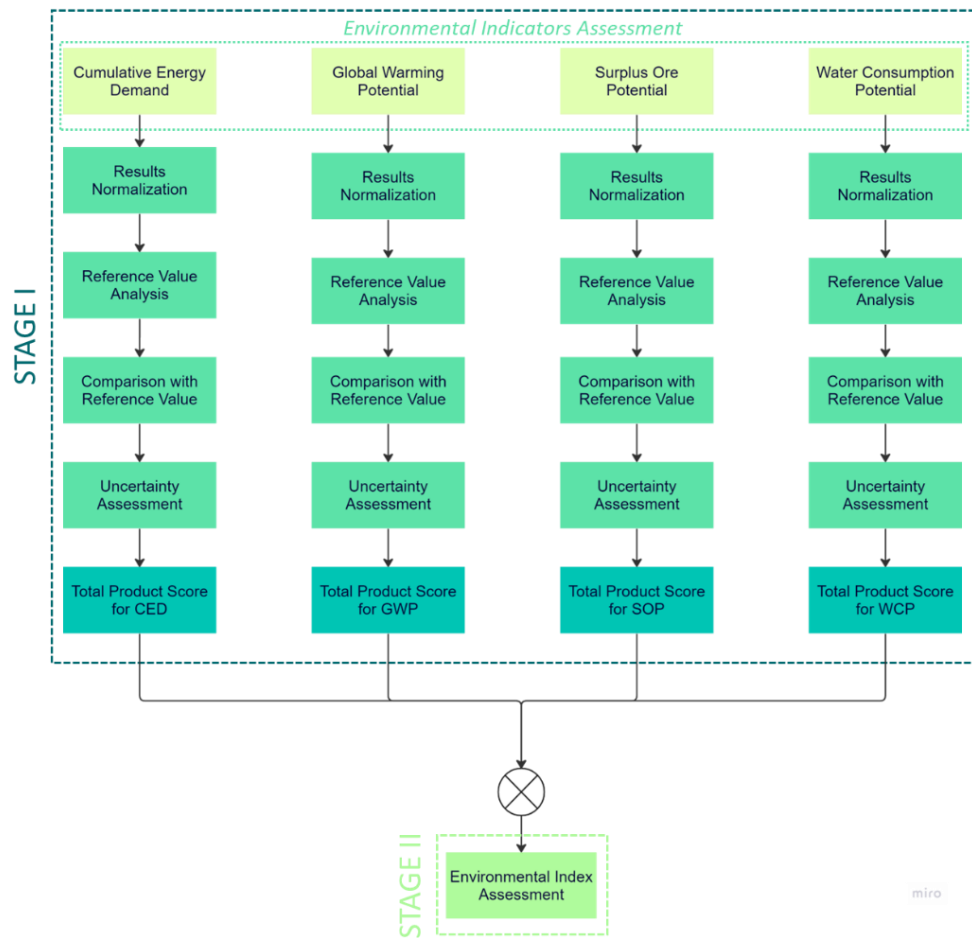


Figure 22. Flowchart for the Environmental Index.

Parameters Assessment

The aim of this phase is to obtain a product score that indicates the environmental impact in each of the considered categories (i.e., Cumulative Energy Demand (CED), Global Warming Potential (GWP), Surplus Ore Potential (SOP), and Water Consumption Potential (WCP)). To achieve this, all the steps shown in Figure 22 (dashed lines of Stage I) must be followed, as detailed below. Those steps include: (i) Environmental Indicators Assessment, (ii) Results Normalization, (iii) Reference Value Analysis, (iv) Comparison with Reference Value, (v) Uncertainty Assessment, and (vi) Total Product Score for the indicator (i.e., CED, GWP, SOP, and WCP).

Environmental Indicators Assessment

This part is analogous to the Life Cycle Impact Assessment (LCIA) defined in ISO 14040:2006 standard (International Organization for Standardization, 2006b), which, starting from all the information collected in the previous phase (inventory), empirically evaluates the environmental impact of certain indicators. For this purpose, the SimaPro software has been selected to perform the analysis. Table 7 collects three of the indicators considered in this methodology, those that come from the application of the ReCiPe Midpoint (H) method (Huijbregts, et al., 2016). These categories are suggested by the methodology as they represent some of the most common midpoint indicators for this type of product and study. However, because each product has its specific characteristics and requirements, other categories can be considered by the designer during the implementation of the methodology.

Table 7. ReCiPe Midpoints (H) indicators (Huijbregts, et al., 2016).

Name	Acronym	Unit	Description
Global Warming Potential	GWP	kg CO ₂ eq	Represents the cumulative radiative forcing impact, calculated over various timeframes (e.g., 20, 100, or 1,000 years), resulting from the emission of 1 kg of a greenhouse gas (GHG) compared to the cumulative radiative forcing impact over the same timeframe caused by the release of 1 kg of CO ₂ .
Water Consumption Potential	WCP	m ³	Cubic meters (m ³) of water consumed per m ³ of water extracted. Water extraction involves taking water from surface water bodies or drawing groundwater from aquifers. It accounts for the total amount of water withdrawn, regardless of whether the water is returned to the water bodies or used efficiently. In contrast, water consumption refers to the volume of water lost by the source watershed.
Surplus Ore Potential	SOP	kg Cu eq	Represents the average additional ore production in the future resulting from the extraction of 1 kg of a mineral resource, denoted as x, when considering all future production of that mineral resource. This is compared to the average additional ore production in the future resulting from the extraction of 1 kg of copper (Cu), taking into account all future copper production.

The last indicator considered is the embodied energy, calculated using the Cumulative Energy Demand (CED) method, which accounts for both the direct and indirect energy consumed during the extraction, manufacturing,

and disposal of raw materials and auxiliary resources (Hischier R., 2010). The units for this indicator are [MJ]. The system boundaries established during the previous phase determine the life cycle phases that will be analysed. Depending on the indicator that is being studied, the units of the results of this step will vary accordantly.

Results Normalization

The results obtained in the previous section are closely tied to the definition of the functional unit and the various assumptions made regarding the product's lifetime and system boundaries. This is one of the current challenges in conducting an LCA study (Gabriel, Boix Rodríguez, Gaha, Mio, & Favi, 2023). In order to obtain an overall sustainability result, it is necessary to compare the outcome of the analysed product with reference values (explained in detail in *Reference Value Analysis*). Therefore, the objective of this section is to obtain normalized results that can be compared with analyses conducted by other practitioners available in the literature. To achieve this, a set of normalized indices (based on several design parameters) relative to each phase of the product's life is defined. As shown in Figure 23, this section is characterized by two main steps (indicated by dashed lines): (i) Systematic Literature Review and (ii) Metric Definition for LCA Comparison. The following sections provide a detailed description of each one.

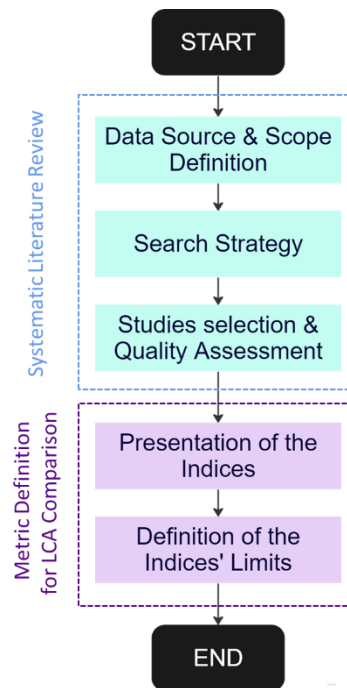


Figure 23. Flowchart for the Results Normalization Stage.

▪ Systematic Literature Review

This normalization is based on a systematic literature review of LCA studies for the mechatronic product under analysis (defined in *Product identification*).

Data source and scope definition

The suggested databases for conducting this analysis are *Scopus*, *Springer*, and *Taylor & Francis*, as they are considered to be the most relevant in the engineering sector. The search can be limited to original articles, conference papers, and book chapters written in English. The review covers the following fields: engineering, environmental sciences, energy, and materials sciences. This selection helps in excluding a significant number of papers that fell outside the scope of the research results. The research encompasses a timeframe that extends from the year of the last update for the ISO 14040/4 standards (2006) (International Organization for Standardization, 2006b) (International Organization for Standardization, 2006a) up to the review's date. This choice is deliberate, taking into account the dynamic nature of the LCA field, to avoid relying on outdated studies that might yield erroneous conclusions. Additionally, the ISO standard was

regarded as the benchmark for LCA methodology, and the indices are developed in alignment with these standards (Gabriel, Boix Rodríguez, Gaha, Mio, & Favi, 2023).

Search strategy

Based on the product family analysed, a keyword-based search method using Boolean operators (AND/OR) should be chosen. An example of that could be: (“LCA” OR “Life Cycle Assessment” OR “Life Cycle Analysis”) AND (“Mechatronic product under analysis”). Filters based on title, abstract, and keywords are used to obtain the total number of records. The research must be customized based on the specific product group that the designer is looking for. In the case study, a practical example is provided to make this phase clearer and more understandable.

Studies selection and quality assessment

After completing the search process, an initial refinement is carried out to remove duplicate articles. Subsequently, a screening process is employed to reduce the total number of papers that will be considered as viable candidates. This screening is based on reading the abstracts of the articles, and in cases where the abstract does not provide sufficient information, the full article is reviewed. The criteria used to exclude studies that are not relevant are as follows (Gabriel, Boix Rodríguez, Gaha, Mio, & Favi, 2023):

- The study does not conform to LCA analysis standards as defined in ISO 14040/44 (International Organization for Standardization, 2006b) (International Organization for Standardization, 2006a).
- The study does not pertain to the mechatronic product category but instead focuses on leisure electronic devices.
- The study examines only a specific component of the device rather than the entire device itself (e.g., packaging, electronic components).
- The study aims to solely compare the use phase while excluding the manufacturing phase.
- The study exclusively focuses on LCC or SLCA.

Once this article refinement and screening process is completed, the final portfolio of records that will be used for the normalisation of the LCA results is obtained.

- **Metric Definition for LCA Comparison**

This section explains the second step highlighted in purple in Figure 23, where the final equations and the criteria used to develop the indices are presented.

Presentation of the indices

Using the article by Gabriel et al., as a reference (Gabriel, Boix Rodríguez, Gaha, Mio, & Favi, 2023), which represents an initial attempt at standardization for a mechatronic product (i.e., cooker hoods), it is established that, by analysing the compiled research works, it is possible to create various indices to standardize the results of the LCIA. These indices vary for each product category, and it will be necessary to evaluate each case separately. They are related to design parameters of the product (e.g., power, size, energy consumption, etc.) in order to normalise the environmental impact value based on specific parameters aligned with the design requirements. The indices encompass the entire product life cycle:

- Raw Material Index (Ri),
- Manufacturing Index (Mi),
- Use Phase Index (Ui),
- EoL Index (Ei),
- Transport Index (Ti),
- Maintenance Index (Si).

In Section 4, through the case studies presented in this research, it can be observed how this methodology is put into practice and how the standardization indices for the particular case of household appliances are derived.

Limits of the indices

The main limitation of this methodology is that normalization can only be carried out when the same impact parameters are considered. For example, it is possible to compare the results of the Global Warming

Potential (GWP), obtained by the CML-IA method, with the result of Climate Change (CC) obtained by ReCiPe method, knowing that some minor differences are present due to the different LCIA methods adopted. This comparison is possible since both indicators are based on the same approach (the IPCC methodology). The interpretation of indices analysis becomes more challenging, however, when different midpoints or endpoints are taken into account. Another drawback of the normalization process is the time period taken into account when choosing the LCIA method (typically 100 years, or 100% of the final records), as well as the allocation method. Additionally, the same grid mix should be considered for a fair comparison of the results referring to the operational phase given that home appliances are ErP. This is an additional restriction of the suggested strategy. The results obtained at the end of this part are not dimensionless, depending on the type of mechatronic product that is being studied, the units will vary accordingly. Again, the system boundaries established determine the phases that will be analysed.

Reference Value Analysis

To determine whether the analysed product has a favourable outcome, it is necessary to have reference values to compare the impacts of each phase. Therefore, the literature analysis conducted in the previous section will also be used to establish these reference values. It is assumed that for each family of mechatronic product, the maximum impact value will be the highest one found in the literature studies.

Results comparison with reference value

The objective of this phase is to transform the impact value obtained previously (with units related to the analysed life cycle phase and the type of product studied) into a result that ranges from 0 to 1. In this manner, a dimensionless score is obtained for each of the life cycle phases. To achieve this dimensionless transformation, the product's result must be compared to the reference value established in the previous step (through literature analysis), following the criteria shown in Table 8. Where "Value" is the outcome obtained after the normalization process of the product under analysis (i.e., R_i , M_i , U_i , E_i , T_i , and S_i), and "Ref" is the outcomes from the study with the highest values of R_i , M_i , U_i , E_i , T_i , and S_i found in literature. As can be seen in the table, the score ranges from 0 to 1, being 0 the worst

scenario (the new mechatronic product has greater impacts than the one used as reference). On the other hand, the best scenario possible (score equal to 1) is when the results for the new product are at least 10 times lower.

Table 8. Dimensionless environmental impacts calculation.

Mathematical rule	Dimensionless environmental impact [0-1]
Value > Ref	0
Ref/10 < Value < Ref	$1 - \frac{Value - \frac{Ref}{10}}{Ref - \frac{Ref}{10}}$ (1)
Value < Ref/10	1

As a result, the dimensionless normalized indices are presented (i.e., Ri_A, Mi_A, Ui_A, Ei_A, Ti_A, and Si_A) are obtained for the environmental indicators studied (i.e., GWP, SOP, WCP, CED). The system boundaries established determine the phases that will be analysed.

Uncertainty assessment

This stage aims to weight the results of each phase of the life cycle based on the reliability of the data. As explained in Table 6, the quality of the information has been defined during the data collection and a weight from 0.5 to 1 has been associated with different types of sources. If the data used in one phase of the life cycle have different levels of uncertainty, it is assumed that the uncertainty of the whole phase will be the average of all the uncertainties present. As a result, for each phase will be assigned a level of uncertainty (U_Mat, U_Man, U_Use, U_EoL, U_Trans, and U_Maint) ranging from 0.5 to 1.

Total product score

The output of this part is the weighted overall product score (from 0 to 1) for the environmental indicators studied (i.e., GWP, SOP, WCP, CED). The system boundaries established determine the phases that will be analysed. The equations to calculate each indicator are shown below:

$$E_{GWP} = W_{Mat} \times (Ri_{AGWP} \times U_{Mat}) + W_{Manuf} \times (Mi_{AGWP} \times U_{Man}) + W_{Use} \times (Ui_{AGWP} \times U_{Use}) + W_{EoL} \times (Ei_{AGWP} \times U_{EoL}) + W_{Trans} \times (Ti_{AGWP} \times U_{Trans}) + W_{Maint} \times (Si_{AGWP} \times U_{Maint}) \quad (2)$$

$$E_{SOP} = W_{Mat} \times (Ri_{ASOP} \times U_{Mat}) + W_{Manuf} \times (Mi_{ASOP} \times U_{Man}) + W_{Use} \times (Ui_{ASOP} \times U_{Use}) + W_{EoL} \times (Ei_{ASOP} \times U_{EoL}) + W_{Trans} \times (Ti_{ASOP} \times U_{Trans}) + W_{Maint} \times (Si_{ASOP} \times U_{Maint}) \quad (3)$$

$$E_{WCP} = W_{Mat} \times (Ri_{AWCP} \times U_{Mat}) + W_{Manuf} \times (Mi_{AWCP} \times U_{Man}) + W_{Use} \times (Ui_{AWCP} \times U_{Use}) + W_{EoL} \times (Ei_{AWCP} \times U_{EoL}) + W_{Trans} \times (Ti_{AWCP} \times U_{Trans}) + W_{Maint} \times (Si_{AWCP} \times U_{Maint}) \quad (4)$$

$$E_{CED} = W_{Mat} \times (Ri_{ACED} \times U_{Mat}) + W_{Manuf} \times (Mi_{ACED} \times U_{Man}) + W_{Use} \times (Ui_{ACED} \times U_{Use}) + W_{EoL} \times (Ei_{ACED} \times U_{EoL}) + W_{Trans} \times (Ti_{ACED} \times U_{Trans}) + W_{Maint} \times (Si_{ACED} \times U_{Maint}) \quad (5)$$

Table 9 summarizes all the parameters used in the equations, all of them are dimensionless.

Table 9. Parameters used for the environmental product score calculation.

Parameter classification	Abb.	Description
Environmental product score for each indicator	E _{GWP}	Total product score for the GWP indicator.
	E _{SOP}	Total product score for the SOP indicator.
	E _{WCP}	Total product score for the WCP indicator.
	E _{CED}	Total product score for the CED indicator.
Dimensionless and normalized raw material index score for each indicator	Ri _{A_GWP}	Ri_A score for the material phase for the GWP indicator.
	Ri _{A_SOP}	Ri_A score for the material phase for the SOP indicator.
	Ri _{A_WCP}	Ri_A score for the material phase for the WCP indicator.
	Ri _{A_CED}	Ri_A score for the material phase for the CED indicator.
Dimensionless and normalized manufacturing index score for each indicator	Mi _{A_GWP}	Mi_A score for the manufacturing phase for the GWP indicator.
	Mi _{A_SOP}	Mi_A score for the manufacturing phase for the SOP indicator.
	Mi _{A_WCP}	Mi_A score for the manufacturing phase for the WCP indicator.
	Mi _{A_CED}	Mi_A score for the manufacturing phase for the CED indicator.
Dimensionless and normalized use index score for each indicator	Ui _{A_GWP}	Ui_A score for the use phase for the GWP indicator.

	$U_{i_A_SOP}$	U_{i_A} score for the use phase for the SOP indicator.
	$U_{i_A_WCP}$	U_{i_A} score for the use phase for the WCP indicator.
	$U_{i_A_CED}$	U_{i_A} score for the use phase for the CED indicator.
Dimensionless and normalized EoL index score for each indicator	$E_{i_A_GWP}$	E_{i_A} score for the EoL phase for the GWP indicator.
	$E_{i_A_SOP}$	E_{i_A} score for the EoL phase for the SOP indicator.
	$E_{i_A_WCP}$	E_{i_A} score for the EoL phase for the WCP indicator.
	$E_{i_A_CED}$	E_{i_A} score for the EoL phase for the CED indicator.
Dimensionless and normalized transport index score for each indicator	$T_{i_A_GWP}$	T_{i_A} score for the transport phase for the GWP indicator.
	$T_{i_A_SOP}$	T_{i_A} score for the transport phase for the SOP indicator.
	$T_{i_A_WCP}$	T_{i_A} score for the transport phase for the WCP indicator.
	$T_{i_A_CED}$	T_{i_A} score for the transport phase for the CED indicator.
Dimensionless and normalized maintenance index score for each indicator	$S_{i_A_GWP}$	S_{i_A} score for the maintenance phase for the GWP indicator.
	$S_{i_A_SOP}$	S_{i_A} score for the maintenance phase for the SOP indicator.
	$S_{i_A_WCP}$	S_{i_A} score for the maintenance phase for the WCP indicator.
	$S_{i_A_CED}$	S_{i_A} score for the maintenance phase for the CED indicator.
Uncertainty scores for each phase of the lifecycle	U_Mat	uncertainty score for the raw material phase.
	U_Manuf	uncertainty score for the manufacturing phase.
	U_Use	uncertainty score for the use phase.
	U_EoL	uncertainty score for the EoL phase.
	U_Trans	uncertainty score for the transportation phase.
	U_Maint	uncertainty score for the maintenance phase.

Weights for each lifecycle phase. Ranging from 1 (the least important) to 3 (the most important)	W_{Mat}	Weight for the materials phase.
	W_{Manf}	Weight for the manufacturing phase.
	W_{Use}	Weight for the use phase.
	W_{EoL}	Weight for the EoL phase.
	W_{Trans}	Weight for the transportation phase.
	W_{Maint}	Weight for the maintenance phase.

Environmental Index Assessment

Once the assessment of all parameters has been completed, and final values have been obtained for each studied indicator, the aggregation of these results into a single score must be carried out (STAGE II of Figure 22). To achieve this, (6) will be used. In this way, the final value of the Environmental Index ($I_{Environmental}$) which ranges from 0 to 1 (being 0 the worst scenario and 1 the best one) is obtained through the weighted average of each indicator. Each metric is associated with a weight (W_{GWP} , W_{SOP} , W_{WCP} , W_{CED}) ranging from 1 to 3, which can be modified by the engineer/designer to ensure maximum flexibility and adapt to specific analysis needs. The one with a higher weight will be considered a priority parameter. For this work, it is suggested to assumed that all four studied indicators are equally important, so $W_{GWP} = W_{SOP} = W_{WCP} = W_{CED} = 2$.

$$I_{Environmental} = \frac{W_{GWP} \times E_{GWP} + W_{SOP} \times E_{SOP} + W_{WCP} \times E_{WCP} + W_{CED} \times E_{CED}}{W_{GWP} + W_{SOP} + W_{WCP} + W_{CED}} \quad (6)$$

3.4.2. Economic Index

Considering the context of this project, which aims to conduct a comprehensive study of the mechatronic products, the analysis of metrics that allow evaluating the economic performance of a product throughout its lifecycle is essential. Traditionally, these analyses used to focus on the initial production costs, but thanks to the holistic approach and the inclusion of LCC, a comprehensive view of economic factors throughout the lifecycle is achieved. This enables decision-making to be more informed and facilitates

arriving at more sustainable solutions. Thanks to the inclusion of these metrics, it is possible to have an analysis of long-term economic impacts, including aspects such as operating costs, maintenance, upgrades, logistic support, and the final disposal of the product. After analysing all these factors, opportunities for improvement can be identified through resource optimization and cost minimization. This approach enables the evaluation of product system costs from various perspectives or stakeholders. In the methodology proposed, the economic analysis is conducted including the perspective of the end user, as suggested by Klöpffer and Ciroth (Klöpffer & Ciroth, 2011). The aim is for the I_{Economic} obtained to guide the designer in reducing possible costs as well as the consumer during the purchasing process. Typically, environmentally friendly products may frequently come with higher initial purchase costs. However, they often prove to be more cost-effective when considering their use phase and/or EoL phase. Therefore, the economic analysis proposed in this methodology can assist consumers in making informed choices, as well as aiding producers and retailers in highlighting the economic benefits of purchasing environmentally friendly products (Klöpffer & Ciroth, 2011) (Iraldo, Facheris, & Nucci, 2017). To calculate the LCC of the mechatronic product under study, the following data described in Table 10 should be determined:

Table 10. Data used in the LCC.

Type of information	Abb.	Units	Description	Calculation
Initial investment cost	C_0	[€]	It represents the purchase price of the mechatronic product at the beginning of the studied period	Can be provided by the manufacturer, or retrieved through a market analysis.
Operations cost	C_{Use}	[€]	It is the cost of the specific consumption items during the usage life of the mechatronic product (e.g., energy consumption, water consumption, etc.)	For each consumption item, the cost related to its consumption (C_{Item}) during the selected studied period (t) will be calculated using the following formula: $\sum_1^t \frac{C_{\text{Item}}}{(1+i)^t} \quad (7)$ This way, the present value (PV) of future expenses is obtained. Where i is the discount rate.
Maintenance & repair cost	C_{Maint}	[€]	It is the cost related to possible	All the maintenance operations during the studied period are considered. Again, the

			<p>maintenance operations (including cost of the replacement parts and the intervention of technical operators)</p>	<p>present value of this future costs is calculated:</p> $\sum_1^t \frac{C_{Maint}}{(1+i)^t} \quad (8)$ <p>Where t represents the years where the maintenance occurred and i is the discount rate.</p>
Replacement cost	C_{Repl}	[€]	<p>If the lifespan of the mechatronic product is shorter than the studied period, a new device needs to be purchased</p>	<p>The present value of this replacement needs to be calculated:</p> $\frac{C_{Repl}}{(1+i)^t} \quad (9)$ <p>Where t represents the year where the replacement occurred and i is the discount rate.</p>
Residual value	V_{res}	[€]	<p>It represents the possible residual value at the end of the studied period. It can happen when the product's lifespan is longer than the timeframe of the study</p>	<p>To calculate the PV of the residual value, the following formula can be used:</p> $\frac{C_0 \times (1 - A \times T)}{(1+i)^t} \quad (10)$ <p>Where t represents the timeframe of the study, C_0 is the initial cost, A is the % of annual amortization used for this family of products, T is the years that the product has been used, and i is the discount rate.</p>
Discount rate	i	[%]	<p>It is the discount rate used to discount future cost flows to present value</p>	<p>The selection of i will depend on the specific objectives of the analysis and on the target market where the product will be sold. This factor carries a high level of uncertainty, as extreme global situations can completely change markets. Therefore, for full transparency and understanding of the results, it is important that when calculating the economic impact, the selection of this parameter is properly documented and justified.</p>

The equation to calculate the LCC [€] of the product is:

$$LCC = C_0 + C_{use} + C_{maint} + C_{repl} - V_{res} \quad (11)$$

Like the environmental impact case, to transform the LCC into a dimensionless result ranging from 0 to 1, it must be compared to a reference LCC (the $LCC_{reference}$). Since one of the goals of this index is to demonstrate to consumers how eco-friendly products can become more economically

viable, the reference value should represent the least efficient product available in the market. To achieve this, a market study of the mechatronic product family under analysis is conducted. In the case that it falls under the products affected by the Energy Labelling Directive, the European Product Registry for Energy Labelling (EPREL) database must be used (European Commission, 2019b). This database allows filtering products sold in the European market by energy efficiency class and specific characteristics of that product family, enabling the selection of the lowest class available for a product analogous to the one being studied. This approach ensures the acquisition of all the necessary data to calculate $LCC_{reference}$. Following the criteria shown in Table 11, the dimensionless score for the economic impact can be obtained. As can be seen in the table, the score ranges from 0 to 1, being 0 the worst scenario (the new mechatronic product has greater impacts than the one used as reference). On the other hand, the best scenario possible (score equal to 1) is when the results for the new product are at least equal to the LCC_{THR} , that is established based on the characteristics of the product family (i.e., price range of products in this mechatronic family, as well as consumer's perception of savings for this product). The LCC_{THR} is set by the designer/engineer during the assessment of the methodology, it is important to justify the assumption made to maintain the transparency of the process.

Table 11. Dimensionless economic impact calculation.

Mathematical rule	Dimensionless economic impact ($A_{Economic}$) [0-1]
$LCC > LCC_{reference}$	0
$LCC_{THR} < LCC < LCC_{reference}$	$1 - \frac{LCC - LCC_{THR}}{LCC_{reference} - LCC_{THR}}$
$LCC < LCC_{THR}$	1

(12)

Finally, once the dimensionless value of the economic impact has been obtained, the result will be weighted based on the reliability of the data used for its calculation. As explained in Table 6, the quality of the information has been defined during the data collection and a weight from 0.5 to 1 has been associated with different types of sources. If the data used have different levels of uncertainty, it is assumed that the uncertainty will be the average of all the uncertainties present.

The final economic index can be calculated using the following equation:

$$I_{Economic} = U_{Economic} \times A_{Economic} \quad (13)$$

Where:

- $U_{Economic}$: the uncertainty of the data used [0.5 - 1]
- $A_{Economic}$: the dimensionless economic impact [0 - 1]

When $I_{Economic}$ is closer to 0, it indicates that the product is less cost-effective, while if it tends towards 1, it is more cost-effective. For the LCC can be observed how the BM selected has a great influence in the reliability of the data and the corresponding uncertainty weight, since in a PSS the costs come from inside the company (high reliability) the result for the economic index will not be penalised (multiplying it with a bad uncertainty score).

3.4.3. Social Index

This phase of the research is dedicated to assessing the social dimensions (positive and negative) during the design of mechatronic products. Guidelines for conducting an SLCA suggest that the most important impact categories to consider are the security and safety of the workers, as well as human rights, work conditions, cultural heritage, governance, and socio-economic repercussions (UNEP, 2009). The social index in this research work encompasses various indicators, which will be weighted to obtain a single score ranging from 0 to 1 (worst to best case, respectively). The methods used to calculate the social index will be transparent and replicable, allowing for the index to be updated and refined over time. The best possible scenario is one in which the company holds an SA8000 or Fair Trade certification. SA8000 is a globally recognized standard created by SAI and based on internationally recognized standards of decent work (e.g., Universal Declaration of Human Rights, ILO conventions, etc.). The certification process is independent and rigorous, based on nine key elements: child labour, forced or compulsory labour, health and safety, freedom of association and right to collective bargaining, discrimination, disciplinary practices, working hours, remuneration, and management system. Therefore, if a product receives this certification, it guarantees that all requirements have been met (SAI - Social Accountability International, 2014). On the other hand, although the Fair Trade certification is more related to the food sector, it can also be applied to factories. This certification is also

carried out by independent entities and is internationally recognized. It is focused on improving the lives of workers and their families, as well as promoting sustainable development. Therefore, if the producing company holds this certification, it ensures compliance with all established standards: safe and healthy working conditions, the elimination of forced labour or child labour, fair and consistent compensation, and environmental protections and product traceability (Fair Trade International, n.d.). If this were not the case and the company does not have any accreditation certifying its good social practices, for this research project, it has been decided to create an index that integrates the principles of the described standards and norms (i.e., promoting respect for the Universal Declaration of Human Rights in the country, as well as ensuring a safe working environment). The formula proposed for the A_{social} is:

$$A_{social} = \frac{I_w + I_F}{2} - 0.1 \quad (14)$$

Two indicators, I_w and I_F , are grouped together to evaluate working conditions and the level of freedom in the country, respectively. To calculate them, the following formulas were used:

$$I_w = \frac{|I_{working\ conditions} - 10|}{10} \quad (15)$$

$$I_F = \frac{I_{freedom}}{100} \quad (16)$$

Where $I_{working\ conditions}$ is an indicator created by the Global Labour University and the Center for Global Workers' Rights at Penn State University, this method provides information on the state of workers' rights in countries around the world and it is based on a set of 97 indicators derived from ILO conventions (ILO - International Labour Organization, 2022) (Kucera & Sari, 2019). This $I_{working\ conditions}$ ranges from 0 to 10, being 0 the best score possible and 10 the worst. After applying the formula, I_w will range from 0 to 1 (worst and best scenario respectively). Figure 24 shows the classification of the different countries in the globe based on their labour rights.

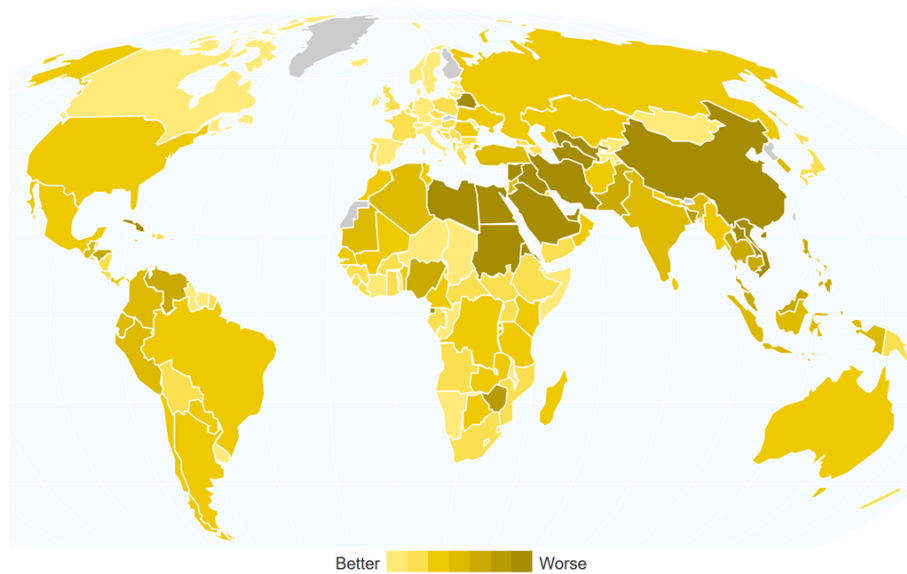


Figure 24. Overview of better and worse countries according to Labour Rights Indicators (Center for Global Workers' Rights, 2023).

On the other hand, I_F is an indicator to assess the “Freedom in the World” through a methodology derived mostly from the Universal Declaration of Human Rights, covering political rights (e.g., electoral process, political pluralism and participation, functioning of government), civil liberties (e.g., freedom of expression and belief, associational and organizational rights, rule of law, personal autonomy and individual rights). Figure 25 shows how the score is assessed [0-40]. After applying (16), a score for I_F will be obtained, ranging from -0.04 to 1 (Freedom House, 2023).

Status	Political Rights score						
	0-5*	6-11	12-17	18-23	24-29	30-35	36-40
53-60	PF	PF	PF	F	F	F	F
44-52	PF	PF	PF	PF	F	F	F
35-43	PF	PF	PF	PF	PF	F	F
26-34	NF	PF	PF	PF	PF	PF	F
17-25	NF	NF	PF	PF	PF	PF	PF
8-16	NF	NF	NF	PF	PF	PF	PF
0-7	NF	NF	NF	NF	PF	PF	PF

KEY: F = Free, PF = Partly Free, and NF = Not Free

Figure 25. I_{freedom} score assessment. * It is possible that the total political rights score can be less than zero (between -1 and -4) if it receives mostly or all zeros for each of the 10 political rights questions and it receives a sufficiently large negative score for the political rights discretionary question. (Freedom House, 2023)

After the calculation of these indicators, the overall A_{social} can be assessed. If the result of this index is negative (as I_F can be negative), a value of 0 will be assigned. In this way, by applying the formula, a result of A_{social} ranging from 0 to 0.9 can be obtained, as 1 is reserved for certified standards. It is

important to note that this index calculation is applied to the entire supply chain, and the final value will be that of the most unfavourable case. Table 12 summarizes the score calculation for each situation.

Table 12. A_{Social} Score calculation [0-1].

Condition	I_{social} score [0-1]
The company is certificated by SA8000 or Fair Trade	1
The company is not certificated by SA8000 or Fair Trade	$I_{\text{social}} = \frac{I_w + I_F}{2} - 0.1$ (17)

As for the $I_{\text{Environmental}}$ and I_{Economic} , the uncertainty (U) of the data source must be considered to calculate the I_{Social} , weighting the result of the A_{Social} with the scores described in Table 6:

$$I_{\text{social}} = U_{\text{social}} \times A_{\text{social}} \tag{18}$$

3.4.4. Circularity Score

The aim of this stage is to analyse if the circularity performance of the product under evaluation is favourable. As explained in Section 2, there are various approaches to assessing a product’s circularity. In this study, reliability and End-of-Life product management are used as circularity parameters, as shown in Figure 26.

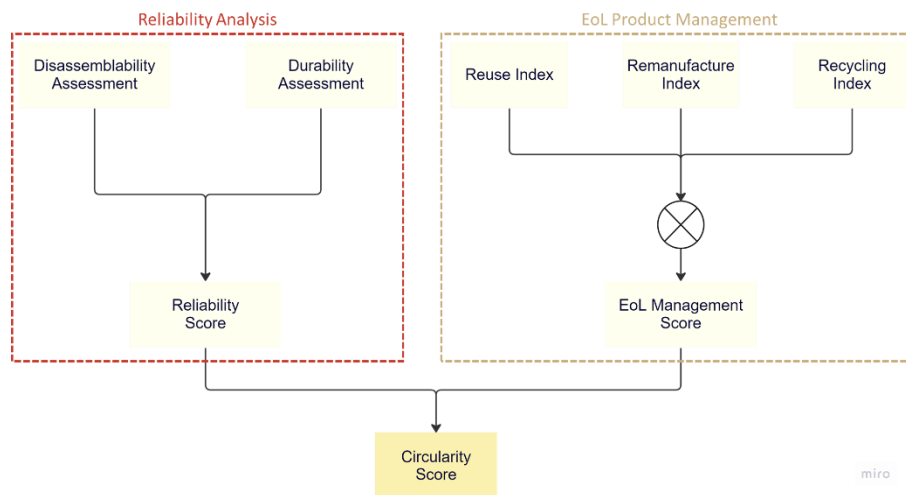


Figure 26. Flowchart for Circularity Score calculation.

Reliability Analysis

The reliability index used in this research work is an indicator that considers the ease of disassembly of the product's target components and their durability compared to other equivalent products in the market. Below, the procedure to calculate each of the parameters needed to obtain this index is provided.

Disassemblability Index Assessment

Numerous scoring systems for evaluating repairability have been documented in the literature, as discussed in the Section 2.2.3. However, given that many of these systems consistently emphasize the same disassembly criteria (e.g., Disassembly Depth, Disassembly Time, Tools, Fasteners, and connectors), and taking into consideration the horizontal standard EN 45554:2020 (CEN/CENELEC, 2020b), which regards the Repair Scoring System as a reference, the Disassemblability Index (I_D) was adopted in this approach. The I_D is one of the indices that make up the RSS; Table 13 displays all the parameters involved in the overall calculation of this value. As one of the primary objectives of this research is to explore eco-design engineering solutions for enhancing repairability, the emphasis is placed on the I_D rather than the comprehensive RSS. Indeed, the combined RSS score considers factors that are not directly tied to the design of the engineering product.

Table 13. Overview of criteria and parameters used within the RSS (Bracquené, et al., 2021).

Criteria	Parameter	Abb.
Disassemblability Index (I_D)	Disassembly depth/sequence	P1
	Fasteners and connectors	P2
	Tools	P3
	Disassembly time	P4
Process Index (I_P)	Diagnosis support and interfaces	P5
	Type and availability of information	P6
	Spare parts	P7
	Software and firmware	P8
	Safety, skills, and working environment	P9
	Data transfer and deletion	P10
	Password reset and restoration of factory settings	P11
Commercial Guarantee Index (I_{CG})	Commercial guarantee	P12

Figure 27 illustrates the three steps comprising this phase: (i) Parameters Analysis, (ii) Parameters Score Assessment, and (iii) Disassemblability Index Assessment.

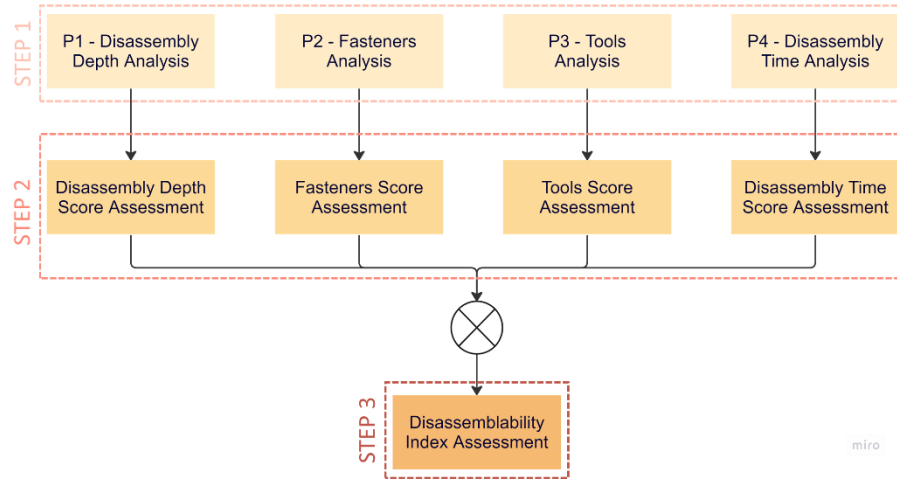


Figure 27. Flowchart for the Disassemblability Index calculation.

▪ **Parameters Analysis**

The first parameter (P1) is the Disassembly depth, which refers to the number of steps required to disassemble a priority part without causing damage to the product. This factor is crucial in calculating the effort needed to repair a component. Following the recommendation of standard EN 45554, “a step can be defined as an operation that finishes with the removal of a part, and/or with a change of tool” (CEN/CENELEC, 2020b). As will be seen later during the calculation of its score, the disassembly depth for the product under analysis is compared to a reference value (D_{ref}), which represents the specified reference depth for the product group at a product-specific level. P2 evaluates the reversibility of the connection based on the type of connector used in the assembly. Table 14 summarizes the different classes of connectors considered:

Table 14. Classification of fastener types (CEN/CENELEC, 2020b).

Type	Description	Acronym
Reusable	A fastening system that can be fully reused (e.g., threaded joints)	FR
Removable	A fastening system that can be removed without damaging the product but cannot be reused (e.g., non-reusable cable ties)	FNR
Neither removable nor reusable	A fastening system which are neither removable nor reusable (e.g., adhesive and welding joints)	FU

The third parameter (P3) refers to the tools employed during the disassembly and penalizes situations where a non-standard tool is required. Like P2, there is a classification of the type of tools that can be used (see Table 15).

Table 15. Classification of tool types (CEN/CENELEC, 2020b).

Type	Description	Acronym
Basic tools, no tools, provided tools	Disassembly can be performed without requiring additional tools, or by utilizing tools provided with the product or spare part, or by using basic tools as outlined in Table 16	TC
Product group-specific tools	Disassembly cannot be accomplished using the previously defined tools but may require a specialized tool or set of tools designed for the specific product	TS
Other commercially available tools	Disassembly cannot be conducted using standard or product-specific tools as defined earlier, but can be accomplished without the need for proprietary tools	TNC
Proprietary tools	Disassembly can only be performed using proprietary tools. These tools are not accessible for the general public to buy or subject to available patents for licensing under fair, reasonable, and non-discriminatory conditions	TP
Not feasible with any existing tool	Disassembly cannot be carried out with any existing tool	TNE

Table 16. List of basic tools. Any size of the listed tools is considered a basic tool (CEN/CENELEC, 2020b).

Tool type	Illustration (informative example)	Reference
Screwdriver for slotted heads, cross recess or for hexalobular recess heads		ISO 2380, ISO 8764, ISO 10664 (International Organization for Standardization, 2004b) (International Organization for Standardization, 2004a) (International Organization for Standardization, 2014b)
Hexagon socket key		ISO 2936 (International Organization for Standardization, 2014a)
Combination wrench		ISO 7738 (International Organization for Standardization, 2015)
Combination pliers		ISO 5746 (International Organization for Standardization, 2004d)

Half round nose pliers		ISO 5745 (International Organization for Standardization, 2004e)
Diagonal cutters		ISO 5749 (International Organization for Standardization, 2004c)
Multigrip pliers (multiple slip joint pliers)		ISO 8976 (International Organization for Standardization, 2021)
Locking pliers		
Combination pliers for wire stripping and terminal crimping		
Prying lever		
Tweezers		
Hammer, steel head		ISO 15601 (International Organization for Standardization, 2000)
Utility knife (cutter) with snap-off blades		
Multimeter		
Voltage tester		
Soldering iron		

 Hot glue gun



 Magnifying glass



The last parameter (P4) refers to the disassembly time, which is an important factor to assess the overall ability of the disassemblability of a product. As for the disassembly depth, during the calculation of its score, the disassembly time for the product under analysis is compared to a reference value (T_{ref}), which represents the specified reference time for the product group at a product-specific level.

- **Parameters Score Assessment**

Below, Table 17 presents all the necessary formulas for calculating the score of each parameter that makes up the I_D . Every target component is indicated by the subscript i , being N the total number of priority parts. Each target component is assigned a specific weight (represented as W_{PP_i}), ranging from 1 (lower relevance) to 3 (greater importance). In this context, a dedicated matrix can be employed, taking into account both the component failure rate and its influence on the overall product functionality. In addition, to reflect the relative importance of each criterion in determining the index, a weight ranging from 1 (indicating lower importance) to 3 (indicating higher importance) is assigned to each parameter (denoted as W_{Param_1} , W_{Param_2} , W_{Param_3} , and W_{Param_4}). The scores for each parameter range between 0 and 1 (worst and best scenario, respectively).

Table 17. Calculation of the parameters score (CEN/CENELEC, 2020b) (Cordella, Alfieri, & Sanfelix Forner, 2019).

Parameter	Priority Part Score ($S_{j,i}$) [0-1]	Priority Part weight ($W_{PP,i}$) [1-3]	Parameter Score (S_j) [0-1]	Parameter weight ($W_{Param,j}$) [1-3]
P1	$S_{1,i} = 1 - \frac{D_i - 1}{D_{ref} - 1}$ (19)	$W_{PP,i}$	$S_1 = \sum_1^N \frac{S_{1,i} \times W_{PP,i}}{W_{PP,i}}$ (20)	$W_{Param,1}$
P2	<ul style="list-style-type: none"> • If P2_i = FR → S_{2,i} = 1 • If P2_i = FNR → S_{2,i} = 0.5 • If P2_i = FU → S_{2,i} = 0 	$W_{PP,i}$	$S_2 = \sum_1^N \frac{S_{2,i} \times W_{PP,i}}{W_{PP,i}}$ (21)	$W_{Param,2}$
P3	<ul style="list-style-type: none"> • If P3_i = TC → S_{3,i} = 1 • If P3_i = TS → S_{3,i} = 0.75 • If P3_i = TNC → S_{3,i} = 0.5 • If P3_i = TP → S_{3,i} = 0.25 • If P3_i = TNE → S_{3,i} = 0 	$W_{PP,i}$	$S_3 = \sum_1^N \frac{S_{3,i} \times W_{PP,i}}{W_{PP,i}}$ (22)	$W_{Param,3}$
P4	$S_{4,i} = 1 - \frac{T_i - 0.4}{T_{ref} - 0.4}$ (23)	$W_{PP,i}$	$S_4 = \sum_1^N \frac{S_{4,i} \times W_{PP,i}}{W_{PP,i}}$ (24)	$W_{Param,4}$

As explained before, D_i represents the number of steps necessary to remove i -th priority part, while D_{ref} represents the reference number of steps for the removal of i -th target component given a specific product family or mechatronic product type. If D_i is equal to or greater than D_{ref} , a score of 0 is automatically assigned. It is worth noting that D_{ref} can be determined through different methods. One of the most prevalent approaches involves conducting a benchmark analysis and calculating D_{ref} as the mean (or maximum) value among the products analysed. Another approach involves conducting a techno-economic analysis of the product and setting a target value that ensures economically viable repair operations.

For the disassembly time score, the horizontal standard EN 45554:2020 proposes to use the ease of Disassembly Metric (eDiM) which is based on the Maynard Operation Sequence Technique (MOST) (Vanegas, et al., 2018). The eDiM database has been modified in order to include more sequences that allow to evaluate more types of mechatronic products (see

Appendix II). In the equation used for the calculation of this score (Boix Rodríguez, Gabriel, Gaha, & Favi, 2023), T_i represents the disassembly time required to remove i -th target component (following the MOST approach), while T_{ref} represents the reference disassembly time for the removal of i -th target component given a specific product family or mechatronic product type. If T_i is equal to or greater than T_{ref} , the score is automatically assigned a value of 0. As for the disassembly depth the value of T_{ref} is defined following different approaches. The most common approach is to perform a benchmark analysis and retrieve this value as a mean (or the max) of the analysed product. Another approach consists in performing a techno-economic analysis of the product and assigning a target value that makes the repair operations economically feasible.

▪ **Disassemblability Index Assessment**

Once the score of each parameter is calculated, (25) can be applied to assess the disassemblability index. The subscript j is used to indicate a specific parameter (ranging from 1 to 4). The I_D score ranges from 0 to 1, being 0 the worst case and 1 the best scenario.

$$I_D = \frac{\sum_1^4 S_j \times W_{Param_j}}{\sum_1^4 W_{Param_j}} \tag{25}$$

Durability Assessment

In this section, the aim is to assign a score that reflects the durability of the product under analysis. To achieve this, (26) is employed, which compares the product’s lifespan with the maximum lifespan for a specific product group of appliances available in the market. The maximum lifespan is determined through a literature analysis, European standards, and different meetings and workshops with industry companies.

$$S_D = \frac{L_{product}}{L_{max}} \tag{26}$$

Where:

- $L_{product}$: lifespan of the product under analysis [years]
- L_{max} : maximum lifespan for the product category under analysis [years]
- S_D : durability score [0-1]

Reliability Score

The ability of a product to function consistently and durably without experiencing frequent failures is known as reliability. A product that is reliable is typically easier to maintain and repair. Once the disassemblability index and durability score are assessed, the overall reliability score can be calculated. As the trade-off between repairability and durability may depend on the specific product and its design, the equation used to calculate this score allows the designer to weight each parameter freely. Those weights (W_D and W_R) range from 1 to 3 (low importance and high importance respectively).

$$S_{reliability} = \frac{W_{Dur} \times S_D + W_{Rep} \times I_D}{W_{Dur} + W_{Rep}} \quad (27)$$

Where:

- W_{Dur} : weight for the durability score
- W_{Rep} : weight for the repairability score
- I_D : disassemblability index [0-1]
- S_D : durability score [0-1]
- $S_{reliability}$: reliability score [0-1]

EoL Management

Proper product EoL and proper industrial waste management are critical factors product development that considers environmental sustainability. While the costs and environmental impacts of design activities do not contribute significantly to the overall product life cycle assessment, decisions made during this stage have a significant impact on the product's performance throughout its life cycle (Mihelcic, et al., 2008). Therefore, designing products with EoL aspects in mind can help reduce the amount of waste going to landfill and promote closed-loop scenarios, where materials are reused and recycled instead of discarded (Mathieux, Froelich, & Moszkowicz, 2008). To achieve this, it has been decided to apply the methodology proposed by Favi et al. (Favi C. , Germani, Luzi, Mandolini, & Marconi, 2017), in order to obtain a quantitative metric to guide engineers and designers during the design phase. The aim is to increase the number of materials and components with a circular life cycle. The approach proposes a set of indices that are based on environmental and cost factors that influence EoL scenarios and treatments, considering the possible revenues

(direct and indirect) and the associated costs of each scenario analysed. Table 18 summarizes the parameters considered for the EoL definition.

Table 18. Classification of parameters considered in the EoL indices (Favi C. , Germani, Luzi, Mandolini, & Marconi, 2017). The units for costs and revenues are [€].

EoL Treatment	Costs		Direct Revenues		Indirect Revenues	
	Parameter	Source	Parameter	Source	Parameter	Source
Reuse	Reverse supply chain (C _{RL}).	Type IV	Value of the reused part (V _{Re}).	Type I	No virgin material used to produce the part (V _{Mat}).	Type V
	Selective disassembly operations (C _{Sd}).	Type III			No manufacturing operations to produce the part (V _{Man}).	Type V
	Cleaning operations (C _c).	Type IV				
Remanufacture	Reverse supply chain (C _{RL}).	Type IV	Value of the manufactured part (V _{Rem}).	Type I	No virgin material used to produce the part (V _{Mat}).	Type V
	Selective disassembly operations (C _{Sd}).	Type III			Value of original manufacturing operations to produce the part not necessary for remanufacture (V _{Man_s}).	Type V
	Cleaning operations (C _c).	Type IV				
	Additional remanufacture operations (C _{Rem}).	Type IV				
Recycling	Reverse supply chain (C _{RL}).	Type IV	Value of the recycled material (V _{Rc}).	Type II	Energy saved by not producing virgin material (V _{En}).	Type V
	Destructive disassembly operations (C _{Dd}).	Type III				

Cleaning operations (Cc). Type IV

Being the type of source:

- Type I: PLM for cost-related factors and other parameters
- Type II: specific DBs for material-related costs and other parameters (e.g., Granta MI®)
- Type III: calculated data (e.g., disassembly time, disassembly cost, recycling factors, etc.)
- Type IV: estimated data from market surveys and literature analysis
- Type V: calculated by formula (see Table 19)

The value of the reused part (V_{Re}) refers to a percentage of the initial value of the analysed part, considering mechanical/fatigue wear due to usage and accounting for consumers' reduced perception of quality in used parts and products. While V_{Rem} indicates a percentage of the original value of the part under consideration, considering deterioration, degradation, and corrosion caused by use, as well as the overall process of refurbishing the part. Furthermore, this item considers consumers' lower quality perception of used parts and products (Hazen, Cegielski, & Hanna, 2011).

Table 19. Formulas for the calculation of several parameters considered in the EoL indices (Favi C. , Germani, Luzi, Mandolini, & Marconi, 2017).

Parameter	Unit	Formula	Formula variables			
			Indicator	Units	Source	
V_{Mat}	€	$V_{Mat} = m \times C_{Mat}$	(28)	Mass (m).	kg	Type I
				Cost of virgin material (C_{Mat}).	€/kg	Type II
V_{Man}	€	$V_{Man} = C_{Man} + C_t$	(29)	Cost of manufacture activities (C_{Man}).	€	Type I
				Cost of transport phases (C_t).	€	Type I
V_{En}	€	$V_{En} = m \times E_s \times C_e$	(30)	Mass (m).	kg	Type I
				Energy saved (difference between primary embodied energy and recycling energy) (E_s).	MJ/kg	Type II
				Cost of energy - industrial (C_e).	€/MJ	Type I
V_{Re}	€		(31)	Mass (m).	kg	Type I

$V_{En} = m \times R_f \times C_{Rc}$	Recycling factor (R_f).	-	Type III
	Cost of recycled material (C_{Rc}).	€/kg	Type II

Below, a detail explanation of the different close-loop scenarios studied is presented.

Reuse Index Assessment

The reuse process involves keeping components and products in use for as long as possible. According to the Ellen Macarthur Foundation, it can be defined as “*The repeated use of a product or component for its intended purpose without significant modification*” (ELLEN MACARTHUR FOUNDATION, 2021a). This EoL scenario is only possible if the component’s lifespan is greater than the product’s lifetime. (32) shows the index calculation for this scenario.

$$I_{Reuse} = \frac{V_{Re} + V_{Mat} + V_{Man} - C_{RL} - C_{Sd} - C_C}{V_{Re} + V_{Mat} + V_{Man}} \quad (32)$$

Remanufacturing Index Assessment

The remanufacturing or refurbishing process is a closed-loop scenario that involves restoring used products to their original condition or upgrading them to meet current standards. According to the Ellen Macarthur Foundation, it can be defined as “*Re-engineer products and components to as-new condition with the same, or improved, level of performance as a newly manufactured one*” (ELLEN MACARTHUR FOUNDATION, 2021a). As for the reuse process, this scenario only makes sense when the lifespan of the component is longer than the lifetime of the product. The index for this scenario is shown in (33).

$$I_{Rem} = \frac{V_{Rem} + V_{Mat} + V_{Man,s} - C_{RL} - C_{Sd} - C_C - C_{Rem}}{V_{Rem} + V_{Mat} + V_{Man,s}} \quad (33)$$

Recycle Index Assessment

The recycling process involves collecting, processing, and remanufacturing materials into new products. According to the Ellen Macarthur Foundation, it can be defined as “*Transform a product or component into its basic materials or substances and reprocess them into new materials*”

(ELLEN MACARTHUR FOUNDATION, 2021a). This index considers the energy savings and possible revenues from the recycled material, as well as the costs of the recycling process. Equation (34) shows the index for the recycle scenario.

$$I_{Rc} = \frac{V_{Rc} + V_{En} - C_{RL} - C_{Dd} - C_C}{V_{Rc} + V_{En}} \quad (34)$$

EoL Index Assessment

The maximum value for each index is 1, that is the ideal scenario where there are no costs, or they tend to zero. This serves as the theoretical upper limit for each index. Consequently, the overarching engineering approach should focus on enhancing the calculated index value for a specific product configuration to reach the predetermined threshold value (THR), and to approach the theoretical maximum value as closely as possible. Depending on the results of the I_{Reuse} , I_{Rem} and I_{Rc} , the overall score for the EoL management (I_{EoL}) can be assessed as shown in Table 20. The determination of the THR relies on various factors, including the characteristics of the product/component being assessed, a cost-benefit evaluation of the end-of-life scenario, or adherence to regulatory requirements. For this reason, the designer should fix the THR in accordance with the type of product under analysis.

Table 20. Rules for obtaining the score of the I_{EoL} [0-1].

Condition	Description	EoL final score (I_{EoL})
I_{Reuse} or I_{Rem} or $I_{Rc} > THR$	All the close-loop scenarios or one of them perform efficiently. Usually, this condition would be reached after applying some eco-design actions (following the methodology of SECTION 3.5).	1
$0 < I_{Reuse} \& I_{Rem} \& I_{Rc} < THR$	All the indicators do not reach the expected threshold, but the target component or product is currently designed to have sustainable EoL management (they are > 0 at least in one category for each target component).	0.75

$0 < I_{Reuse} \text{ or } I_{Rem} \text{ or } I_{Rc} < THR$	Some of the indicators are designed to have sustainable EoL, but they do not reach the threshold. The other indicator/indicators present a value lower than 0.	0.50
$I_{Reuse} \& I_{Rem} \& I_{Rc} < 0$	All the indicators are negative, which means that the component or product are not design for a sustainable and efficient EoL close-loop.	0

Circularity score

After analysing the reliability and EoL management parameters, the aggregated circularity score (from 0 to 1) can be calculated using the following formula. Where W_{Rel} and W_{Manag_EoL} are the weights of each parameter (ranging from 1 to 3). This allows the operator the flexibility to adjust the parameters based on their needs. As a baseline, it is established that the importance of both is equal, so $W_{Rel} = W_{Manag_EoL} = 2$.

$$A_{Circularity} = \frac{W_{Rel} \times S_{reliability} + W_{ManagEoL} \times I_{EoL}}{W_{Rel} + W_{ManagEoL}} \tag{35}$$

In order to obtain the final circularity score, it is needed to weight the result obtained above with the uncertainty (U) of the data source (see Table 6). As for the other indicators, the total score for $U_{Circularity}$ will be the average of the different uncertainties used.

$$I_{Circularity} = U_{Circularity} \times A_{Circularity} \tag{36}$$

3.4.5. Sustainability Index

The final stage of the PHASE III: SUSTAINABILITY INDEX ASSESSMENT aims to obtain a single metric that allows for the comprehensive evaluation of an appliance. To achieve this, the four indices obtained previously will be grouped, as shown in Figure 21.

To make this research a flexible methodology that can be tailored to the specific needs of each project, a weight (from 1 to 3) will be assigned to the four indices, allowing for greater importance to be placed on one index or

another based on project requirements. As a baseline, it is established that this weight is the same for all the design parameters, meaning $W_{Env}=W_{Ec}=W_{Circ}= 3$, while $W_{Social}=1$. Equation (37) allows for the calculation of the overall sustainability index [0-1].

$$I_{Sustainability} = \frac{W_{Env} \times I_{Environmental} + W_{Ec} \times I_{Economic} + W_{Social} \times I_{Social} + W_{Circ} \times I_{Circularity}}{W_{Env} + W_{Ec} + W_{Soc} + W_{Circ}} \quad (37)$$

Table 21 shows the different categories for classifying the product based on its sustainability index.

Table 21. Classification of products based on the $I_{Sustainability}$.

Condition	Product class
Score >=0.9	A
0.8<= Score <0.9	B
0.7<= Score <0.8	C
0.6<= Score <0.7	D
0.5<= Score <0.6	E
0.3<= Score <0.5	F
0<= Score <0.3	G

3.5. PHASE IV: IMPLEMENTATION OF ECO-DESING METHODOLOGY

This phase of the methodology is focused on developing eco-design actions for the specific product category under analysis. Based on the critical areas identified during the evaluation of the sustainability index results, it becomes possible to determine which areas are critical and which components require redesign. As shown in Figure 28, when the Sustainability Index falls below a specific threshold, remedial actions will be implemented until the threshold is met. This threshold can change based on the specific requirements of the product, but as a baseline, it is established that the overall sustainability must be at least equal to “E”.

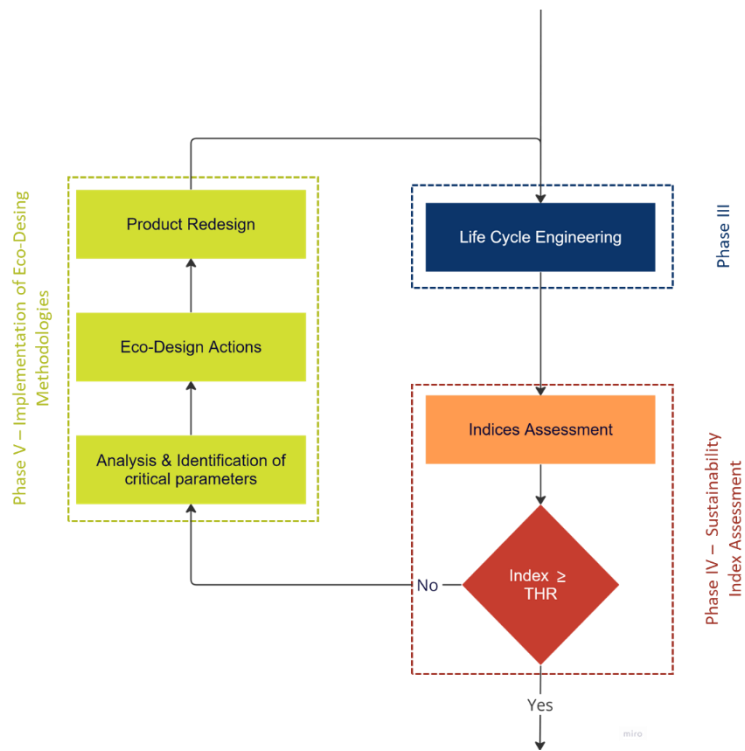


Figure 28. Flowchart for the implementation of Eco-Design methodologies.

The approach will be to analyse the index parameters to determine which one is causing the inadequate overall score of the product. Table 22 is used for this purpose.

Table 22. Identification of critical parameters of the $I_{Sustainability}$.

Index	Mathematical rule	Action
$I_{Environmental}$	$I_{Environmental} < 0.5$	To analyse in detail the environmental indicator (see Table 23)
$I_{Economic}$	$I_{Economic} < 0.5$	To analyse in detail the economic indicator (see Table 24)
I_{Social}	$I_{Social} < 0.5$	To analyse in detail the social indicator (see Table 25)
$I_{Circular}$	$I_{Circular} < 0.5$	To analyse in detail the circular indicator (see Table 26)

Next, the application of the eco-design methodology for each specific index is described in detail, so that the strategy to follow is completely defined in case any of the indices does not meet the condition established in Table 22. All the eco-design actions collected in the next sections (i.e., after identifying environmental, economic, social, or circular criticalities) are grouped into a best practices guideline, allowing for updates and the addition of new actions in the future. This way, a continuously expanding

guidelines of redesign actions is maintained, always kept up to date with relevant standards and constraints. It is also important to confirm that the origin of the data is reliable, and the level of uncertainty (U) is not critical (score lower than 3 in Table 6), causing the overall indices for each category to be lower than 0.5. If this is not the case, the first suggestion will be to improve the data source reliability.

3.5.1. Eco-Design for the Environmental Index

The methodology to be applied is shown in Figure 28, considering that the environmental factor is the one being analysed. As can be seen, the first step is to examine the parameters that make up this index to determine which one is causing an unsatisfactory result. To do this, it must be checked whether $E_{GWP} < 0.5$, $E_{WCP} < 0.5$, $E_{SOP} < 0.5$, $E_{CED} < 0.5$ or all are less than 0.5. Table 23 presents how to proceed in each case.

Table 23. Identification of critical parameters of the Environmental Index.

Parameter	Mathematical rule	Criticality	Eco-Design action
E_{GWP}	$E_{GWP} < 0.5$	<ul style="list-style-type: none"> Some materials selected in the product have a significant impact on GWP due to their GHG emissions. The sourcing of materials is unsustainable, and there is limited capability for recycling or reusing them. The use of non-renewable energy sources in the manufacturing plant significantly contributes to GHG. Inefficient manufacturing processes and resource wastage. 	<ul style="list-style-type: none"> To identify the material that has the highest impact and try to substitute it with an alternative with similar properties but less environmental impact (for components and also for the packaging). To promote materials that have greater recycling rates or those acquired from sustainable suppliers. To use renewable sources to power the manufacturing plant. To minimise energy consumption, waste generation, and emissions during the manufacturing phase.

		<ul style="list-style-type: none"> • Inefficient transportation and a high environmental impact in the supply chain. • Despite efforts to reduce the impact, certain aspects of the manufacturing or supply process are inherently difficult to reduce (and compensation is required). • Users are unaware of how to use the product efficiently and responsibly. • The product has high energy consumption during the use phase. 	<ul style="list-style-type: none"> • To optimize transportation to reduce emissions related to the supply chain. • To compensate the unavoidable impact investing in carbon offset initiatives. • To inform the user about responsible practices to reduce the impact during the use phase. • To optimise energy efficiency to minimise resource consumption during the use phase.
E_{SOP}	$E_{SOP} < 0.5$	<ul style="list-style-type: none"> • Excessive use of materials and generation of waste in the manufacturing process. • Limited component reusability, necessitating a higher demand for new materials. • Materials with low recycling rates or unsustainable sourcing practices. • Inefficient or environmentally unfriendly manufacturing processes resulting in significant material losses and waste generation. 	<ul style="list-style-type: none"> • To minimize the consumption of materials and waste generation during manufacturing. • To promote the reuse of components (e.g., implementing modular design) to reduce the amount of new material needed. • To promote materials with higher recycling rates or those acquired from sustainable suppliers. • To evaluate environmentally friendly manufacturing techniques that reduce material losses and waste.
E_{WCP}	$E_{WCP} < 0.5$	<ul style="list-style-type: none"> • Excessive water usage during manufacturing. • Materials with high water use in extraction and manufacturing stages. • Lack of water-saving practices in manufacturing. • Lack of water recycling or reuse during 	<ul style="list-style-type: none"> • To minimize the use of water during the manufacturing process. • To select materials with low water environmental impact in during extraction and production. • To promote water-saving practices for the manufacturing process. • To recycle/reuse water if possible in the production plant.

		<p>manufacturing (when possible).</p> <ul style="list-style-type: none"> • Lack of user awareness about responsible water consumption during use. • Lack of water-saving features or components in the product. • Suppliers with high water consumption practices. • Water-intensive cleaning methods employed during manufacturing phase. • The energy grid-mix used has a high impact of water consumption. 	<ul style="list-style-type: none"> • To inform the user about responsible practices to reduce the water consumption during the use phase. • To promote maintenance to prevent possible water wastage. • To integrate components (e.g., sensor) to enhance water efficiency during the use phase. • To promote water consumption reduction among all the suppliers. • To use waterless or low-water cleaning processes during the manufacturing phase. • To promote the use of renewable sources for energy production.
E _{CED}	E _{CED} < 0.5	<ul style="list-style-type: none"> • Inefficient product design that leads to high energy consumption during the use phase. • Poorly chosen components and improper integration. • The manufacturing plant relies on non-renewable energy sources. • Materials used in the product require a substantial amount of energy for extraction and manufacturing. • Inefficient manufacturing processes that generate a significant amount of material waste, increasing energy demand. • Failure to integrate energy recovery systems, missing out on opportunities to reduce the energy consumption. 	<ul style="list-style-type: none"> • To design the mechatronic product to optimise the energy-efficiency during the use phase. • To optimise the selection of components and their integration to minimise the energy consumption. • To use renewable sources to power the manufacturing plant. • To promote materials that require less energy during their extraction, processing, and manufacturing. • To reduce material waste during the manufacturing phase. • To incorporate energy recovery systems if the type of mechatronic product allows it.

- Lack of user awareness about the importance of maintenance, leading to reduce product efficiency.
- Inefficient transportation and supply chain processes.
- Lack of user awareness about energy-saving practices.
- Lack of tools for users to monitor and optimize energy consumption.
- Despite efforts to reduce energy demand, certain aspects of the product's life cycle have unavoidable energy demands.
- To promote maintenance to keep the maximum efficiency during the use phase.
- To optimize transportation to reduce emissions related to the supply chain.
- To inform the user about responsible practices to reduce the impact during the use phase.
- To promote energy monitoring devices to track and optimize energy consumption during use phase.
- To compensate the unavoidable impact investing in carbon offset initiatives.

3.5.2. Eco-Design for the Economic Index

The methodology to be applied is shown in Figure 28, considering that the economic factor is the one being analysed. As can be seen, the first step is to examine the parameters that make up this index to determine which one is causing an unsatisfactory result. Below it is explained how to proceed in each case.

Table 24. Identification of critical parameters of the Economic Index.

Parameter	Mathematical rule	Criticality	Eco-Design action
C_0	$C_0 > C_{0Ref}$	<ul style="list-style-type: none"> • High material costs without consideration for cost-efficient alternatives. • Inefficient manufacturing processes leading to high production costs. • High waste generation during manufacturing due to the absence of lean manufacturing principles. 	<ul style="list-style-type: none"> • To propose alternatives for materials that are more cost-efficiency (maintaining mechanical properties and quality standards). • To change manufacturing processes to optimise the production and reduce costs. • To reduce waste production during the manufacturing

			following lean manufacturing principles.
C_{Use}	$C_{Use} > C_{UseRef}$	<ul style="list-style-type: none"> Inefficient supply chain management leading to high transportation costs. Product's energy efficiency is low, resulting in high energy consumption and increased operating costs. Inefficient use of resources (e.g., water, fuel, etc.) contributing to higher operating costs. Reliance on non-renewable energy sources and electricity market variability for energy prices. Lack of user awareness about responsible product usage, leading to unnecessary consumption. 	<ul style="list-style-type: none"> To optimise the supply chain, reducing transportation costs. To improve the energy efficiency of the product to reduce the cost associated to energy consumption. To optimize other resources (e.g., water, fuel, etc.) consumption during use phase. To promote use of renewable energy sources to avoid excessive prices for the electricity. To promote responsible use of the product to avoid extra consumption.
C_{Maint}	$C_{Maint} > C_{Repl}$	<ul style="list-style-type: none"> Complex and costly maintenance due to lack of design for repair perspective. Lack of access to product documentation and maintenance guidelines for end-users. Use of materials and components that are prone to wear and tear. Lack of predictive maintenance capabilities, leading to unexpected breakdowns (usually emergency repairs are more costly). Inadequate protection against environmental factors (e.g., dust). Limited availability of spare parts. 	<ul style="list-style-type: none"> To improve the repairability of the product (to check Table 26), reducing maintenance time and costs. Provide comprehensive user manuals and online resources for maintenance guidance, empowering users to perform basic maintenance tasks. Select durable materials and components that have longer lifespans, reducing the frequency of replacements. To integrate sensors to allow early detection of issues and planned maintenance. To avoid environmental damage improving product sealing. To ensure availability of spare parts and promote supply chain strategies to

			facilitate the end-user access to them.
		<ul style="list-style-type: none"> Lack of user-friendly diagnostics leading to do not identify problems correctly. 	<ul style="list-style-type: none"> To develop user-friendly software interfaces, facilitating the identification of problems for the users.
C_{Repl}	$C_{Repl} > 0$	<ul style="list-style-type: none"> The durability of the product is not enough 	<ul style="list-style-type: none"> To extend the durability of the product through materials/components selection

3.5.3. Eco-Design for the Social Index

The methodology to be applied is shown in Figure 28, considering that the social factor is the one being analysed. As can be seen, the first step is to examine the parameters that make up this index to determine which one is causing an unsatisfactory result. Below it is explained how to proceed in each case.

Table 25. Identification of critical parameters of the Social Index.

Parameter	Mathematical rule	Criticality	Eco-Design action
I_F	$I_F < 0.5$	<ul style="list-style-type: none"> Failure to monitor and enforce ethical labour practices among suppliers. Restrictions on employees' rights to organize, limiting their freedom to advocate for their interests. Lack of inclusion and diversity. Use of materials sourced from conflict zones, where mining activities may contribute to social and political instability. Lack of engagement with stakeholders or employees, 	<ul style="list-style-type: none"> To audit suppliers regularly to ensure they follow ethical labour practices and provide safe working conditions for their employees. To encourage employees' rights to organize and negotiate collectively. To encourage inclusion and diversity in the workplace to promote a company culture that values and respects employee differences. To avoid components or materials (e.g., tin, tungsten, tantalum, gold) sourced from conflict zones. To seek for new opportunities of

		<p>missing opportunities to identify and address social issues that may affect the freedom of the population.</p> <ul style="list-style-type: none"> • Lack of commitment to social responsibility. 	<p>improvement through stakeholders, employees, NGOs, etc.</p> <ul style="list-style-type: none"> • To follow ISO 26000 and to obtain certifications such as Fair Trade or SA8000, demonstrating a commitment to social responsibility and ethical practices.
I_w	$I_w < 0.5$	<ul style="list-style-type: none"> • Lack of oversight and awareness of unethical labour practices among the suppliers. • Absence of clear labour standards in the company and supply chain. • Low wages and excessive working hours for employees, potentially violating workers' rights. • Lack of mechanism to detect and eliminate child labour and forced labour in the supply chain. • Neglecting safety and health measures. • Sourcing materials from conflict zones, indirectly supporting labour rights violations and conflict. • Inadequate disposal and recycling processes that can harm workers in recycling facilities. • Failing to seek feedback and input from relevant parties. 	<ul style="list-style-type: none"> • To audit suppliers regularly to ensure they follow ethical labour practices and provide safe working conditions for their employees. • To create a code of conduct for the company and suppliers that specifies labour standards. • To guarantee that workers are paid an appropriate salary and work reasonable hours. • To ban child labour and forced labour in the supply chain, and put in place mechanisms to detect and eliminate such practices. • To implement strong safety measures, to provide training, and to assess regularly risks, prioritizing workers health and safety. • To avoid components or materials (e.g., tin, tungsten, tantalum, gold) sourced from conflict zones. • To plan a responsible disposal and recycling of the mechatronic product, avoiding harm to workers and communities in some recycling facilities. • To seek for new opportunities of improvement through stakeholders, employees, NGOs, etc.

- Lack of established standards and certifications to demonstrate commitment with ethical labour practices.
- To follow ISO 26000 and to obtain certifications such as Fair Trade or SA8000, demonstrating a commitment to social responsibility and ethical practices.

3.5.4. Eco-Design for the Circularity Score

The methodology to be applied is shown in Figure 28, considering that the circularity factor is the one being analysed. As can be seen, the first step is to examine the parameters that make up this index to determine which one is causing an unsatisfactory result. To do this, it must be checked whether $S_{Reliability} < 0.5$, $I_{EoL} < 0.5$, or both are less than 0.5. Below it is explained how to proceed in each case.

Analysis of the reliability score

If this parameter is lower than 0.5, means that the performance of the product in terms of repairability and durability is not good enough. The following table is created to assign a mathematical rule to analyse each parameter and the actions to be taken to solve the design problem.

Table 26. Identification of critical parameters of the reliability score.

Parameter	Reference parameter	Mathematical rule	Rationale	Eco-Design action
D_i	D_{ref}	$\frac{D_i}{D_{ref}} \geq THR$	Cost-benefit analysis validated with the ROC method for the considered mechatronic product family.	To reduce the number of steps for the disassembly operation.
D_{change}	D_i	$\frac{D_{change}}{D_i} > 0.5$	Since D_i is the sum of two parameters (D_{change} and $D_{removal}$) if this ratio is lower than 0.5 D_{change} is the most critical parameter that downgrade D_i .	To uniform the type of fasteners used for the product assembly.
$D_{removal}$	D_i	$\frac{D_{removal}}{D_i} > 0.5$	Since D_i is the sum of two parameters (D_{change} and $D_{removal}$) if this ratio is lower than 0.5 $D_{removal}$ is the most critical parameter that downgrade D_i .	To reduce the number of components that need to be removed to reach the target.

Fasteners	Removable and reusable connector	$S_{2,i} < 1$	Whenever different fasteners than “removable and reusable connector” is used this value is strongly influenced.	To change the type of fasteners or connectors (avoiding non-reusable or permanent joints).
Tools	Common tool	$S_{3,i} < 1$	Whenever different tools than “common tool” is used this value is strongly influenced.	To change the type of tools needed (avoiding specific or proprietary tools).
T_i	T_{ref}	$\frac{T_i}{T_{ref}} \geq THR$	Cost-benefit analysis validated with the ROC method for the considered mechatronic product family.	To simplify the operations to reduce the disassembly time.
T_{change}	T_i	$\frac{T_{change}}{T_i} > 0.20$	Since T_i is the sum of five parameters if this ratio is lower than 0.2, T_{change} is the most critical parameter.	To uniform the type of fasteners used for the product assembly.
T_{manip}	T_i	$\frac{T_{manip}}{T_i} > 0.20$	Since T_i is the sum of five parameters if this ratio is lower than 0.2, T_{manip} is the most critical parameter.	To allow easy access to the target component (avoiding the need to rotate the product).
$T_{position}$	T_i	$\frac{T_{position}}{T_i} > 0.20$	Since T_i is the sum of five parameters if this ratio is lower than 0.2, $T_{position}$ is the most critical parameter.	To simplify the type of connectors or to reduce their number (avoiding the need for heavy pressure or excessive precision).
T_{discon}	T_i	$\frac{T_{discon}}{T_i} > 0.20$	Since T_i is the sum of five parameters if this ratio is lower than 0.2, T_{discon} is the most critical parameter.	To reduce the number of connectors or to simplify them (e.g., avoiding the use of excessively long screws).
$T_{removal}$	T_i	$\frac{T_{removal}}{T_i} > 0.20$	Since T_i is the sum of five parameters if this ratio is lower than 0.2, $T_{removal}$ is the most critical parameter.	To reduce the number of components that need to be removed to reach the target.
$L_{product}$	L_{max}	$S_D < 0.50$	The lifespan of the product is less than half of the maximum lifespan available in the market.	To increase the product lifetime (e.g., to use quality materials).

Analysis of the EoL management

Table 27 shows possible eco-design actions to implement in each case.

Table 27. Identification of critical parameters of the EoL management score.
 V_{New} is the value of that component when it is brand new.

Parameter	Mathematical rule	Criticality	Eco-Design action
$V_{Re} \ \& \ V_{Rem}$	$\frac{V_{Re}}{V_{New}} < 0.5$ $\frac{V_{Rem}}{V_{New}} < 0.8$	<ul style="list-style-type: none"> • Components are permanently fixed, making it difficult to access them and reuse valuable parts. • Materials used are perceived as lower quality, reducing the appeal of remanufactured products. • Failing to meet quality standards when reusing or remanufacturing products. • Lack of awareness among customers regarding the benefits of reusing products. • Limited available platforms for reselling used or remanufactured products. • Non-standard interfaces, making the interoperability of remanufactured products harder. • Consumer concerns about reliability and durability of reused/remanufactured products. 	<ul style="list-style-type: none"> • To avoid permanent fixing for valuable components. • To select other material that is perceived as “better quality” by the consumer. • To ensure that reused/remanufacture products meet the same quality standards as new ones. • To educate costumers on the advantages of reusing products. • To establish platforms for reselling used/remanufactured products. • To use standardised interfaces to reduce probability of obsolescence. • To offer extra warranty on reused/remanufactured products to increase consumer confidence.
C_{Sd}	$\frac{C_{Sd}}{V_{Man}} > 1$	<ul style="list-style-type: none"> • Lack of modularity, making disassembly difficult and costly. • Excessive number of components, leading to complex disassembly processes. • Intricate disassembly procedures. • Incorporation of non-removable connections, 	<ul style="list-style-type: none"> • To design products with modular components that can be removed easily. • To reduce the number of components. • To reduce the number of steps to remove each component. • To avoid non removable connections.

		making disassembly impossible or expensive.	
		<ul style="list-style-type: none"> • Complex and time-consuming disassembly process, increasing labour costs. • Lack of incentives to encourage customers to return products. 	<ul style="list-style-type: none"> • To simplify disassembly operations to reduce disassembly time. • To offer incentives for customers to return their used products.
C_{RL}	$\frac{C_{RL}}{V_{Man}} > 1$	<ul style="list-style-type: none"> • Inefficient reverse logistics operations, increasing costs of transportation, handling, and processing. • Lack of effective take-back programs, resulting in low product collection rates. 	<ul style="list-style-type: none"> • To optimize the reverse logistics. • To create take-back programs (to increase the amount of products collected).
C_C	$\frac{C_C}{V_{Man}} > 1$	<ul style="list-style-type: none"> • Inefficient and costly cleaning operations (e.g., use of excessive resources, energy, or cleaning agents). 	<ul style="list-style-type: none"> • To optimize the cleaning operations.
C_{Rem}	$\frac{C_{Rem}}{V_{Man}} > 1$	<ul style="list-style-type: none"> • Inefficient remanufacturing processes and lack of worker skills. 	<ul style="list-style-type: none"> • To train workers to improve efficiency during remanufacturing.
C_{Dd}	$\frac{C_{Dd}}{V_{Rc}} > 1$	<ul style="list-style-type: none"> • Inefficient disassembly processes and difficulty in locating hazardous components during product disposal. 	<ul style="list-style-type: none"> • To separate hazardous components in one module to allow for the removal of a single non-recyclable module rather than searching for several different hazardous parts.
V_{Rc}	$\frac{V_{Rc}}{C_C} < 1$	<ul style="list-style-type: none"> • The use of coatings on the product makes it difficult to recycle and reduces the value of recycled materials. 	<ul style="list-style-type: none"> • To avoid the use of coatings, they pollute the streams.
	Or the material used is on the "SIN list" (chemsec, n.d.)	<ul style="list-style-type: none"> • Incorporating substances on the "SIN list" in the product. 	<ul style="list-style-type: none"> • To avoid using substances that are on the "SIN list" of substances that will be restricted in the future.
R_f	$R_f < 0.6$	<ul style="list-style-type: none"> • The use of halogenated polymers hinders recycling due to toxicity and difficulties in processing. • The use of uncommon or hard-to-recycle plastics complicates the recycling process. 	<ul style="list-style-type: none"> • To avoid halogenated polymers (e.g., PVC). • To suggest the use of common plastics (e.g., ABS, PE, PP, etc.).

- The inclusion of glass fibres in plastics makes recycling more complex and less efficient.
- To avoid glass fibres plastics, to use carbon fibre or mineral filled plastics instead.

3.6. PHASE V: REPORT PRODUCTION

The last phase of the methodology seeks to create a comprehensive report that summarizes the findings and recommendations generated throughout the sustainability assessment process and the Eco-Design methodology. The goal is that these can be applied by designers and engineers, becoming part of the company’s know-how. In addition, to facilitate the interpretation of these results, a label will be created (see Figure 29) that shows the overall result of the sustainability index with a colour scale, the result of each of the four indices that compose it, as well as a notice regarding the uncertainty of the sources used, so that when interpreting these results, this factor is considered.

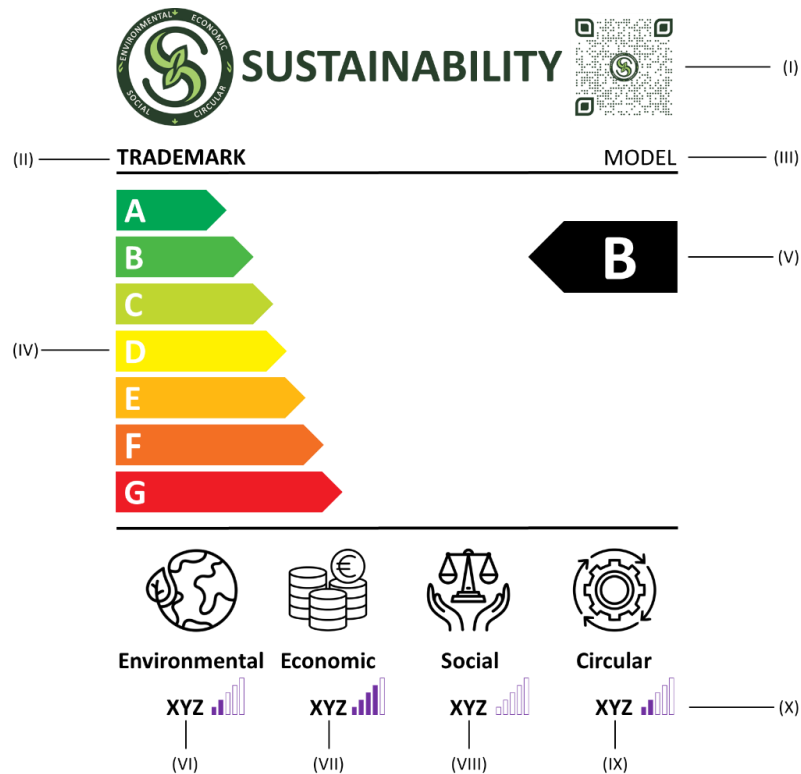


Figure 29. Example of the sustainability label proposed.

The following information shall be included in the sustainable label for mechatronic products:

- (I) A QR code to provide additional information not included on the label.
- (II) The trade mark.
- (III) The supplier’s model identifier.
- (IV) The scale of sustainability class from A to G.
- (V) The sustainability class determined in accordance with the methodology proposed.
- (VI) The environmental index result in accordance with the methodology proposed from 0 to 1.
- (VII) The economic index result in accordance with the methodology proposed from 0 to 1.
- (VIII) The social index result in accordance with the methodology proposed from 0 to 1.
- (IX) The circular score result in accordance with the methodology proposed from 0 to 1.
- (X) The level of uncertainty for the calculation of each index from 0 to 5 (as explained in Table 6). Figure 30 shows the legenda for each icon used.



Figure 30. Icons for uncertainty levels.

4. CASE STUDIES

The goal of this chapter is to demonstrate how the approach explained in this research work can help designers during the development of the product and to show that improvements can be gained through the application of the eco-design actions proposed. The proposed methodology has been tested in real business cases, to assist the activities of design departments in the development of sustainable products and services. The products selected are mechatronic devices that fall into the category of household appliance, following the definition of “large household appliances” presented in the European Directive on waste of electrical and electronic equipment (European Parliament, 2018d). These appliances are also commonly referred to as “white goods”. Below, the families of household appliances that are related to household chores are presented:

- Cold food storage systems (e.g., refrigerator)
- Food freezing systems (e.g., freezer)
- Heat cooking systems (e.g., oven)
- Kitchen vacuum systems (e.g., cooker hood)
- Dishwashing systems (e.g., dishwasher)
- House heating systems (e.g., boiler)
- House cooling systems (e.g., air conditioner)
- Clothes washing systems (e.g., washing machine)
- Clothes drying systems (e.g., dryer)

The products selected are: (i) a built-in electro-mechanical oven belonging to the heat cooking systems family, and (ii) a cooker hood belonging to the kitchen vacuum systems family. The companies involved in this test campaign are significant players in the manufacturing and assembly of household appliances, as well as in the production of mechatronic product components. Through this case studies, the author aims to clarify the feasibility of applying sustainability-oriented strategies in mechatronic products. Thus, contributing to a more eco-friendly, economically viable, and socially responsible product design. In the following sections, the steps presented in the previous chapter are reported for the products under investigation, identifying the advantages and disadvantages of the proposed methodology in a challenging product.

4.1. BUILT-IN OVEN

4.1.1. Phase I: Product Classification

The first case study for this project is an electric oven, which falls into the category of household appliance, particularly in the family of heat cooking systems. This type of product is designed to be installed in the kitchen (either built into a cabinet or mounted on the wall). This appliance combines electrical and electronic components (e.g., heating elements, PCB) with mechanical parts (e.g., a fan) to efficiently cook food. In Europe, such products are subject to various standards and regulations to ensure their safety, energy efficiency, and compliance with minimum sustainability standards (European Parliament, 2017) (European Parliament, 2018d). Among their core functions it can be found the ability to cook using different cooking modes, accurately control temperature, and distribute heat efficiently. Due to their widespread use in Europe, their significant energy consumption during the usage phase, and the potential environmental impacts associated with this product, it is considered an excellent example for the application of design for sustainability methodology. Figure 31 provides a schematic representation of this product, while Table 28 summarizes the key technical characteristics of the oven.

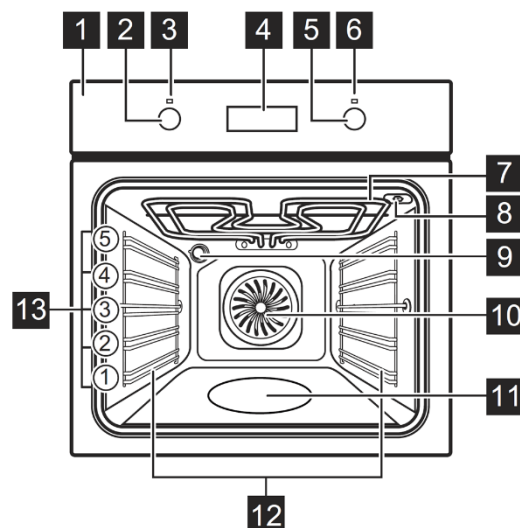


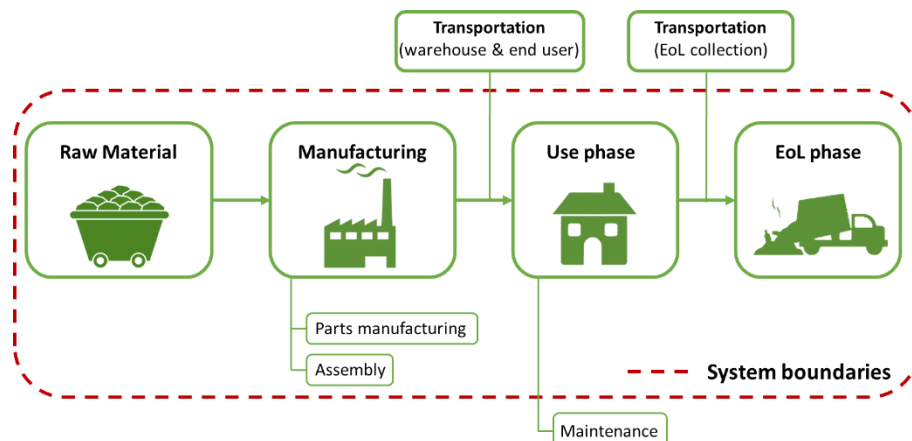
Figure 31. Overview of the electric built-in oven.

Table 28. Product specifications – Case study: Electric Oven.

Parameter	Value
Dimensions (HxWxD)	594 x 594 x 568 [mm]
Total electricity loading	2790 [W]
Weight	31.30 [kg]
Energy class	A++
Energy consumption per cycle (fan-forced convection mode)	0.52 [kWh/cycle]
Max. Temperature	275°C
Cavity Size	71 [l]

4.1.2. Phase II: Life Cycle Engineering analysis

First, the system boundaries are defined, specifying which life cycle phases are included in the analysis. As shown in Figure 32, the study excludes the maintenance and the transportation of the final product (to the end user and to the disposal plant), since their impact on this type of product is not significant (Favi C. , Germani, Landi, Mengarelli, & Rossi, 2018). The product’s useful life has been set at 15 years, based on manufacturer-provided data.

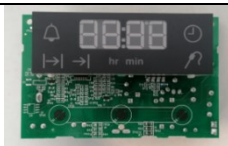

**Figure 32. System boundaries – Case study: Electric Oven.**

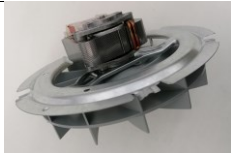
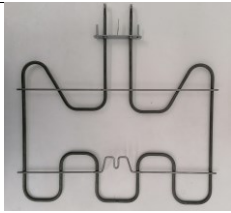

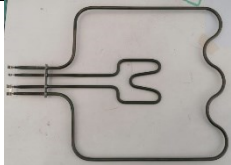


The functional unit established for the calculation of environmental impact is: *“Baking food in the Italian context for a lifespan of 15 years”*. The reference flow is represented by an electric oven with an energy class of A++, measuring the consumption through the standard test for labelling certification. The lifetime scenario considered is the use of the oven 185 cycles/year, which corresponds to an average oven usage of approximately 3.5 times per week (between a “non-intensive” of 2 days/week use and an




“intensive” 5 days/week use of the oven) (Landi, Consolini, Germani, & Favi, 2019).

The inventory with all the necessary data for the LCA analysis of the oven is presented in Appendix III, including all materials to be considered, types of manufacturing processes, transportation of the raw materials and components, and the end-of-life for each component. The production plant is located in Italy, where it is assumed that the product will be sold and processed at the end of its life. Electronic components are imported from China, while the rest of the subassemblies and materials come from European suppliers. To obtain all the necessary information for the reliability analysis, a manual disassembly test of the electric oven was conducted, following the workflow proposed in Section 3.3.3: identification of target components, disassembly analysis, and data collection. The oven that has been analysed combines all the features of a standard product (e.g., conventional cooking options (top and bottom heating), grill function, defrosting, and the use of a fan for convection mode). The list of target components has been identified following two paths: (i) failure analysis of the product components, and (ii) market analysis of spare parts sales done with company experts. Table 29 presents the full list of priority parts as well as a description of each one. The list of target components has been identified after conducting a market analysis of spare parts sales. To do this, it was requested to an oven manufacturing company information regarding these sales for the last 10 years. From this studied period, the components that account for more than 75% of failures have been selected.

Table 29. List of priority parts - Case study: Electric Oven.

Abb.	PP name	Description	Image
PP1	User Interface	Allows the user to interact with the oven (e.g., setting different cooking modes, controlling temperature, etc.). It consists of a digital display and a PCB with different buttons. The most common failures during the oven’s lifespan are button failure, display failure, and control board failure (e.g., due to overheating or other electrical issues)	
PP2	Hot air motor	It allows the proper functioning of the oven, being responsible for the circulation of hot air throughout the oven cavity. It is located on the back of the oven and is powered by an electric motor. The most common failures during the	

		oven's lifespan are motor failure (e.g., overheating or electrical issues) and bearing failure (e.g., lack of lubrication, wear)	
PP3	Cooling motor and fan	It is responsible for cooling the oven and preventing it from overheating. It works by drawing cool air into the oven and pushing hot air out. The most common failures during the oven's lifespan are the same as those for the hot air motor, including in this case the fan blade damage (due to foreign objects or the blade hitting the oven structure)	
PP4	Top heating element	It is responsible for providing heat from the top of the oven cavity, powered by an electric current. The most common failures during the oven's lifespan are element failure (due to overheating or electrical issues), burnt-out element (e.g., faulty component), and loose connection (e.g., by wear and tear or due to damage)	
PP5	Ring heating element	It is responsible for providing heat from the back of the oven cavity, powered by an electric current. The most common failures during the oven's lifespan are the same as those presented for the top heating element	
PP6	Bottom heating element	It is responsible for providing heat from the bottom of the oven cavity, powered by an electric current. The most common failures during the oven's lifespan are the same as those presented for the top heating element	
PP7	Temperature sensor	It measures the temperature inside the cavity and sends the information to the control board. Located at the back of the oven and powered by an electric current. The most common failures during the oven's lifespan are sensor failure (e.g., overheating or electrical issues), burnt-out sensor (e.g., faulty component), touching the walls of the oven, and loose connection (e.g., by wear and tear)	
PP8	Lamp	It illuminates the oven cavity, located at the top corner of the oven, and it is powered by an electric current. The most common failures during the oven's lifespan are bulb failure (e.g., due to wear and tear, or damage to the bulb filament), burnt-out bulb (e.g., faulty bulb, overheating), and loose connection (e.g., damage to the connection)	

PP9	Door glasses	The glass panels that form the door of the oven. Usually made of tempered glass, they are designed to withstand high temperatures. The most common failures during the oven's lifespan are glass breakage (e.g., thermal shock or impact), cracks (e.g., wear and tear or damage to the glass), and loose hinges	
PP10	Hinges	Responsible for attaching the oven door to the oven structure and allowing it to open and close. Usually made of metal, they are designed to withstand the weight of the door. The most common failures during the oven's lifespan are loose hinges (e.g., wear and tear), broken hinges (e.g., excessive force or impact), and worn hinges (e.g., lack of lubrication)	
PP11	Motherboard	It is the main circuit board that controls the oven's functions and components. The most common failures during the oven's lifespan are power surges (e.g., electrical issues), overheating (e.g., faulty cooling system or poor ventilation), and component failure (wear and tear or damage to the components that form the motherboard)	

The disassembly test was performed at the university facilities, with the real physical prototype, by expert operators in the field, following the disassembly path of each target component that minimizes the number of steps. Table 30 shows the data collection related to the identified target components. All the information was collected through a spreadsheet to facilitate the analysis.

Table 30. Data collected during disassembly test of the oven. NA - Not applicable.

Priority Parts	Steps		Fasteners		Tools		Time
	D _i	D _{ref}	Type	Description	Type	Description	
User Interface	10	10	FR	13 torx screw T20	TC	Screwdriver T20x100	Assessed by the extended eDiM, based on the data collected.
			FR	1 cable plug	TC	By hand	
Hot air motor	10	10	FR	15 torx screw T20	TC	Screwdriver T20x100	
			FR	1 nut 10mm	TC	Socket wrench 10	
			FR	2 faston	TC	By hand	
Cooling motor and fan	8	8	FR	11 torx screw T20	TC	Screwdriver T20x100	
			FR	3 faston	TC	By hand	

Top heating element	8	8	FR	7 torx screw T20	TC	Screwdriver T20x100
			FR	4 faston	TC	By hand
			FR	1 clamp	TS	Group-specific tool
			FR	2 nut 7mm	TC	Socket wrench 7
Ring heating element	8	9	FR	11 torx screw T20	TC	Screwdriver T20x100
			FR	2 faston	TC	By hand
			FR	2 nut 7mm	TC	Socket wrench 7
Bottom heating element	9	9	FR	12 torx screw T20	TC	Screwdriver T20x100
			FR	3 faston	TC	By hand
			FR	7 metal tabs	TC	By hand
Temperature sensor	9	11	FR	13 torx screw T20	TC	Screwdriver T20x100
			FR	1 cable plug	TC	By hand
Lamp	7	7	FR	4 torx screw T15	TC	Screwdriver T15x100
Door glasses	10	12	FR	2 metal tabs	TC	By hand
			FR	2 snapfits	TC	By hand
			FR	2 torx screw T20	TC	Screwdriver T20x100
			FU	Glued components	NA	NA
Hinges	11	12	FR	2 metal tabs	TC	By hand
			FR	2 snapfits	TC	By hand
			FR	4 torx screw T20	TC	Screwdriver T20x100
Motherboard	9	9	FR	11 torx T20	TC	Screwdriver T20x100
			FR	11 faston	TC	By hand
			FR	11 cable plugs	TC	By hand
			FR	4 snapfits	TC	Small flat screwdriver

4.1.3. Phase III: Sustainability Index Assessment

In this section, all the indices that make up the sustainability index will be calculated. Describing in each case the reasons and motivations to get those results.

Environmental Index

Following the methodology proposed in Section 3.4.1 (see Figure 22), the first step is to conduct an environmental analysis of the selected indicators.

Using all the data collected in Table App. III. 1 and with the assistance of SimaPro 9 software, the results presented in Table 31 for the analysed product life phases have been obtained. The impacts for the phases of raw material extraction and manufacturing processes have been considered together, contrary to what was described in the methodology. This is because the information available in the article used as a reference (for obtaining the dimensionless environmental indicator) combined these two phases, making it impossible to analyse them separately. This does not pose an issue for the calculation of the indices, as both phases use the same formula and units; it only affects the identification of the sources of criticalities (making it impossible to distinguish whether they are due to the material or the production process).

Table 31. Results for the Environmental Indicators Assessment step - Case study: Electric Oven.

Environmental indicator	Units	Material + Manufacturing phase	Use phase	EoL phase
GWP	kg CO ₂ eq	2.77E+02	5.54E+02	4.09E+00
WCP	m ³	3.63E+00	1.00E+01	3.33E-04
SOP	kg Cu eq	1.22E+01	1.11E+00	1.71E-04
CED	MJ	4.16E+00	1.18E+01	8.88E-04

The next action involves the normalization of the results obtained so that these values can be compared with those of a reference oven. As was explained in *Results Normalization*, the first step is to perform a systematic literature review of the product under analysis. Appendix IV details the process followed for the literature review. The formulas for the indices normalization of the ovens are the ones proposed in Table App. IV. 2 for the "Heat cooking systems - Closed systems". They can be found below and Table 32 describes their parameters and units.

- Raw Material Index

$$Ri = \frac{Ei_{RM}}{\frac{VC}{w} \times y} \quad (38)$$

- Manufacturing Index

$$Mi = \frac{Ei_M}{\frac{Vc}{w} \times y} \quad (39)$$

- Use phase Index

$$Ui = \frac{Ei_U}{\frac{Vc}{P \times tb} \times h \times Y} \quad (40)$$

- EoL Index

$$Ei = \frac{Ei_EoL}{w \times y} \quad (41)$$

- Transport Index

$$Ti = \frac{Ei_T}{\frac{D}{V \times w} \times y} \quad (42)$$

- Maintenance Index

$$Si = \frac{Ei_S}{\frac{1}{ws} \times ys} \quad (43)$$

Table 32. Parameters for the normalization indices – Case study: Electric Oven.

Abb.	Units	Description
Ri	[Pt*kg*m ⁻³ *years ⁻¹]	Normalization index for the raw materials extraction phase. “Pt” is used as the unit of measurement for environmental, it will be replaced with the corresponding unit of measure for the specific LCIA indicators (kg CO ₂ eq, m ³ , kg Cu eq, GJ, or others if different indicators are considered). The philosophy followed has been to consider a ratio that defines the designer’s ability to use less material while maintaining the same performance (e.g., cooking volume). In this way, assuming that the required volume to be covered is the same (Vc), if the weight of the oven is greater (w), the result of the proportion will be smaller, and therefore the index increases. The product duration must be added to the denominator in order to determine whether a particular design decision extends the lifespan of the appliance.
Mi	[Pt*kg*m ⁻³ *years ⁻¹]	Normalization index for the manufacturing phase. “Pt” is used as the unit of measurement for environmental, it will be replaced with the corresponding unit of measure for the

		<p>specific LCIA indicators (kg CO₂ eq, m³, kg Cu eq, GJ, or others if different indicators are considered).</p> <p>The processes followed to retrieve the index is analogous to the one explained for the Ri.</p>
Ui	[Pt*W*m ⁻³]	<p>Normalization index for the use phase.</p> <p>“Pt” is used as the unit of measurement for environmental, it will be replaced with the corresponding unit of measure for the specific LCIA indicators (kg CO₂ eq, m³, kg Cu eq, GJ, or others if different indicators are considered).</p> <p>A ratio of design/performance parameters multiplied by the total hours of use over the years considered in the study has been utilised.</p>
Ei	[Pt*kg ⁻¹ *years ⁻¹]	<p>Normalization index for the EoL phase.</p> <p>“Pt” is used as the unit of measurement for environmental, it will be replaced with the corresponding unit of measure for the specific LCIA indicators (kg CO₂ eq, m³, kg Cu eq, GJ, or others if different indicators are considered).</p> <p>The Ei has been established based on the product’s weight (w) because it serves as an indicator of how End-of-Life processes are carried out and can be identify the adoption of closed-loop EoL strategies for the product.</p>
Ti	[Pt*m ³ *kg*km ⁻¹ *years ⁻¹]	<p>Normalization index for the transportation phase.</p> <p>“Pt” is used as the unit of measurement for environmental, it will be replaced with the corresponding unit of measure for the specific LCIA indicators (kg CO₂ eq, m³, kg Cu eq, GJ, or others if different indicators are considered).</p> <p>The ratio of distance (D) to volume (V) and weight (w) has been considered. Thus, assuming the travelled distance is the same, if the volume or weight of the product is greater, the result will be lower, and therefore, the index increases.</p>
Si	[Pt*kg*years ⁻¹]	<p>Normalization index for the maintenance phase.</p> <p>“Pt” is used as the unit of measurement for environmental, it will be replaced with the corresponding unit of measure for the specific LCIA indicators (kg CO₂ eq, m³, kg Cu eq, GJ, or others if different indicators are considered).</p> <p>Si refers solely to the production of a new spare part, the ratio of the spare part’s lifespan (ys) to the component’s weight (ws) has been considered. Thus, all other factors being equal in terms of spare part durability, the one with less weight will have a lower Si.</p>
Ei_RM	Depends on the environmental indicator (i.e., GWP, WCP, SOP, CED, or others considered by the designer)	Environmental impact for the raw material phase. Retrieved directly from SimaPro.
Ei_M	Depends on the environmental indicator (i.e., GWP, WCP, SOP, CED, or	Environmental impact for the manufacturing phase. Retrieved directly from SimaPro.

	others considered by the designer)	
Ei_U	Depends on the environmental indicator (i.e., GWP, WCP, SOP, CED, or others considered by the designer)	Environmental impact for the use phase. Retrieved directly from SimaPro.
Ei_EoL	Depends on the environmental indicator (i.e., GWP, WCP, SOP, CED, or others considered by the designer)	Environmental impact for the EoL phase. Retrieved directly from SimaPro.
Ei_T	Depends on the environmental indicator (i.e., GWP, WCP, SOP, CED, or others considered by the designer)	Environmental impact for the transport phase. Retrieved directly from SimaPro.
Ei_S	Depends on the environmental indicator (i.e., GWP, WCP, SOP, CED, or others considered by the designer)	Environmental impact for the maintenance phase. Retrieved directly from SimaPro.
w	kg	Product weight.
Vc	m ³	Volume of cooking capacity.
y	years	Duration of the product (lifespan).
P	W	Maximum power.
tb	h	Time needed to heat up a chilled wet brick from 5°C to 60°C (standard EN15181) (CEN/CENELEC, 2020a).
h	h/year	Time of use per year considered.
Y	years	Timeframe considered in the scope of the study.
D	km	Distance for the transport phase.
V	m ³	Volume of the product during transportation.
ws	kg	Weight of the spare part component.
ys	years	Duration (lifespan) of the spare part.

After applying the different indices, the values in Table 33 are obtained.

Table 33. Results after the normalization process - Case study: Electric Oven.

Normalized Environmental Indicator	Units for "Pt"	Ri + Mi [Pt*kg*m ⁻³ *years ⁻¹]	Ui [Pt*W*m ⁻³]	Ei [Pt*kg ⁻¹ *years ⁻¹]
GWP	kg CO ₂ eq	8.02E+03	1.48E+00	8.52E-03
WCP	m ³	1.05E+02	2.69E-02	7.09E-07
SOP	kg Cu eq	3.53E+02	2.97E-03	3.62E-07

CED	MJ	1.21E+02	3.16E-02	1.90E-06
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Next, reference values must be established for each indicator. To do this, the impacts from studies related to electric ovens found in the literature (that also uses the Italian energy grid mix) (Landi, Consolini, Germani, & Favi, 2019) (Favi, Formentini, & Boix Rodríguez, *Eco-design of cooking appliances based on food habits and diets*, 2020) have been normalized (using the formulas presented above), with the maximum values of R_i , M_i , U_i , and E_i found serving as the reference. Once this is done, Table 8 can be applied to obtain the dimensionless environmental impact value (see Table 34).

Table 34. Dimensionless environmental indicator for each phase of the life cycle -Case study: Electric Oven.

Environmental indicator	$R_i_A + M_i_A$	U_i_A	E_i_A
GWP	0.08	0.89	0.00
WCP	0.28	1	0.00
SOP	0.00	0.35	0.00
CED	0.70	0.97	0.00

At this point, these results should be weighted based on the relative uncertainty of the sources, as shown in Table 6. In the particular case of the oven, the average uncertainty factor for each phase is 0.7, which means “Part of the data is not available or based on assumptions”. It is worth highlighting the importance of the source’s reliability, as the final value of the Environmental Index depends significantly on it. In this way, this methodology promotes the use of trustworthy sources to ensure the most favourable results possible. It is also necessary to define the weight that each phase will have when calculating each indicator. For this type of product, the usage phase is the most important, and its results are critical in achieving sustainability throughout its entire lifespan (Bevilacqua, Caresana, Comodi, & Venella, 2010) (Xiao, Zhang, Liu, & Yuan, 2015). It has been established that the weight of the Material and Manufacturing phase is 2.5, for the Use phase is 3, and for the End-of-Life phase is 1. The results for the environmental indicators for all the lifecycle phases considered within the system boundaries are $E_{GWP} = 0.46$, $E_{WCP}=0.53$, $E_{SOP}=0.18$, and $E_{CED}=0.51$. Finally, the environmental index can be calculated using (6), resulting in $I_{Environmental}=0.42$ in the analysed case.

From the analysis of these results, various conclusions can be drawn. The first is that the normalization process of environmental indicators allows for a fair comparison of two LCA analyses with diverse functional units and different time frames. In fact, by considering design factors (e.g., power, capacity) to normalize the indicators, it can be observed that the GWP during the usage phase is much more favourable in the case study oven compared to the one used as a reference, even though it may not have been evident when observing the kg CO₂ eq values before the normalization. As can be seen, for all the analysed indicators, the end-of-life phase of the oven performs worse than the reference. This can be explained by considering that the study assumes a very optimistic scenario of recycling percentages, whereas in the analysed case study, a more realistic scenario is considered, and the normalized results are greater than the ones used as reference. The fact that the E_{WCP} indicator is 0.53 (greater than 0.5) is because one of the factors that greatly influences this parameter is the energy consumed from the Italian grid mix during the usage phase (and the related water consumption). Therefore, being an energy-efficient product in this case (class A++), it exhibits better performance compared to the reference product. The same occurs with the $E_{CED} = 0.51$, for this indicator the energy efficiency is also critical. The E_{GWP} is slightly below 0.50, so through small redesign modifications, it is possible to improve the results. On the other hand, $E_{SOP} = 0.18$, this parameter is closely related to the amount of mineral resources consumed. The result is very low primarily due to the quantity of electronic components present in the case study (e.g., UI, PCB), which the reference oven lacked. This is the main critical point of this product, so efforts should be made to reduce the consumption of mineral materials during production. Finally, it can be noted that the Environmental Index is 0.42, indicating that there is room for improvement in this aspect of the product.

Economic Index

In this section, the calculation of the Economic Index of the product using the formula explained in the methodology is presented. It is important to note that, as the product will be sold in Italy, the discount rate has been estimated for this scenario. As described in the methodology, this is one of the more complex parameters to define. Statistics from ISTAT (Camera di Commercio Reggio Emilia, 2023) dating back to 1995 (see Figure 33) to thoroughly analyse this parameter have been used. According to the trends,

it is expected to decrease approximately 3% (Istituto Nazionale di Statistica, 2023).

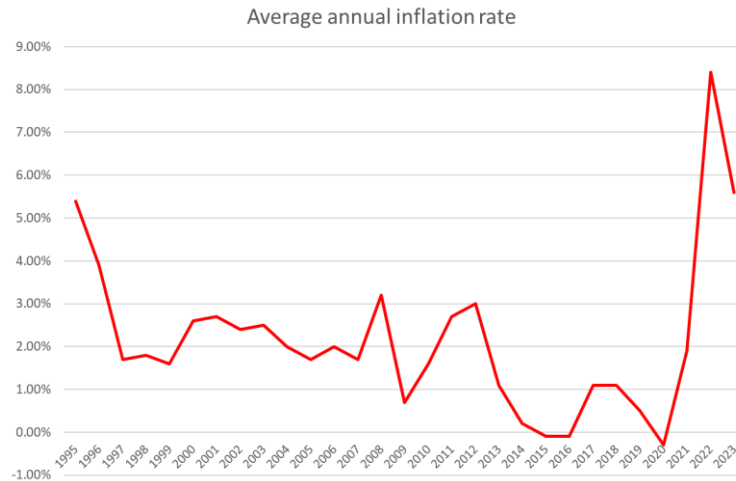


Figure 33. Discount rate trend for Italy from 1995 to 2023.

For this case study, the operational costs are related to the energy consumption used. The electricity price has been taken from the Eurostat Database for the first half of the year 2022, the cost for Italy is 0.3115 €/kWh (Eurostat, 2023). With the information provided during the product description and the lifetime scenario considered for the LCA, all the necessary data for calculating the operating cost (C_{use}) over the 15-year product lifespan are obtained. The maintenance cost of 215 € at year 10 includes the cost for the replacement of some parts and the operator's work, this estimation has been done using available scientific documents (Iraldo, Facheris, & Nucci, 2017). The oven used as a reference has a lifespan of 10 years (5 years less than the study period), so a new one with the same features will be purchased (C_{repl}). This new oven will not reach the end of its lifespan before the study period concludes, so its residual value (V_{res}) will be discounted from the LCC, taking into account an amortization coefficient of 12%, as recommended for these products (Iraldo, Facheris, & Nucci, 2017).

Table 35. Cost data used in the LCC -Case study: Electric Oven. PV - Present value. NA - Not applicable.

Expenses [€]	Case study - Oven			Reference Oven		
	Total cost	Year	PV	Total cost	Year	PV
C_0	560.00	0	560.00	450.00	0	450.00
C_{use}	449.49	15	357.74	855.77	15	681.07

C_{maint}	215.00	10	159.98	N.A.	N.A.	N.A.
C_{repl}	N.A.	N.A.	N.A.	450.00	10	334.84
V_{res}	N.A.	N.A.	N.A.	180.00	15	115.54
PV of the total LCC		1077.72			1350.38	

After calculating the LCC adjusted to present value, it can be observed that the oven under analysis exhibits a lower economic impact over its entire lifespan, even though its initial cost was higher. This is attributed to the difference in energy efficiency between the two models (A++ vs. A), which results in the presented case study having a C_{use} that is approximately half of the reference one. The next step is to calculate the dimensionless LCC value following the guidelines in Table 11. After conducting a market analysis and different meetings with industry experts, it has been concluded that for this category of mechatronic product (i.e., household appliances), it is considered an ideal scenario (i.e., score equal to 1) for the LCC to be less than one-third of the $LCC_{\text{Reference}}$. Thus, establishing the value of the LCC_{THR} . After the application of the equation shown in Table 11, the dimensionless economic impact is calculated: $A_{\text{Economic}} = 0.61$. The average uncertainty for the source of information in the different phases of the LCC is $U_{\text{Economic}} = 0.7$ (see Table 6), resulting in a final economic index of $I_{\text{Economic}} = 0.42$. It can be observed that this value is close to 0.5, so with some simple eco-design actions, it can be improved.

Social Index

For the social index analysis, both the production facility and suppliers will be considered (i.e., all the stakeholders that take part on the lifecycle of the product). In this case study, production takes place in Italy, and the company does not hold any of the certifications described in the methodology (see Section 3.4.3). The uncertainty score is $U_{\text{Social}} = 0.9$ (see Table 6). Using (18), an $I_{\text{Social}} = 0.67$ for the manufacturing plant can be obtained. However, the supplier of electronic components is located in China, which yields a social index value of 0. Thus, when considering the worst-case scenario, the final index will be $I_{\text{Social}} = 0$. It is evident that efforts to improve this value will focus on exploring alternative electronic component suppliers.

Circularity Score

Reliability Analysis

As explained in the Section 3.4.4, in order to calculate the *disassemblability index* it is needed to define the parameters' weight and the priority parts' weight. For the parameters' weight, previous studies were used as a reference for this definition (Cordella, Alfieri, & Sanfelix Forner, 2019) (European Commission - Directorate-General for Environment; Ricardo-AEA Ltd, 2015) (Consumer reports, 2019), where W_{Param_1} , W_{Param_2} , and W_{Param_4} are set to 3 (the maximum value possible, representing their importance in this analysis), and W_{Param_3} is set to 1. Concerning the weight for each target component, a specific matrix was developed considering the "failure rate" and the "failure impact".

		Failure Rate		
		L	M	H
Failure Impact	L	0.50	0.75	1
	M	1	1.75	2
	H	1.25	2.25	3

Figure 34. Weight matrix for priority parts.

The failure rate is the probability that a given target component can fail during the product's useful life. Three different ranges have been set for failure rate, high (H), medium (M), and low (L). These three ranges were defined in accordance with the market analysis of spare parts sales. The same approach was used for the failure impact which is the influence on the product functionality when a given target component fails. Three different ranges have been set for failure impact, high (H), medium (M), and low (L). These three ranges were defined considering if the failure of a given component can totally compromise the product functionality (e.g., the heating elements) or only partially (e.g., the lamp). By making use of the matrix shown in Figure 34, the following weights were assigned to the PPs: $W_{PP_1} = 2.25$, $W_{PP_2} = 2.25$, $W_{PP_3} = 1.25$, $W_{PP_4} = 3$, $W_{PP_5} = 3$, $W_{PP_6} = 3$, $W_{PP_7} = 2.25$, $W_{PP_8} = 2.25$, $W_{PP_9} = 1$, $W_{PP_{10}} = 1$, $W_{PP_{11}} = 2.25$.

After establishing the weights for each parameter, the Product Index can be calculated, with the I_D global value being 0.46, less than 0.5, so it will be necessary to implement some eco-design actions to improve this product's reparability performance. On the other hand, Table 36 shows the results for each PP, in order to identify the most critical target components. For the sake of comprehension, a colour map has been defined to identify critical and non-critical components. The "high-critical component" presents a disassembly index value lower than 0.5 (red colour), while "medium-critical component" presents a disassembly index value between 0.5 and 0.65 (yellow colour), and "non-critical component" presents a disassembly index above 0.65 (green colour). Following the proposed classification, not even one target component is classified as "non-critical component". Only three components are classified as "medium-critical component" (i.e., ring heating element, temperature sensor, and hinges) while all the others are "high-critical component". This can be explained by the high number of steps required to remove each of the components, as will be studied in more depth in the following section.

Table 36. Disassemblability Index of priority parts [0-1] – Case study: Electric Oven.

Priority Parts	I_D
User Interface	0.43
Hot air motor	0.43
Cooling motor and fan	0.43
Top heating element	0.49
Ring heating element	0.51
Bottom heating element	0.43
Temperature sensor	0.59
Lamp	0.43
Door glasses	0.19
Hinges	0.51
Motherboard	0.43

For the *durability score*, the analysed product has a lifespan of 15 years, which is quite close to the maximum found in the market for this type of oven. Through market analysis and discussions with different manufacturers, it has been established at 17 years with proper product maintenance. So, the durability score for the studied oven is:

$$S_D = \frac{L_{product}}{L_{max}} = 0.88$$

Using (27), the $S_{reliability}$ can be calculated, but first, the weights for durability and repairability must be defined. In this specific case, there is no intention to prioritize one circularity factor over the other, so the weights will be $W_{Dur}=W_{Rep}=2$. However, it is important to note that this trade-off should be determined by the designer/engineer based on the characteristics and nature of their study, with complete freedom to modify them and conduct relevant sensitivity analyses.

$$S_{reliability} = \frac{W_{Dur} \times S_D + W_{Rep} \times I_D}{W_{Dur} + W_{Rep}} = 0.67$$

Thanks to the good durability performance, the final result of the reliability of the oven studied is higher than 0.5, making it non-critical. Although improvements in product reparability will have a positive impact in other areas, such as in economic analysis, by potentially reducing C_{Maint} expenses.

EoL Product Management

Finally, the EoL management indices must be calculated following the procedure outlined in Section 3.4.4. Table 37 displays the results for each of the established scenarios, with the design requirement set at a THR of 0.5 (after performing a cost-benefit analysis validated with the ROC method). Applying the classification from Table 20, the final score for the I_{EoL} is 1, as all the target components manage to exceed the THR in at least one category.

Table 37. EoL management indices per priority part - Case study: Electric Oven.

Component	I_{Reuse}	I_{Rem}	I_{Rc}
UI	0.88	0.90	-11.00
Hot air motor	0.66	0.71	-1.42
Cooling motor and fan	0.74	0.78	-0.86
Top HE	0.65	0.70	-2.64
Ring HE	0.53	0.60	-5.84
Bottom HE	0.58	0.65	-5.72
Temperature sensor	0.57	0.64	-48.74
Lamp	0.42	0.50	-19.46
Door	-0.94	0.51	0.30
Hinges	0.54	0.60	-0.82
Motherboard	0.91	0.92	-6.91

The fact that the door is the only component with a negative impact on the reuse index is due to the use of adhesive joints that do not allow for the separation of plastic components from the glass. It is worth noting that the remanufacturing potential of all the analysed components is very high, which is a positive aspect (although, following the circularity philosophy, the first strategy should be repair, followed by reuse). Finally, the recycling index is very low because almost all the components analysed have a very low weight for the value of recycled material to offset all recycling costs.

Circularity Score

After analysing the reliability and EoL management parameters, the circularity score (from 0 to 1) can be calculated: $A_{\text{Circularity}} = 0.83$. Considering that the uncertainty associated with the data acquisition is $U_{\text{Circularity}} = 0.7$, the final score for the index is $I_{\text{Circularity}} = 0.58$.

Sustainability Index

Table 38 summarizes the scores and weights for each index considered in this case study. The overall sustainability score is $I_{\text{Sustainable}}=0.43$, corresponding to a product class equal to F.

Table 38. Final scores for the sustainability indicators – Case study: Electric Oven.

Indicator	Score [0-1]	Weight [1-3]
Environmental	0.42	3
Economic	0.42	3
Social	0.00	1
Circularity	0.58	3

The product label before the implementation of the eco-design actions is shown in Figure 35. For confidentiality reasons, the label displayed in this research work does not include the product brand, and the QR code does not direct you to the specific page of the analysed model, but rather to the domestic ovens' generic database.

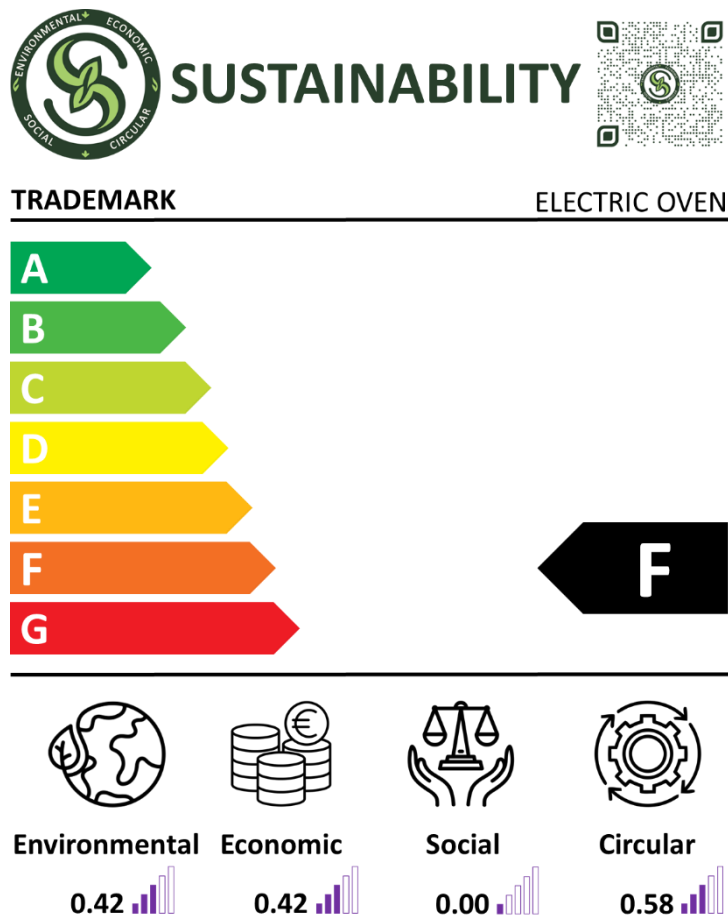


Figure 35. Sustainability label - Case study: Electric Oven.

4.1.4. Phase IV: Implementation of Eco-Design methodologies

In order to improve the sustainability of the product studied, the first area addressed is the Social Index, since it is the one that presents the worst results. It is observed that the issue is related to the electronics supplier that have the manufacturing facilities in China, being China the world's leading exporter of electronics. After conducting a market analysis, it was found that a possible alternative for importing electronic components is South Korea. If the country of origin is changed, the social index would increase from 0 to $I_{\text{Social}}=0.50$, which is the threshold to be considered acceptable. If only this change is done, it would imply an 11% increase in the sustainability index, not enough to improve the overall category of the product. This can be explained because the weight of the social index is 1 instead of 3, like the other parameters. On the other hand, it is important to highlight that the

most significant recommendation for improving the social impact is to attain accreditation from one of the standards proposed in the methodology. If the manufacturer gets certified, the I_{Social} becomes 1, and the sustainability index increases by 19%, moving from category F to E.

Following the methodology to obtain eco-design actions for the environmental impact, a detailed analysis of the GWP and SOP indicators, which were all below 0.5, should be conducted. The primary focus should be on improving SOP, as it was the most critical. Table 39 summarizes the potential redesign actions.

Table 39. Identification Eco-Design actions for the Environmental Index.

Parameter	Eco-Design action
$I_{\text{GWP}}, I_{\text{SOP}}$	<ul style="list-style-type: none"> • To reduce the weight of the cavity and the oven structure a 5% since they are the components that impact the most (after the PCB). • To reduce the weight of the packaging by 30%. • To use renewable sources to power the manufacturing plant (avoiding the high impact of the Italian grid mix). The new energy consumption is reduced up to 50%. • To compensate the unavoidable impact investing in carbon offset initiatives. • To inform the user about responsible practices to reduce the impact during the use phase (reduction of 5% of energy consumption). • To improve the energy efficiency until it is the maximum available, reducing impacts during the use phase (A+++). • To examine potential alternatives to traditional PCBs, assessing the feasibility of using plant-based biodegradable PCBs (Guna, et al., 2016) or Inkjet-printed PCBs (Wan, Kanth, Yang, Chen, & Zheng, 2015) (Sudheshwar, Malinverno, Hischer, Nowack, & Som, 2023), which significantly reduce carbon emissions during production. Or to promote the reused of some of the electronic components, avoiding the impacts of new material extraction and manufacturing. • To optimize the supply chain (assumption of 5% of impacts reduction).

The new environmental results after the implementation of the eco-design actions are:

- $E_{\text{GWP}}=0.52,$
- $E_{\text{SOP}}=0.36,$
- $E_{\text{WCP}}=0.58,$
- $E_{\text{CED}}=0.57.$

The modifications done also affected positively to the WCP and CED indicators. The new $I_{\text{Environmental}}$ is 0.51, greater than 0.5. The impact of this

improvement results in a 5% increase in the sustainability index (also considering the social accreditation action done before). If it were possible to enhance the reliability of the data used, for instance, through the incorporation of the Digital Product Passport (DPP) (which aims to provide reliable information about the life of materials/components/products) and if it were possible to avoid certain assumptions made, improving U from 0.7 to 0.8 (at a minimum, see Table 6), it results in the $I_{\text{Environmental}}$ being equal to 0.58 (an increment of approximately 13%). This highlights the importance of data selection. Some of the actions taken for the improvement of the environmental indicator also affect the economic one. For example, the reduction of the amount of raw material used for the production or the shift to renewable energy supply for the manufacturing plant. All those actions will reduce the initial cost of the appliance (C_0), which was one of the criticalities highlighted after the application of the methodology presented in Table 24 (reduction of 5%). Together with the maintenance cost (C_{Maint}). To address the maintenance issue, the first thing is to ensure the availability of spare parts during the whole lifespan of the product, as the oven analysed has a fairly long useful life. Then, in order to reduce the complexity of the repair process, as suggested by Table 24, Table 26 will be analysed. To address the analysis of the disassemblability index, first of all it is needed to define the THR present in Table 26. For parameter P1, if D_i is greater than 0.9 times D_{ref} , it is considered a criticality. This THR of 0.9 was set using the cost-benefit analysis validated with the ROC method for the considered mechatronic product family (i.e., electric oven). The values of True Positive Rate (TPR) and False Positive Rate (FPR) are 0.88 and 0.33 respectively. Finally, for parameter P4 the approach is similar to the one followed for parameter P1, a criticality is identified when T_i is greater than 0.9 times T_{ref} . The THR of 0.9 was again set using the cost-benefit analysis validated with the ROC method. In this case the values of TPR and FPR are 0.88 and 0 respectively. Once the THR is established, the mathematical rules defined in the methodology can be evaluated. Table 40 summarizes the guidelines for improving the reparability of some of the priority parts of the case study, making it easy to identify the criticality of each component. Through reverse engineering of the index analysis, areas for improvement are identified.

Table 40. Eco-design guidelines for some target components of the electric built-in oven.

Component	Parameter AS-IS	Mathematical rule	Eco-design actions
Top Heating Element	$D_i = 8$ $D_{ref} = 8$ $S_3 = 0.75$	$\frac{D_i}{D_{ref}} = 1 \geq 0.9$ $S_3 < 1$	Attempt to obtain a solution that enables unlocking the door without the need for an additional step, making it something that can be incorporated as part of the door-opening movement. Change the clamp type so that it can be removed and reused using only common tools or by hand.
User Interface	$D_i = 10$ $D_{ref} = 10$ $T_i = 68.04 \text{ s}$ $T_{ref} = 40 \text{ s}$ $T_{position} = 21.60 \text{ s}$ $T_{discon} = 28.44 \text{ s}$	$\frac{D_i}{D_{ref}} = 1 \geq 0.9$ $\frac{T_i}{T_{ref}} = 1.7$ ≥ 0.9 $\frac{T_{position}}{T_i} = 0.32$ > 0.20 $\frac{T_{discon}}{T_i} = 0.42$ > 0.20	To redesign the front panel in a way that it can be removed without the need to disassemble additional components (e.g., back panel, top panel). This action would reduce the D_i as well as T_{discon} and $T_{position}$ (and consequently the overall T_i).
Door glasses	$S_2 = 0$ $D_{removal} = 6$ $D_i = 10$ $T_i = 642.84 \text{ s}$ $T_{ref} = 60 \text{ s}$ $T_{discon} = 607.20 \text{ s}$	$S_{2,i} < 1$ $\frac{D_{removal}}{D_i} = 0.6$ > 0.5 $\frac{T_i}{T_{ref}} = 10.71$ ≥ 0.9 $\frac{T_{discon}}{T_i} = 0.94$ > 0.20	Attempt to use an alternative fastening method that allows for complete disassembly of this component (avoiding the use of adhesive joints to connect the plastic frames to the glass). This criticality is primarily associated with end-of-life and recyclability. To reduce the number of components that need to be removed to reach the target, simplifying the removal of the door. To avoid the use of adhesive to reduce the T_{discon} (avoiding the heating up).

An example of criticality referring to the disassembly of the PP “Top heating element” is shown in Figure 36. On the left (Figure 36 A) the current design presents a specific clamp for a water hose that needs to be removed by the use of a dedicated/specific tool (TS). In this case, the assessment of the disassembly index clearly indicated that the score associated with the parameter P3 is 0.75, failing to respect the equation proposed for the tool parameter ($S_{3,i} < 1$). On the right (Figure 36 B), designers proposed a different type of clamp which requires the use of a flat screwdriver (TC) and increasing the score associated with P3 from 0.75 to 1. Applying this specific rule an increment of disassembly time is noticed and accounted for the score

associated with P4. However, the score associated with P4 is less penalized (downgrade) compared with the score associated with P3.

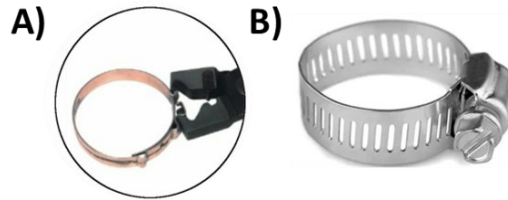


Figure 36. Example of criticality and solution for the PP "Top heating element". A) PP that uses a product-specific tool, and B) PP that uses common tools.

Another example is the one referring to the PP "Door glasses" (see Figure 37) where the use of an adhesive joint (Figure 37 A) downgrades the score associated with P2 parameter (fasteners) since the adhesive joint is neither removable nor reusable (FU). The use of adhesive for oven door glass assembly deals with the aesthetic requirements of the product. The assessment of the disassembly index clearly indicated that the score associated with the parameter P2 is 0, failing to respect the equation proposed for the fastener parameter ($S_{2,i} < 1$). Following the identification of this pain point, designers decided to avoid the use of adhesive joints, adopting an eco-design solution that makes use of reversible fasteners (e.g., screws). By adopting this approach (Figure 37 B), the score associated with the P2 parameter rises from 0 to 1. Even though with this solution the oven functionality is kept, the increment in the repairability index is in contrast with the aesthetic requirements of the oven.

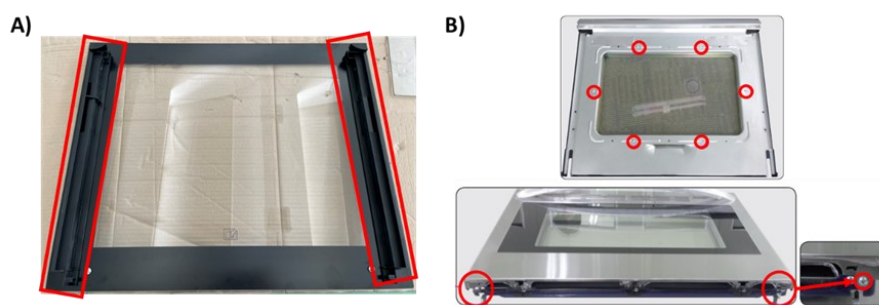


Figure 37. Example of criticality and solution for the PP "Door glasses". A) PP that uses adhesive as joining method, and B) PP that uses screws as joining method.

Table 41 shows the results of the disassemblability index after the application of these eco-design actions. As can be seen, this tool is useful for

improving product design. After implementing the eco-design actions, the Disassemblability Index of the PPs studied has increased. The PP that improved its results the most was the “door glasses” since that target component was the most critical due to the use of adhesive as a joining method. All these redesign actions are leading toward a 66% increment in the overall I_D , and consequently an increase in the $I_{\text{Circularity}}$ of 9%, the new value is $I_{\text{Circularity}} = 0.64$.

Table 41. Disassemblability Index of some of the priority parts after the application of the eco-design actions [0-1] - Case study: Electric Oven.

Priority Parts	I_D
User Interface	0.62
Top heating element	0.57
Door glasses	0.58

As previously explained, this improvement in reparability entails a reduction in maintenance costs (C_{Maint}), specifically a 20% reduction. So, the new economic index (taking into account the reduction of C_0 and C_{Maint}) will be 0.52. Once all the indices have been calculated after implementing the various redesign actions (see Table 42), the final score for the sustainability index can be obtained, $I_{\text{Sustainability}} = 0.62$, 32% higher than before. Now, the sustainability class is D, which is not consider critical.

Table 42. Final scores for the sustainability indicators before and after eco-design actions - Case study: Electric Oven.

Indicator	Weight [1-3]	Score before redesign [0-1]	Score after redesign [0-1]
Environmental	3	0.42	0.58
Economic	3	0.42	0.52
Social	1	0.00	1.00
Circularity	3	0.58	0.64

4.1.5. Phase V: Report production

The final label for the redesign product is depicted in Figure 38. Similar to the previous version, this label excludes the product’s brand, and the QR code does not direct to the specific page of the model under examination.

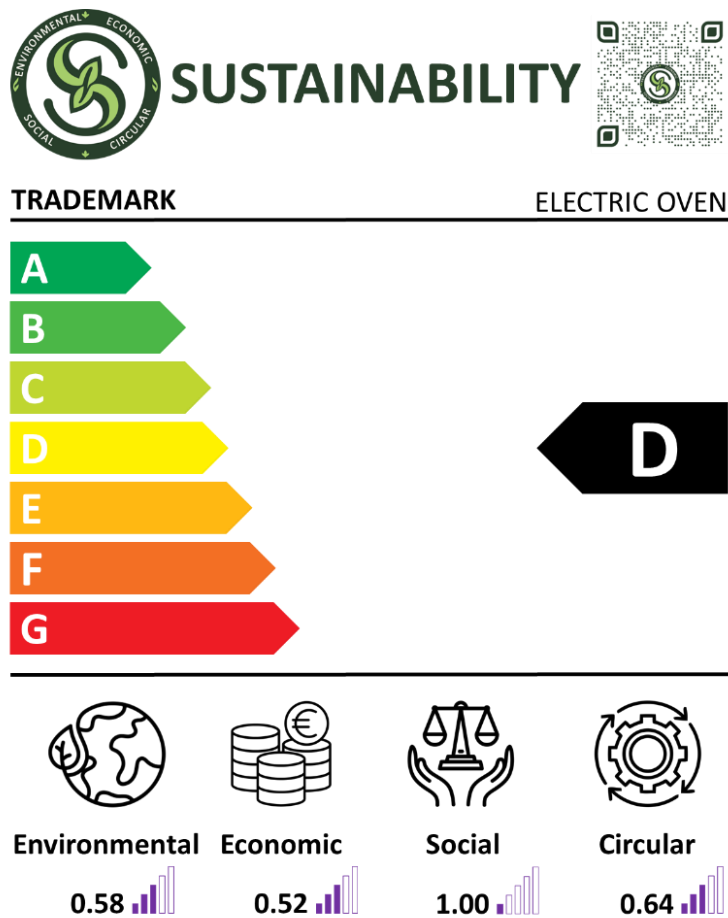


Figure 38. Sustainability label after eco-design actions - Case study: Electric oven.

4.2. COOKER HOOD

4.2.1. Phase I: Product classification

The second case study for this project is a range hood, which falls under the category of household appliances, specifically within the family of kitchen ventilation systems. This product is equipped with a mechanical fan, typically suspended above the cooktop in a kitchen setting. Its primary function involves the extraction or filtration of airborne grease, smoke, or steam, effectively improving the air quality within the kitchen. This type of product can be installed in as conventional hoods (i.e., mounted on the wall above the hob), integrated cooker hoods (i.e., built into the cabinets),

designer hoods (i.e., the design of the appliance complements the kitchen style), chimney hoods (i.e., introducing an industrial or urban aesthetic to), downdraft hoods (i.e., built into the worktop), or island hoods (i.e., they can be integrated into the ceiling or hung above the island hob). The model under analysis belongs to this last category, the island cooker hoods, specifically the so-called T-shape island hood. Figure 39 provides a schematic representation of the hood, while Table 43 summarizes the key technical characteristics of the product.

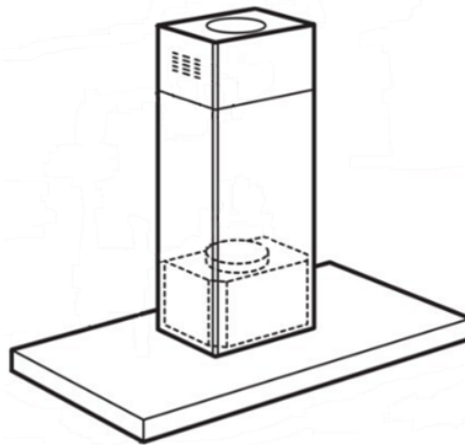


Figure 39. Overview of the T-shape island hood.

Table 43. Product specifications – Case study: cooker hood.

Parameter	Value
Dimensions (HxWxD)	730 x 898 x 614 [mm]
Maximum height	1150 [mm]
Annual energy consumption	56.1 [kWh/year]
Weight	31.30 [kg]
Energy efficiency class	A
Energy consumption per cycle	0.52 [kWh/cycle]
Fluid dynamic efficiency	32
Lighting efficiency	38.1 [Lux/W]
Grease filtering efficiency	65.1%
Air flow (max speed normal use)	615 [m ³ /h]
Airborne acoustical A-weighted sound power emissions (max speed normal use)	68 dB
Power consumption in off mode (W)	0.49 [W]

4.2.2. Phase II: Life Cycle Engineering analysis

Following the methodology proposed, the first step of the LCE analysis is to define the system boundaries, indicating the phases that will be considered during the environmental analysis. The same considerations explained during the first case study are also applied to the cooker hood, since both of them are in the same product category. In addition, examining the Italian utilization context, the use phase has the most significant influence on the environmental footprint of hoods (Bevilacqua, Caresana, Comodi, & Venella, 2010). Therefore, the phases included in the system boundaries are those shown in Figure 32 (i.e., raw material extraction, manufacturing and assembly processes, use phase, and EoL). The product's useful life has been set at 15 years, based on manufacturer-provided data.





The functional unit established for the calculation of environmental impact is: *“to maintain good air conditions during the preparation of a full daily meal in the Italian context for a lifespan of 15 years”*. The reference flow is represented by a cooker hood with an energy class of A, measuring the consumption through the standard test for labelling certification.




The inventory with all the necessary data for the LCA analysis of the cooker hood is presented in Appendix III, including all materials to be considered, types of manufacturing processes, transportation of the raw materials and components, and the end-of-life for each component. The production plant is located in Italy, where it is assumed that the product will be sold and processed at the end of its life. Electronic components are imported from South Korea, while the rest of the subassemblies and materials come from European suppliers. To obtain all the necessary information for the reliability analysis, a manual disassembly test of the range hood was conducted, following the workflow proposed in Section 3.3.3: identification of target components, disassembly analysis, and data collection.

The list of target components has been identified following the same two paths explained for the oven: (i) failure analysis of the product components, and (ii) market analysis of spare parts sales done with company experts. Table 44 presents the full list of priority parts as well as a description of each one. The list of target components has been identified after conducting a market analysis of spare parts sales. To do this, it was requested to a range

hood manufacturing company information regarding these sales for the last 10 years. From this studied period, the components that account for more than 75% of failures have been selected.

Table 44. List of priority parts – Cooker hood.

Abb.	PP name	Description	Image
PP1	Power cord	Its primary function is to provide electrical power to the hood and its associated components. Typically, it is constructed from a flexible material capable of withstanding elevated temperatures. The most common failures during the hood's lifespan are wear and tear (e.g., broken cord), damage (e.g., prolonged exposure to heat, moisture, or environmental elements), or incorrect installation (e.g., electrical connection problems).	
PP2	User Interface	It allows the user to interact with the hood (e.g., setting different aspiration modes, controlling lights, etc.). It consists of a PCB with different buttons. The most common failures during the hood's lifespan are button failure, wiring failure (e.g., the wiring that connects the UI and the PCB can become loose or damaged over time), and control board failure (e.g., due to power surge or other electrical issues).	
PP3	Motherboard	It is the main circuit board that controls the hood's functions and components. The most common failures during the hood's lifespan are power surges (e.g., electrical issues), overheating, and component failure (e.g., moisture can cause corrosion, wear and tear or damage to the components that form the motherboard).	
PP4	Led driver	It regulates the power supply to the LED lights in the hood. It plays a crucial role in transforming incoming AC voltage into a suitable DC voltage to power the LEDs. Additionally, it has the capability to regulate the brightness of the LEDs, allowing for adjustments in light intensity as required. The most common failures during the hood's lifespan are element failure (due to overheating, exposure to moisture, or electrical issues), burnt-out element (e.g., faulty component), and loose connection (e.g., by wear and tear or due to damage).	

PP5	Blower	It is responsible for the intake of air and smoke from the cooking area and subsequently expelling it outdoors. The most common failures during the hood's lifespan are motor failure (e.g., due to wear and tear or overheating), blower wheel damage (e.g., due to grease accumulation or unintended incidents), or electrical connections (e.g., loose or damaged electrical connections).	
PP6	Lamp	It illuminates the cooking surface, located on the underside of the hood, and it is powered by an electric current. The most common failures during the hood's lifespan are bulb failure (e.g., due to wear and tear, or damage to the bulb filament), burnt-out bulb (e.g., faulty bulb, overheating), and loose connection (e.g., damage to the connection).	
PP7	Grease filter	It captures grease and other cooking byproducts. Typically situated beneath the hood, this filter can be crafted from materials such as aluminium or stainless-steel mesh. The most common failures during the hood's lifespan are clogging (e.g., due to grease and other particles accumulation), filter damage (e.g., due to accidental impacts or regular wear and tear), or improper installation.	

The disassembly test was performed at the university facilities, with the real physical prototype, by expert operators in the field, following the disassembly path of each target component that minimizes the number of steps. Table 45 shows the data collection related to the identified target components. All the information was collected through a spreadsheet to facilitate the analysis.

Table 45. Data collected during disassembly test of the range hood. NA - Not applicable.

Priority Parts	Steps		Fasteners		Tools		Time
	D _i	D _{ref}	Type	Description	Type	Description	
Power cord	4	15	FR	2 cross screw PH2	TC	Screwdriver PH2x100	Assessed by the extended eDiM, based on the data collected.
			FR	1 plastic tab	TC	By hand	
			FR	3 flat screw	TC	Screwdriver 0.8X4	
User Interface	13	13	FR	8 cross screw PH2	TC	Screwdriver PH2x100	
			FR	9 snapfits	TC	By hand	
			FR	2 electrical connectors	TC	By hand	
Motherboard	6	17	FR	5 cross screw PH2	TC	Screwdriver PH2x100	
			FR	4 electrical connectors	TC	By hand	
Led driver	6	11	FR	5 cross screw PH2	TC	Screwdriver PH2x100	
			FR	2 faston	TC	By hand	
			FR	2 snapfits	TC	By hand	
			FR	1 electrical connector	TC	By hand	
Blower	13	27	FR	5 cross screw PH2	TC	Screwdriver PH2x100	
			FR	3 snapfits	TC	By hand	
			FR	1 metal tabs	TC	Small flat screwdriver	
			FNR	1 cable tie	TC	Scissors	
			FR	1 nut 13mm	TC	Socket wrench 13	
Lamps	19	27	FR	11 snapfits	TC	By hand	
			FR	4 faston	TC	By hand	
			FR	8 cross screw PH2	TC	Screwdriver PH2x100	
Grease filters	7	7	FR	3 snapfits	TC	By hand	

4.2.3. Phase III: Sustainability Index Assessment

In this section, all the indices that make up the sustainability index will be calculated. Describing in each case the reasons and motivations to get those results.

Environmental Index

Following the methodology proposed in Section 3.4.1 (see Figure 22), the first step is to conduct an environmental analysis of the selected indicators. Using all the data collected in Table App. III. 2 and with the assistance of SimaPro 9 software, the results presented in Table 46 for the analysed product life phases have been obtained.

Table 46. Results for the Environmental Indicators Assessment step - Case study: Cooker Hood.

Environmental indicator	Units	Raw material phase	Manufacturing phase	Use phase	EoL phase
GWP	kg CO ₂ eq	1.71E+02	4.68E+01	3.48E+02	3.45E+00
WCP	m ³	3.63E+00	2.09E-01	5.83E+00	1.46E-04
SOP	kg Cu eq	9.79E+00	9.55E-01	1.22E+00	8.95E-05
CED	MJ	2.81E+03	7.02E+02	7.38E+03	4.76E-01

The next action involves the normalization of the results obtained so that these values can be compared with those of a reference oven. The process is analogous to the one done for the ovens. The formulas for the indices normalization of the cooker hoods are the ones proposed in Table App. IV. 2 for the “Kitchen vacuum systems”. They can be found below and Table 47 describes their parameters and units.

- Raw Material Index

$$Ri = \frac{Ei_{RM}}{\frac{A}{w} \times y} \quad (44)$$

- Manufacturing Index

$$Mi = \frac{Ei_M}{\frac{A}{w} \times y} \quad (45)$$

- Use phase Index

$$Ui = \frac{Ei_U}{\frac{Q}{P} \times h \times Y} \quad (46)$$

- EoL Index

$$Ei = \frac{Ei_EoL}{w \times y} \tag{47}$$

- Transport Inex

$$Ti = \frac{Ei_T}{\frac{D}{V \times w} \times y} \tag{48}$$

- Maintenance Index

$$Si = \frac{Ei_S}{\frac{1}{ws} \times ys} \tag{49}$$

Table 47. Parameters for the normalization indices – Case study: Cooker Hood.

Abb.	Units	Description
Ri	[Pt*kg*m ⁻² *years ⁻¹]	<p>Normalization index for the raw materials extraction phase. “Pt” is used as the unit of measurement for environmental, it will be replaced with the corresponding unit of measure for the specific LCIA indicators (kg CO₂ eq, m³, kg Cu eq, GJ, or others if different indicators are considered).</p> <p>The philosophy followed has been to consider a ratio that defines the designer’s ability to use less material while maintaining the same performance (e.g., cooking surface area). In this way, assuming that the required total cooking surface area to be covered is the same (A), if the weight of the hood is greater (w), the result of the proportion will be smaller, and therefore the index increases. The product duration must be added to the denominator to determine whether a particular design decision extends the lifespan of the appliance.</p>
Mi	[Pt*kg*m ⁻² *years ⁻¹]	<p>Normalization index for the manufacturing phase. “Pt” is used as the unit of measurement for environmental, it will be replaced with the corresponding unit of measure for the specific LCIA indicators (kg CO₂ eq, m³, kg Cu eq, GJ, or others if different indicators are considered).</p> <p>The processes followed to retrieve the index is analogous to the one explained for the Ri.</p>
Ui	[Pt*W*m ³]	<p>Normalization index for the use phase. “Pt” is used as the unit of measurement for environmental, it will be replaced with the corresponding unit of measure for the specific LCIA indicators (kg CO₂ eq, m³, kg Cu eq, GJ, or others if different indicators are considered).</p> <p>A ratio of design/performance parameters multiplied by the total hours of use over the years considered in the study has been utilised. For the case of cooker hoods, this ratio es between the maximum air flow rate (Q) and the maximum power (P).</p>

Ei	[Pt*kg ⁻¹ *years ⁻¹]	<p>Normalization index for the EoL phase.</p> <p>“Pt” is used as the unit of measurement for environmental, it will be replaced with the corresponding unit of measure for the specific LCIA indicators (kg CO₂ eq, m³, kg Cu eq, GJ, or others if different indicators are considered).</p> <p>The Ei has been established based on the product’s weight (w) because it serves as an indicator of how End-of-Life processes are carried out and can be identify the adoption of closed-loop EoL strategies for the product.</p>
Ti	[Pt*m ³ *kg*km ⁻¹ *years ⁻¹]	<p>Normalization index for the transportation phase.</p> <p>“Pt” is used as the unit of measurement for environmental, it will be replaced with the corresponding unit of measure for the specific LCIA indicators (kg CO₂ eq, m³, kg Cu eq, GJ, or others if different indicators are considered).</p> <p>The ratio of distance (D) to volume (V) and weight (w) has been considered. Thus, assuming the travelled distance is the same, if the volume or weight of the product is greater, the result will be lower, and therefore, the index increases.</p>
Si	[Pt*kg*years ⁻¹]	<p>Normalization index for the maintenance phase.</p> <p>“Pt” is used as the unit of measurement for environmental, it will be replaced with the corresponding unit of measure for the specific LCIA indicators (kg CO₂ eq, m³, kg Cu eq, GJ, or others if different indicators are considered).</p> <p>Si refers solely to the production of a new spare part, the ratio of the spare part’s lifespan (ys) to the component’s weight (ws) has been considered. Thus, all other factors being equal in terms of spare part durability, the one with less weight will have a lower Si.</p>
Ei_RM	Depends on the environmental indicator (i.e., GWP, WCP, SOP, CED, or others considered by the designer)	Environmental impact for the raw material phase. Retrieved directly from SimaPro.
Ei_M	Depends on the environmental indicator (i.e., GWP, WCP, SOP, CED, or others considered by the designer)	Environmental impact for the manufacturing phase. Retrieved directly from SimaPro.
Ei_U	Depends on the environmental indicator (i.e., GWP, WCP, SOP, CED, or others considered by the designer)	Environmental impact for the use phase. Retrieved directly from SimaPro.
Ei_EoL	Depends on the environmental indicator (i.e., GWP, WCP, SOP, CED, or	Environmental impact for the EoL phase. Retrieved directly from SimaPro.

	others considered by the designer)	
Ei_T	Depends on the environmental indicator (i.e., GWP, WCP, SOP, CED, or others considered by the designer)	Environmental impact for the transport phase. Retrieved directly from SimaPro.
Ei_S	Depends on the environmental indicator (i.e., GWP, WCP, SOP, CED, or others considered by the designer)	Environmental impact for the maintenance phase. Retrieved directly from SimaPro.
w	kg	Product weight.
A	m ²	Total cooking surface area.
y	years	Duration of the product (lifespan).
P	W	Maximum power.
Q	m ³ /h	Maximum air flow rate.
h	h/year	Time of use per year considered.
Y	years	Timeframe considered in the scope of the study.
D	km	Distance for the transport phase.
V	m ³	Volume of the product during transportation.
ws	kg	Weight of the spare part component.
ys	years	Duration (lifespan) of the spare part.

After applying the different indices, the values in Table 48 are obtained.

Table 48. Results after the normalization process - Case study: Cooker Hood.

Normalized Environmental Indicator	Units for "Pt"	Ri [Pt*kg*m ⁻² *years ⁻¹]	Mi [Pt*kg*m ⁻² *years ⁻¹]	Ui [Pt*W*m ⁻³]	Ei [Pt*kg ⁻¹ *years ⁻¹]
GWP	kg CO ₂ eq	8.58E+02	2.69E+02	1.90E+00	7.42E-03
WCP	m ³	1.85E+01	1.30E+00	3.18E-02	3.14E-07
SOP	kg Cu eq	4.97E+01	5.78E+00	6.66E-03	1.92E-07
CED	MJ	1.41E+04	4.02E+03	4.03E+01	1.02E-03

Next, reference values must be established for each indicator. The purpose of this reference value is to enable a comparison of the product being analysed with the worst-performing product (within the same category) found in the market from an environmental perspective (as explained in the methodology). However, for this second case study, due to life cycle analyses conducted by the author on various range hoods, higher

impact results were obtained compared to the literature (Castorani, Rossi, Germani, Mandolini, & Vita, 2018). Therefore, these internal analyses have been used as a reference. Table 49 presents the normalized results that will be used as reference.

Table 49. Results after the normalization process - Reference Cooker Hood.

Normalized Environmental Indicator	Units for "Pt"	Ri [Pt*kg*m ⁻² *years ⁻¹]	Mi [Pt*kg*m ⁻² *years ⁻¹]	Ui [Pt*W*m ⁻³]	Ei [Pt*kg ⁻¹ *years ⁻¹]
GWP	kg CO ₂ eq	1.81E+03	2.24E+02	1.56E+00	2.00E-02
WCP	m ³	1.46E+01	8.73E-01	2.62E-02	1.14E-06
SOP	kg Cu eq	7.92E+01	2.13E+00	5.50E-03	6.61E-07
CED	MJ	2.69E+04	3.81E+03	3.31E+01	3.38E-03

Applying the rules established in Table 8, the dimensionless environmental impact value for the range hood can be obtained (see Table 50).

Table 50. Dimensionless environmental indicator for each phase of the life cycle - Case study: Cooker Hood.

Environmental indicator	Ri_A	Mi_A	Ui_A	Ei_A
GWP	0.58	0.00	0.00	0.70
WCP	0.00	0.00	0.00	0.81
SOP	0.41	0.00	0.00	0.79
CED	0.53	0.00	0.00	0.77

At this point, these results should be weighted based on the relative uncertainty of the sources, as shown in Table 6. In the case of the hood, the average uncertainty factor for each phase is 0.7, which means "Part of the data is not available or based on assumptions".

It is also necessary to define the weight that each phase will have when calculating each indicator. For this type of product (e.g., cooker hoods), the usage phase is the most important, and its results are critical in achieving sustainability throughout its entire lifespan (Castorani, Rossi, Germani, Mandolini, & Vita, 2018). It has been established that the weight of the Raw Material and Manufacturing phases is 2.5, for the Use phase is 3, and for the End-of-Life phase is 1. The results for the environmental indicators for all the lifecycle phases considered within the system boundaries are:

- $E_{GWP} = 0.17$,
- $E_{WCP} = 0.06$,
- $E_{SOP} = 0.14$,
- $E_{CED} = 0.16$.

Finally, the environmental index can be calculated using (6), resulting in $I_{Environmental} = 0.13$ in the analysed case. As can be seen, this critical result is mainly due to the manufacturing and usage phases, so eco-design actions will focus on them (e.g., improving engine efficiency, reducing processes with significant impacts in manufacturing, etc.). On the other hand, the fact that the results of the end-of-life phase are all greater than 0.5 is due to the long-lasting durability of this product, which allows components to remain in circulation for a longer period of time.

Economic Index

Because the product from the second case study will be sold in Italy, just like the first one (i.e., the oven), the same inflation rate of 3% and electricity price of 0.3115 €/kWh are assumed (Eurostat, 2023). The operational costs for this product are related to energy consumption during its lifetime to operate the blower and lights. The maintenance cost of 100 € has been calculated following the recommendations of the manufacturing company, including the cost of replacing some components in the 10th year (e.g., grease filters or LED lamps). The analysed hood's lifespan is greater than the one chosen as a reference (i.e., 15 years instead of 10), so a second reference hood with the same characteristics will need to be purchased (C_{repl}), which will have a certain residual value at the end of the study (V_{res}). The amortization coefficient to estimate the residual value is 12%, just like for the oven, as both are appliances and are assumed to undergo the same depreciation (Iraldo, Facheris, & Nucci, 2017).

Table 51. Cost data used in the LCC of the Cooker Hood. PV - Present value. NA - Not applicable.

Expenses [€]	Case study - Hood			Reference Hood		
	Total cost	Year	PV	Total cost	Year	PV
C_0	455.00	0	455.00	419.99	0	419.99
C_{use}	275.68	15	219.40	380.34	15	302.70
C_{maint}	100.00	10	74.41	N.A.	N.A.	N.A.
C_{repl}	N.A.	N.A.	N.A.	419.99	10	312.51
V_{res}	N.A.	N.A.	N.A.	167.996	15	107.83
PV of the total LCC	748.81			927.37		

After calculating the LCC adjusted to present value, it can be observed that the hood under analysis exhibits a lower economic impact over its entire lifespan, even though its initial cost was slightly higher. As for the first case study, this is attributed to the difference in energy efficiency between the two models (A vs. D), which results in the presented case study having a C_{use} significantly lower than the reference. The importance of product durability can also be appreciated, as having a longer lifespan than the reference product can prevent the need to purchase a second device, thus helping to reduce the total LCC. The next step is to calculate the dimensionless LCC value following the guidelines in Table 11. Since both the first and second case studies belong to the same product category (i.e., household appliances), the same cutoff value has been established for the LCC_{THR} (i.e., one-third of the $LCC_{Reference}$). After the application of the equation shown in Table 11, the dimensionless economic impact is calculated: $A_{Economic} = 0.58$. The average uncertainty for the source of information in the different phases of the LCC is $U_{Economic} = 0.7$ (see Table 6), resulting in a final economic index of $I_{Economic} = 0.40$. It can be observed that this value is close to 0.5, so with some simple eco-design actions, it can be improved.

Social Index

For the social index analysis, all the stakeholders that take part on the lifecycle of the product are considered. In this case study, production takes place in Italy, and the company does not hold any of the certifications described in the methodology (see Section 3.4.3). The uncertainty score is $U_{Social} = 0.9$ (see Table 6). Using (18), an $I_{Social} = 0.67$ for the manufacturing plant can be obtained (that is the same that the other case study). However, for this case as well, the supplier of electronic components is located in South Korea, resulting in a social index value of 0.50. Thus, when considering the worst-case scenario, the final index will be $I_{Social} = 0.50$ (i.e., not a critical aspect).

Circularity Score

Reliability Analysis

To calculate the *disassemblability index*, the same considerations as explained in the first case study have been taken into account, where the

weight of the parameters has been based on previous reference studies (Cordella, Alfieri, & Sanfelix Forner, 2019) (European Commission - Directorate-General for Environment; Ricardo-AEA Ltd, 2015) (Consumer reports, 2019), where W_{Param_1} , W_{Param_2} , and W_{Param_4} are set to 3 (the maximum value possible, representing their importance in this analysis), and W_{Param_3} is set to 1. For the weighting of the priority parts, the matrix presented in Figure 34 has been used again, which takes into account three different ranges for the failure rate and failure impact (i.e., high, medium, and low). For the failure rate, the ranges were defined in accordance with the market analysis of spare parts sales. While for the failure impact, were defined considering if the failure of a given component can totally compromise the product functionality (e.g., the blower) or only partially (e.g., the lamp). By making use of the matrix shown in Figure 34, the following weights were assigned to the PPs: $W_{PP_1} = 1.25$, $W_{PP_2} = 2.25$, $W_{PP_3} = 2.25$, $W_{PP_4} = 2.25$, $W_{PP_5} = 2.25$, $W_{PP_6} = 0.75$, $W_{PP_7} = 0.50$.

After establishing the weights for each parameter, the Product Index can be calculated, with the I_D global value being 0.61. As can be seen, it is higher than 0.5, so the reparability of the product is not a high-critical factor. In order to analysed more in detail the disassemblability results for each target component, Table 52 is presented. A colour map has been defined to identify critical and non-critical components. The “high-critical component” presents a disassembly index value lower than 0.5 (red colour), while “medium-critical component” presents a disassembly index value between 0.5 and 0.65 (yellow colour), and “non-critical component” presents a disassembly index above 0.65 (green colour). Following the proposed classification, two priority parts can be considered as “non-critical components”, the power cord and the motherboard. Only two PPs are “high-critical components” (i.e., user interface and grease filter), while all the others are “medium-critical components”. This can be explained by the low number of steps required to remove most of the components, and the use of common tools and reusable connectors for almost all the components.

Table 52. Disassemblability Index of priority parts [0-1] - Case study: Cooker Hood.

Priority Parts	I_D
Power cord	0.81
User Interface	0.40
Motherboard	0.74

Led driver	0.64
Blower	0.62
Lamps	0.63
Grease filter	0.40

For the *durability score*, the analysed product has a lifespan of 15 years (with a proper maintenance), which is the maximum found in the market for this type of hood. Through market analysis and discussions with different manufacturers, it has been established at 15 years with proper product maintenance. So, the durability score for the studied oven is:

$$S_D = \frac{L_{product}}{L_{max}} = 1$$

Using (27), the $S_{Reliability}$ can be calculated, but first, the weights for durability and repairability must be defined. There is no intention to prioritize one circularity factor over the other, so the weights will be $W_{Dur}=W_{Rep}=2$. However, it is important to note that this trade-off should be determined by the designer/engineer based on the characteristics and nature of their study, with complete freedom to modify them and conduct relevant sensitivity analyses.

$$S_{Reliability} = \frac{W_{Dur} \times S_D + W_{Rep} \times I_D}{W_{Dur} + W_{Rep}} = 0.81$$

Thanks to the great durability and the good repairability performances, the final result of the reliability of the oven studied is 0.81, significantly higher than 0.5, making it non-critical.

EoL Product Management

Finally, the EoL management indices must be calculated following the procedure outlined in Section 3.4.4. Table 53 displays the results for each of the established scenarios, with the design requirement set at a THR of 0.5 (after performing a cost-benefit analysis validated with the ROC method).

Table 53. EoL management indices per priority part – Case study: Cooker Hood.

Component	I _{Reuse}	I _{Rem}	I _{Rc}
Power cord	0.43	0.44	-4.22
User Interface	0.91	0.91	-1.65
Motherboard	0.92	0.92	-1.03

Led driver	0.87	0.88	-2.79
Blower	0.92	0.92	-4.88
Lamps	0.22	0.27	-68.74
Grease filters	0.57	0.57	-41.14

Applying the classification from Table 20, the final score for the I_{EoL} is 0.75, as not all the target components managed to exceed the THR in at least one category, but all of them present positive values in at least one category. The avoidance of non-reusable connectors and the good disassemblability of the product can be noticed in the good results of the reuse and remanufacture index, since the costs related to the selective disassembly operations are very low. The electronic components (e.g., user interface, motherboard) present very high reuse and remanufacture index, which is a very positive aspect, since they contain valuable materials. Finally, the recycling index is very low because almost all the components analysed have a very low weight for the value of recycled material to offset all recycling costs.

Circularity Score

After analysing the reliability and EoL management parameters, the circularity score (from 0 to 1) can be calculated: $A_{Circularity} = 0.78$. Considering that the uncertainty associated with the data acquisition is $U = 0.7$, the final score for the index is $I_{Circularity} = 0.54$.

Sustainability Index

Table 54 summarizes the scores and weights for each index considered in this case study. The overall sustainability score is $I_{Sustainable} = 0.37$, corresponding to a product class equal to F.

Table 54. Final scores for the sustainability indicators - Case study: Cooker Hood.

Indicator	Score [0-1]	Weight [1-3]
Environmental	0.13	3
Economic	0.40	3
Social	0.50	1
Circularity	0.54	3

The product label before the implementation of the eco-design actions is shown in Figure 40.

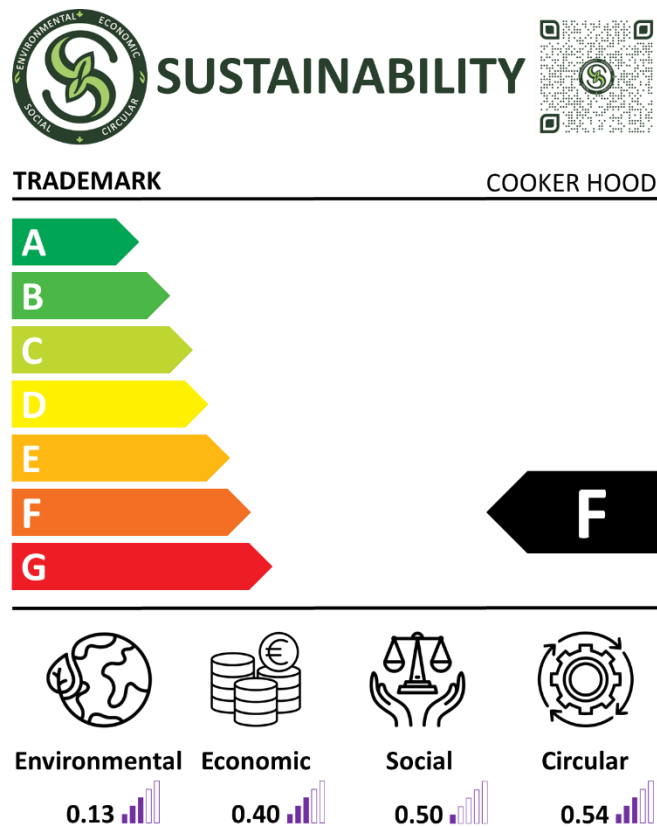


Figure 40. Sustainability label - Case study: Cooker Hood.

4.2.4. Phase IV: Implementation of Eco-Design methodologies

The sustainable class for the hood under analysis is F, lower than the limit established in the methodology as the minimum requirement (i.e., E). To improve it a detailed analysis will be required for those categories with a score below 0.5 (i.e., environmental, and economic). Following the methodology to obtain eco-design actions for the environmental impact, a detailed analysis of all the indicators should be conducted. It has been proven that, for all indicators, the manufacturing and usage phases are critical, so efforts should be focused on minimizing certain production processes with high environmental impacts (e.g., casting for aluminium) and improving the energy efficiency of the blower motor. This way, the total energy consumption throughout its lifespan is reduced, which has a significant impact, among other things, on the WCP due to Italy's energy grid mix. Table 55 summarizes the potential redesign actions, some of them are common to more than one parameter.

Table 55. Identification Eco-Design actions for the Environmental Index - Case study: Cooker Hood.

Parameter	Eco-Design action
E_{GWP}	<ul style="list-style-type: none"> To reduce the weight of the hood's structure a 5% since it is the component that impact the most (after the electronics). To reduce the weight of the packaging by 30%. To use renewable sources to power the manufacturing plant (avoiding the high impact of the Italian grid mix). The new energy consumption is reduced up to 50%. To inform the user about responsible practices to reduce the impact during the use phase (reduction of 5% of energy consumption). To improve the energy efficiency of the motor until it is the maximum available, reducing impacts during the use phase (A+++). To optimize the supply chain (assumption of 5% of impacts reduction)
E_{SOP}	<ul style="list-style-type: none"> To examine potential alternatives to traditional PCBs, assessing the feasibility of using plant-based biodegradable PCBs (Guna, et al., 2016) or Inkjet-printed PCBs (Wan, Kanth, Yang, Chen, & Zheng, 2015) (Sudheshwar, Malinverno, Hischier, Nowack, & Som, 2023), which significantly reduce carbon emissions during production. Or to promote the reused of some of the electronic components, avoiding the impacts of new material extraction and manufacturing. To reduce the amount of material that will be process through using environmentally impactful techniques, such as the casting for the aluminium (by 10% for the hood studied).
E_{WCP}	<ul style="list-style-type: none"> To promote water-saving practices during the manufacturing. To inform the user about responsible practices to reduce the impact during the use phase, since the WCP is penalised by the Italian grid mix. To improve the energy efficiency of the motor until it is the maximum available, reducing impacts during the use phase (A+++). To use renewable sources to power the manufacturing plant (avoiding the high impact of the Italian grid mix). The new energy consumption is reduced up to 50%.
E_{CED}	<ul style="list-style-type: none"> To improve the energy efficiency of the motor until it is the maximum available, reducing impacts during the use phase (A+++). To use renewable sources to power the manufacturing plant (avoiding the high impact of the Italian grid mix). The new energy consumption is reduced up to 50%. To promote maintenance to keep the maximum efficiency during the use phase, allowing the cooker hood to complete its expected life of 15 years. To inform the user about responsible practices to reduce the impact during the use phase (reduction of 5% of energy consumption).

To increase the energy efficiency of the engine, the option of replacing the current version (i.e., induction motor) with an improved brushless motor has been proposed. This change results in a reduction of 60% in energy consumption, achieving an annual energy consumption of 23.6 kWh. The

new environmental results after the implementation of the eco-design actions are:

- $E_{GWP}=0.57$,
- $E_{SOP}=0.20$,
- $E_{WCP}=0.62$,
- $E_{CED}=0.62$.

The new $I_{Environmental}$ is 0.50. The impact of this improvement results in a 23% increase in the sustainability index. After the environmental eco-design actions, the overall sustainability is still class F, but very close to the class E, which is the minimum level of sustainability accepted by the methodology. Some of the actions taken for the improvement of the environmental indicator also affect the economic one. For example, the reduction of the amount of raw material used for the production or the shift to renewable energy supply for the manufacturing plant. All those actions will reduce the initial cost of the appliance (C_0), which was one of the criticalities highlighted after the application of the methodology presented in Table 24 (the reduction achieved is 3%). This improvement, along with the increase in energy efficiency that reduces C_{Use} by 61%, leads to the attainment of $I_{Economic} = 0.70$.

After carrying out the eco-design actions for the indices below 0.5, the overall sustainability index reaches $I_{Sustainability} = 0.57$ (product class equal to E). However, some of the aspects that have been modified for these areas also affect circularity (e.g., end of life management). For instance, when redesigning the more efficient engine, efforts have been made to address the disassembly criticality (following the methodology of Table 26). To further enhance the product sustainability, a detailed circularity analysis has been conducted. To address the analysis of the disassemblability index, first of all it is needed to define the THR present in Table 26. For parameter P1, if D_i is greater than 0.55 times D_{ref} , it is considered a criticality. This THR of 0.55 was set using the cost-benefit analysis validated with the ROC method for the considered mechatronic product (i.e., cooker hoods). The values of TPR and FPR are 1 and 0.2 respectively. Finally, for parameter P4 the approach is similar to the one followed for parameter P1, a criticality is identified when T_i is greater than 0.7 times T_{ref} . The THR of 0.7 was again set using the cost-benefit analysis validated with the ROC method. In this case the values of TPR and FPR are 1 and 0 respectively (the ideal situation). Once the THR is

established, the mathematical rules defined in the methodology can be evaluated. Table 56 displays the identified criticalities and their eco-design actions for some of the priority parts of the cooker hood. Through reverse engineering of the index analysis, areas for improvement are identified.

Table 56. Eco-design guidelines for some target components of the cooker hood.

Component	Parameter AS-IS	Mathematical rule	Eco-design actions
Blower	$S_3 = 0.50$	$S_3 < 1$	To change the not reusable fastener (i.e., cable tie). To avoid extra connections that increase the T_{discon} , simplifying the overall disassemblability of the component (e.g., the extra ground connection).
	$T_{position} = 16.56 \text{ s}$	$\frac{T_{position}}{T_i} = 0.34 > 0.20$	
	$T_{discon} = 13.68 \text{ s}$	$\frac{T_{discon}}{T_i} = 0.28 > 0.20$	
User Interface	$D_i = 13$ $D_{ref} = 13$ $T_i = 62.28 \text{ s}$ $T_{ref} = 62.28 \text{ s}$ $T_{position} = 27.36 \text{ s}$ $T_{discon} = 21.24 \text{ s}$	$\frac{D_i}{D_{ref}} = 1 \geq 0.55$ $\frac{T_i}{T_{ref}} = 1 \geq 0.7$ $\frac{T_{position}}{T_i} = 0.44 > 0.20$ $\frac{T_{discon}}{T_i} = 0.34 > 0.20$	To redesign the front panel in a way that it can be removed without the need to disassemble additional components (e.g., grease filters). This action would reduce the D_i as well as T_{discon} and $T_{position}$ (and consequently the overall T_i).
Lamps	$D_i = 19$ $D_{ref} = 27$ $T_{position} = 31.68 \text{ s}$ $T_{discon} = 22.68 \text{ s}$	$\frac{D_i}{D_{ref}} = 0.7 > 0.55$ $\frac{T_{position}}{T_i} = 0.47 > 0.20$ $\frac{T_{discon}}{T_i} = 0.33 > 0.20$	Attempt to use an alternative fastening method that allows the disassembly of the lamps without removing extra components (e.g., grease filters, metal panels), this new design should allow the removal from the external part, reducing the number of steps and the associate time.

Figure 41 presents an example of criticality referring the target component “Blower”, where a removable but not reusable (FNR) fastener is used (see Figure 41A). During the assessment of the disassemblability index, the score associated with the parameter P2 is 0.5, not adhering the suggested equation proposed for the fastener parameter ($S_{2,i} < 1$). On Figure 41B, a different type of cable tie that can be removed and reused is proposed, increasing the score of P2 from 0.5 to 1. In addition, to reduce the disconnection time, the ground connection of the blower has been changed, in order to avoid unnecessary

steps to be able to remove it (e.g., rotation of the hood, removal of metal panel, etc.).

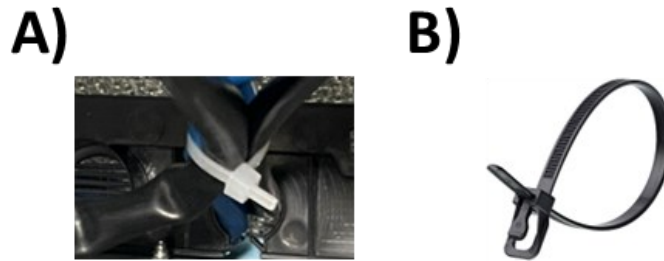


Figure 41. Example of criticality and solution for the PP “Blower”. A) PP that uses FNR fastener, and B) PP that uses FR connectors.

Another example of criticality, in this case for the PP “Lamps” (see Figure 42), in order to disassemble them, the removal of many other components is needed (e.g., three grease filters, some metal panels, etc.). The proposed solution suggests enabling access to the lamp’s electrical connections without the need to remove additional components. This can be achieved by using a bayonet system in which, upon turning the lamp, it disengages from the panel, allowing access for cable disconnection. This way, the total number of steps is reduced from 19 to 8.

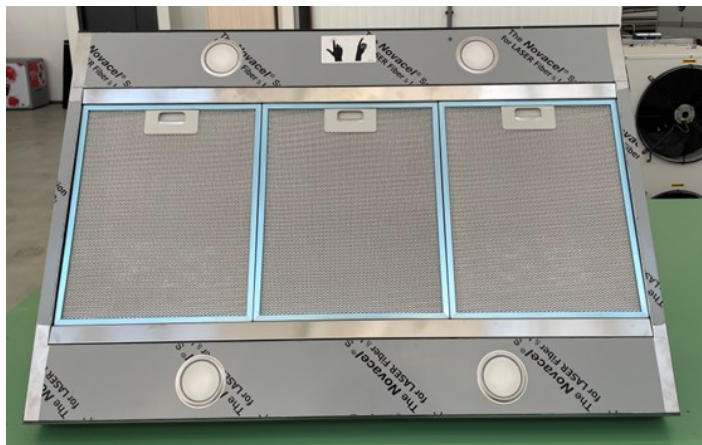


Figure 42. Example of the PP “Lamps” for the cooker hood.

Table 57 presents the new results of the disassemblability index after the modifications. It can be seen how the methodology proposed is effective in order to improve the reparability of target components, and the new results are not critical.

Table 57. Disassemblability Index of some priority parts [0-1] after eco-design – Case study: Cooker Hood.

Priority Parts	I _D Before	I _D After
User Interface	0.40	0.66
Blower	0.62	0.81
Lamps	0.63	0.84

The changes implemented to enhance repairability also help reduce the costs associated with selective disassembly at the end of the product's life. In this way, it also helps improve some of the end-of-life management indices (i.e., reuse, remanufacturing), ensuring that now all the priority parts have a value greater than 0.5 in at least one category, thereby achieving a global index of I_{EoL} equal to 1 (see Table 20).

After all the eco-design presented, the improved sustainability indicators are shown in Table 58, being the sustainability index for the cooker hood $I_{Sustainability} = 0.61$, achieving the class D, 39% higher than before the application of the eco-design methodology.

Table 58. Final scores for the sustainability indicators before and after eco-design actions – Case study: Cooker Hood.

Indicator	Weight [1-3]	Score Before [0-1]	Score After [0-1]
Environmental	3	0.13	0.50
Economic	3	0.40	0.70
Social	1	0.50	0.50
Circularity	3	0.54	0.65

To highlight the importance of data reliability, an analysis has been conducted to assess how sustainability index values would change after the implementation of eco-design actions based on the variation of U (i.e., uncertainty weight). To do this, the uncertainty value for each index has been varied while keeping the other parameters constant (i.e., One-Factor-At-Time method) (Formentini, et al., 2021). The new predicted uncertainty value assumes that the data obtained is reliable, and the ideal option would be to incorporate the DPP as a source of information. Table 59 displays these results, and it can be observed that by improving the reliability of economic data, a 9% increase in the sustainability index is achieved. Similar results are obtained when varying the circularity factor. Conversely, if all

improvements were applied simultaneously, the sustainability index would be 0.74, representing a 18% increase and a shift from class D to class C.

Table 59. Variation of the sustainability index based on the uncertainty level (one-factor-at-time) – Case study: Cooker Hood.

Indicator	Current values after eco-design actions			New values with more reliable information		
	U	Indices	Sustainability	U	Indices	Sustainability
Environmental	0.7	I _{Environmental} =0.50	I _{Sustainability} =0.61 Class D	0.9	I _{Environmental} =0.56	I _{Sustainability} =0.62 Class D
Economic	0.7	I _{Economic} =0.70	I _{Sustainability} =0.61 Class D	0.9	I _{Economic} =0.90	I _{Sustainability} =0.67 Class D
Social	0.9	I _{Social} =0.50	I _{Sustainability} =0.61 Class D	0.9	I _{Social} =0.50	I _{Sustainability} =0.61 Class D
Circularity	0.7	I _{Circularity} =0.65	I _{Sustainability} =0.61 Class D	0.9	I _{Circularity} =0.84	I _{Sustainability} =0.66 Class D

4.2.5. Phase V: Final report production

Figure 43 shows the final label for the redesign product. For confidentiality reasons, the label displayed in this research work does not include the product brand, and the QR code does not direct you to the specific page of the analysed model, but rather to the range hoods' generic database.

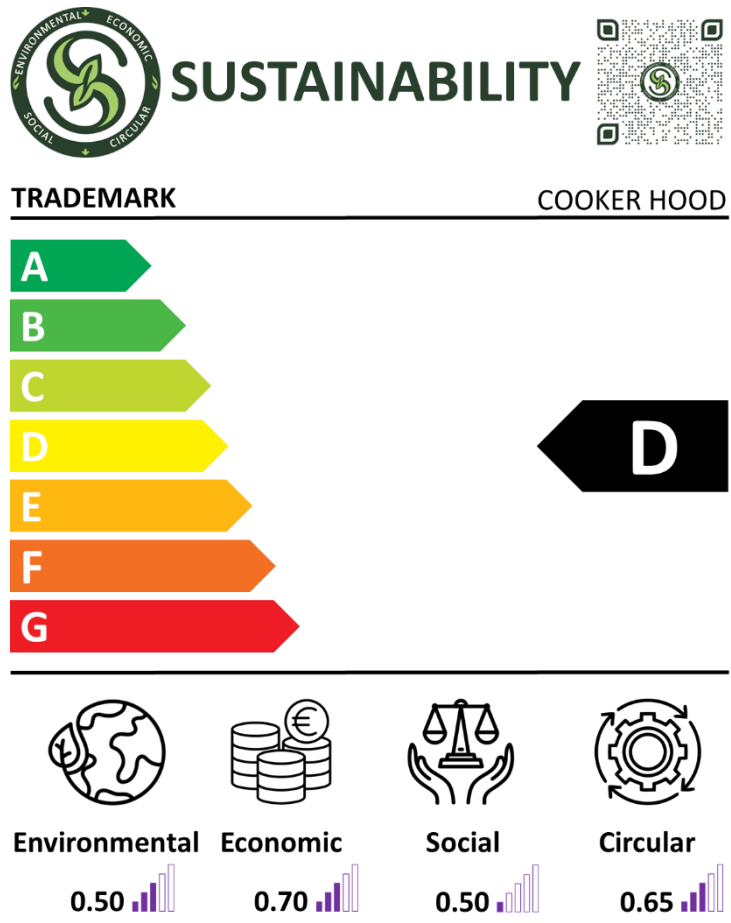


Figure 43. Sustainability label after eco-design actions - Case study: Cooker Hood.

5. FUTURE WORKS FOR METHODOLOGY VALIDATION

This chapter delves into future lines of work aimed at validating and enhancing the applicability of the proposed methodology presented in the thesis. Validation is a critical step to ensure that research outcomes are usable in practical scenarios. Four lines of validation are envisioned: (i) product, (ii) companies, (iii) stakeholders, and (iv) standardization bodies.

- **Product validation:** The previous section detailed the validation of the methodology through an in-depth analysis of two products – an electric oven and a cooker hood. As future actions, the proposal suggests expanding the range of analysed products as part of ongoing product validation. Including more categories will allow for evaluating the robustness and generalizability of the methodology across diverse mechatronic design contexts.
- **Companies validation:** Collaborating with practitioners involved in the design and production of mechatronic products will provide valuable insights into the methodology's applicability in industrial settings. The next steps should focus on establishing collaborations with companies in the household appliances sector (e.g., Electrolux, BSH Hausgeräte, LG Electronics, Miele, Arçelik, etc.), as both case studies belong to this category. This facilitates the implementation of the methodology within the company (through a series of workshops explaining how it works in detail). Once it begins to be used within engineers and designers in real projects, all feedback must be collected, particularly highlighting aspects that have posed greater difficulty or whose implementation may be open to interpretation. This allows for the method to be improved and optimized based on practical needs and specific industry challenges, with the next step being its implementation and assessment in a company that produces a different type of mechatronic products. This will help confirm that the methodology is transferable and adaptable to the requirements of each sector.

- **Stakeholders validation:** Involving key stakeholders, including end-users and environmental organizations, will enrich the understanding of sustainability from diverse perspectives. Future actions should involve organizing engagement sessions with relevant stakeholders (e.g., IFIXIT, Ellen MacArthur Foundation, or the European Environmental Bureau) to gather insights on the methodology, identify areas for improvement, and ensure alignment with the expectations and needs of various interested parties. These sessions (e.g., focus groups, surveys, webinars, and review panels) will also help to identify and address concerns raised by stakeholders, ensuring that the methodology reflects a broad spectrum of interests, which is crucial for assessing sustainability.
- **Standardization bodies validation:** Standardization is crucial for widespread adoption of the methodology in the industry. It is critical to explore the possibility of collaborating with standardization bodies to assess the methodology's applicability at a regulatory level. The final step is to seek recognition and acceptance of the methodology as a standard tool in sustainable mechatronic product design. To achieve this, the methodology will be proposed to the CEN-CENELEC and the Environmental Coalition on Standards, initiating a process to test and validate the index proposed among different product categories. Seeking guidance on the types of tests and sensitivity analyses that are relevant and acceptable for demonstrating compliance with standards.

This chapter has outlined a plan for future validation of the proposed methodology. Acknowledging the importance of feedback from practitioners and policy researchers, it emphasizes the need to refine the methodology for practical application in industrial and policy contexts. Inclusion of more products, collaboration with companies, stakeholder engagement, and exploration of standardization are presented as crucial steps toward continuous improvement and widespread adoption of the design for sustainability methodology in the mechatronic domain.

6. CONCLUSIONS

The awareness of environmental and social responsibility, as well as the demand for sustainable products, has increased in recent years. Consumers are becoming more engaged with the planet, which, in turn, leads to a greater level of responsibility for brands to meet customer needs. The younger generations are the most dedicated to ecology and the environment, with 61% of millennials willing to pay more for sustainable and eco-friendly products (Compromiso RSE, 2020). Movements advocating for the circular economy, such as Fridays for Future (Fridays for future, n.d.), Zero Waste Europe (Zero Waste Europe, n.d.), or Right to Repair (Right to Repair, n.d.), whose goal is to eliminate obstacles hindering the repair of products, enabling them to have a longer lifespan, have empowered consumers. This growing demand for sustainable products from consumers and the European political community has driven the need to address sustainability and circularity in the design of mechatronic products. A comprehensive approach is essential to address environmental, economic, and social aspects throughout the product's lifecycle.

The following describes how the methodology proposed in this work has effectively addressed the research questions posed in Section 2.5:

- **Answer to RQ1:** The research introduces a robust eco-design methodology that effectively considers short-term and long-term impacts across a mechatronic product's lifecycle. By integrating the three pillars of sustainability and circularity principles, this methodology equips designers with a five-phase approach: (i) Product classification, (ii) Life Cycle Engineering, (iii) Sustainability Index Assessment, (iv) Implementation of Eco-Design Methodologies, and (v) Final report production. This method enables data collection and analysis to guide eco-design actions, enhancing both sustainability and circularity aspects in mechatronic product development.
- **Answer to RQ2:** The methodology proposes a multi-dimensional approach for evaluating sustainability in mechatronic products. The integration of eco-design rules tailored to each sustainability indicator results in measurable

enhancements across these areas. The effectiveness of this method can be seen in the two case studies, belonging to the group family household appliances. Results have indicated that its application generate significant improvements in the overall sustainability of mechatronic products. The first case study was conducted on an electric oven, and the results show that the most critical indicator was the social one due to the strict evaluation standards for this criterion in the methodology, followed by the environmental and economic indicators. Through the application of the methodology, total product sustainability is increased by 32%. In particular, the social issue is resolved by promoting the attainment of accreditation that ensures the rights and freedoms of workers are respected throughout the supply chain. Furthermore, the environmental indicator is improved by approximately 28%, the economic indicator by 19 %, and the circular indicator by 9 %. On the other hand, the second case study focused on a cooker hood. The most unfavourable aspects for this product were the environmental and economic impacts. Following the methodology, efforts related to the environmental impact were focused on improving the product's efficiency during its use, which was the main cause of the poor result. By replacing the motor with a new one, annual consumption has been reduced by 60%. This, along with the optimization of resources during manufacturing and other eco-design actions retrieve from the methodology, has led to a 39% increase in the sustainability index. This demonstrates that the implementation of these eco-design actions outlined in the guidelines created can have a significant impact on the sustainability of mechatronic products.

- **Answer to RQ3:** The method effectively answers to this question. A repository of 33 eco-design guidelines have been retrieved for the environmental pillar, 16 for the economic pillar, 15 for the social pillar, and 35 for the circular aspect. Moreover, by adopting the developed rules the two products analysed in this work have improved their sustainability rating from class F to D.
- **Answer to RQ4:** The proposed sustainability label aims to empower consumers with transparent and accessible information about a product's impacts. This label categorizes the product on a

scale from A to G (best to worst, respectively), and it also presents the results of the four indicators considered for assessing sustainability (i.e., environmental, economic, social, and circular). This research advances the development of a clear and understandable sustainability label that allows consumers to make well-informed decisions based on a product's merits and shortcomings across various sustainability dimensions.

While the methodology shows promise in identifying key areas for redesign, there remain certain unresolved issues, such as the absence of a standard for defining some reference values used in the research work (e.g., D_{ref} , T_{ref}) or lack of a standardized list of priority parts for each product category (Boix Rodríguez, Gabriel, Gaha, & Favi, 2023). Based on the conclusions drawn from this study, several potential areas for future research emerge. The first one involves a detailed examination of the DPP to attempt its integration into the proposed methodology, ensuring that the source of data for each product life phase is certified. The importance of data reliability throughout the sustainability evaluation process is also emphasized during the methodology proposed, as it can significantly impact the final results of various indices and thus influence the product's sustainability classification. In the case of the cooker hood, it has been demonstrated that improving the reliability of the data used for the economic indicator can lead to a 9% increase in the sustainability index. Furthermore, the DPP can also help determine the product's end-of-life condition, which, as explained by Formentini et al., is a crucial factor in calculating the disassembly effort (Formentini & Ramanujan, 2023).

Furthermore, leveraging Machine Learning (ML) to streamline the LCI phase can be studied, since it is a time-consuming stage that is susceptible to errors. ML can play a vital role in automating data gathering and classification from diverse sources, encompassing tasks like data cleansing and the generation of inventory data for scenario assessments. Additionally, ML can find application in forecasting system output flows and performance, given the extensive data it can analyse. The establishment of eco-design guidelines supported by suitable ontologies will guide ML algorithms towards enhancing the optimization of products and systems (Algren, Fisher, & Landis, 2021).

Exploring the potential application of the suggested methodology to different product categories would also be a valuable step, facilitating a more comprehensive grasp of the challenges related to sustainability. To evaluate the resilience of this index, a more thorough sensitivity analysis can be conducted.

After full validation of these indices, the subsequent phase will involve the implementation of the suggested method into a software program capable of automatically computing the methodology by extracting information straight from 3D models and corporate repositories. This action will undoubtedly improve the practicality of the proposed approach and facilitate its adoption during the early design phases, streamlining the analysis process and making it more automated.

BIBLIOGRAPHY

- Abdel-Salam, A. H., & Simonson, C. J. (2014). Annual evaluation of energy, environmental and economic performances of a membrane liquid desiccant air conditioning system with/without ERV. *Applied Energy*, 116, 134-148. doi:10.1016/j.apenergy.2013.11.047
- Abramovici, M., Quezada, A., & Schindler, T. (2014). Methodical approach for rough energy assessment and compliance checking of energy-related product design options. *Procedia CIRP*, 21, 421-426.
- Abusoglu, A., & Sedeeq, M. S. (2013). Comparative exergoenvironmental analysis and assessment of various residential heating systems. *Energy and Buildings*, 62, 268-277. doi:10.1016/j.enbuild.2013.03.024
- Abuzied, H., Senbel, H., Awad, M., & Abbas, A. (2020). A review of advances in design for disassembly with active disassembly applications. *Engineering Science and Technology, an International Journal*, 23, 618-624. doi:10.1016/j.jestch.2019.07.003
- Adibi, N., Lafhaj, Z., Yehya, M., & Payet, J. (2017). Global Resource Indicator for life cycle impact assessment: Applied in wind turbine case study. *Journal of Cleaner Production*, 165, 1517-1528. doi:10.1016/j.jclepro.2017.07.226
- Albin, S. L., & Crefeld III, P. J. (1994). Getting started: Concurrent engineering for a medium-sized manufacturer. *Journal of Manufacturing Systems*, 13, 48-58. doi:10.1016/0278-6125(94)90017-5
- Algren, M., Fisher, W., & Landis, A. E. (2021). Machine learning in life cycle assessment. *Data Science Applied to Sustainability Analysis*, 167-190.
- Allais, R., & Gobert, J. (2016). A multidisciplinary method for sustainability assessment of PSS: Challenges and developments. *CIRP journal of manufacturing science and technology*, 15, 56-64. doi:10.1016/j.cirpj.2016.04.007
- Allione, C., De Giorgi, C., Lerma, B., & Petrucci, L. (2012). From ecodesign products guidelines to materials guidelines for a sustainable product.

Qualitative and quantitative multicriteria environmental profile of a material. *Energy*, 39(1), 90-99.

Apple. (n.d.). *Certified Refurbished*. Retrieved 2023, from <https://www.apple.com/shop/refurbished>

Arain, A. L., Neitzel, R. L., Nambunmee, K., Hischer, R., Jindaphong, S., Austin-Breneman, J., & Jolliet, O. (2022). Material flow, economic and environmental life cycle performances of informal electronic waste recycling in a Thai community. *Resources, Conservation and Recycling*, 180, 106129. doi:10.1016/j.resconrec.2021.106129

Arcos, B. P., Bakker, C., Flipsen, B., & Balkenende, R. (2020). Practices of fault diagnosis in household appliances: Insights for design. *Journal of Cleaner Production*, 265, 121812.

Austrian Standards. (2014). *ONR 192102: Label of excellence for durable, repair-friendly designed electrical and electronic appliances*.

Bartolozzi, I., Rizzi, F., & Frey, M. (2017). Are district heating systems and renewable energy sources always an environmental win-win solution? A life cycle assessment case study in Tuscany, Italy. *Renewable and Sustainable Energy Reviews*, 80, 408-420. doi:10.1016/j.rser.2017.05.231

Baumann, H., & Tillman, A. M. (2004). *The hitch Hiker's guide to LCA: An orientation in life cycle assessment methodology and application*. Lund: Studentlitteratur.

Beemsterboer, S., Baumann, H., & Wallbaum, H. (2020). Ways to get work done: a review and systematisation of simplification practices in the LCA literature. *The International Journal of Life Cycle Assessment*, 25, 2154-2168. doi:10.1007/s11367-020-01821-w

Benabdellah, A. C., Bouhaddou, I., Benghabrit, A., & Benghabrit, O. (2019). A systematic review of design for X techniques from 1980 to 2018: concepts, applications, and perspectives. *The International Journal of Advanced Manufacturing Technology*, 102, 3473-3502. doi:10.1007/s00170-019-03418-6

- Beuth publishing DIN. (2014). *ONR 192102:2014-10-01 - Label of excellence for durable, repair-friendly designed electrical and electronic appliances*. Berlin.
- Bevilacqua, M., Caresana, F., Comodi, G., & Venella, P. (2010). Life cycle assessment of a domestic cooker hood. *Journal of Cleaner Production*, 18(18), 1822-1832. doi:10.1016/j.jclepro.2010.08.001
- Bishop, R. H. (2018). *The Mechatronics Handbook* (Vol. 2). CRC press.
- Bocken, N. M., De Pauw, I., Bakker, C., & Van Der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of industrial and production engineering*, 33(5), 308-320.
- Bogue, R. (2007). Design for disassembly: a critical twenty-first century discipline. *Assembly Automation*, 27, 285-289. doi:10.1108/01445150710827069
- Boix Rodríguez, N., & Favi, C. (2022). Disassembly Analysis of Gas Cooktops: Towards Eco-Design Rules for Product Repairability. *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, 86250, V005T05A017. doi:10.1115/DETC2022-89860
- Boix Rodríguez, N., & Favi, C. (2023a). De-manufacturing Analysis for Product Repairability and Serviceability in Cooking Systems. *Proceedings of the Changeable, Agile, Reconfigurable and Virtual Production Conference and the World Mass Customization & Personalization Conference*, 452-460. doi:10.1007/978-3-031-34821-1_49
- Boix Rodríguez, N., & Favi, C. (2023b). Disassembly and repairability of mechatronic products: insight for engineering design. [*Manuscript submitted for publication to Journal of Mechanical Design*].
- Boix Rodríguez, N., Gabriel, C., Gaha, R., & Favi, C. (2023). Analysis of disassembly parameters in repairability scores: limitations for engineering design and suggestions for improvement. *Procedia CIRP*, 116, 738-743. doi:10.1016/j.procir.2023.02.124
- Boix Rodríguez, N., Rossi, M., Cappelletti, F., & Favi, C. (2023). Engineering eco-design of heat exchangers in domestic heating systems using life

cycle assessment methodology. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, 1-23. doi:10.1007/s12008-023-01301-z

Bonvoisin, J., Halstenberg, F., Buchert, T., & Stark, R. (2016). A systematic literature review on modular product design. *Journal of Engineering Design*, 27(7), 488-514.

Boothroyd, G., Dewhurst, P., & Knight, W. A. (2011). *Product Design for Manufacture and Assembly* (3 ed.). CRC Press - Taylor & Francis Group.

Bovea, M. D., & Pérez-Belis, V. (2012). A taxonomy of ecodesign tools for integrating environmental requirements into the product design process. *Journal of Cleaner Production*, 20(1), 61-71. doi:10.1016/j.jclepro.2011.07.012

Bovea, M. D., & Pérez-Belis, V. (2018). Identifying design guidelines to meet the circular economy principles: A case study on electric and electronic equipment. *Journal of Environmental Management*, 228, 483-494. doi:10.1016/j.jenvman.2018.08.014

Bracquené, E., Brusselaers, J., Dams, Y., Peeters, J., De Schepper, K., Duflou, J., & Dewulf, W. (2018). *Repairability criteria for energy related products: Study in the BeNeLux context to evaluate the options to extend the product life time - Final report.*

Bracquené, E., Martinez, M. G., Wagner, E., Wagner, F., Boudewijn, A., Peeters, J., & Duflou, J. (2021). Quantifying the environmental impact of clustering strategies in waste management: A case study for plastic recycling from large household appliances. *Waste Management*, 126, 497-507. doi:10.1016/j.wasman.2021.03.039

Bracquené, E., Peeters, J. R., Alfieri, F., Sanfélix, J., Duflou, J. R., Dewulf, W., & Cordella, M. (2021). Analysis of evaluation systems for product repairability: A case study for washing machines. *Journal of Cleaner Production*, 281, 125122. doi:https://doi.org/10.1016/j.jclepro.2020.125122

- Bracquene, E., Peeters, J. R., Burez, J., De Schepper, K., Duflou, J. R., & Dewulf, W. (2019). Repairability evaluation for energy related products. *Procedia CIRP*, 80, 536-541. doi:<https://doi.org/10.1016/j.procir.2019.01.069>
- Bradley, D., & Russell, D. W. (2010). *Mechatronics in Action - Case Studies in Mechatronics - Applications and Education*. Springer. doi:10.1007/978-1-84996-080-9
- Brambila Macias, S. A., & Sakao, T. (2021). Effective ecodesign implementation with the support of a lifecycle engineer. *Journal of Cleaner Production*, 279, 123520. doi:10.1016/j.jclepro.2020.123520
- Brezet, H., & Van Hemel, C. (n.d.). *Ecodesign: a Promising Approach to Sustainable Production and Consumption*. Paris: Edited by UNEP.
- British Standards Document. (2009). *BS 8887-2:2009 Design for manufacture, assembly, disassembly and end-of-life processing (MADE). Terms and definitions*. doi:10.3403/30182997U
- Camera di Commercio Reggio Emilia. (2023, 08 07). *Tasso d'inflazione medio annuo calcolato dall'ISTAT*. Retrieved 2023, from <https://www.re.camcom.gov.it/promuovere-limpresa-e-il-territorio/informazione-economica-e-statistica/indici-istat/tasso-dinflazione-medio-annuo-calcolato-dallistat>
- Cappelli, F., Delogu, M., & Pierini, M. (2006). Integration of LCA and EcoDesign guideline in a virtual cad framework. *Proceedings of LCE*, 185-188.
- Castorani, V., Rossi, M., Germani, M., Mandolini, M., & Vita, A. (2018). Life cycle assessment of home smart objects: kitchen hood cases. *Procedia CIRP*, 69, 499-504. doi:10.1016/j.procir.2017.11.113
- Cayzer, S., Griffiths, P., & Beghetto, V. (2017). Design of indicators for measuring product performance in the circular economy. *International Journal of Sustainable Engineering*, 10(4-5), 289-298. doi:10.1080/19397038.2017.1333543

- CEN/CENELEC. (2014). *SIST EN 62542:2014 - Environmental standardization for electrical and electronic products and systems - Standardization of environmental aspects - Glossary of terms.*
- CEN/CENELEC. (2020a). *SIST EN 15181:2017+A1:2020 - Measuring method of the energy consumption of gas fired ovens.*
- CEN/CENELEC. (2020b). *SIST EN 45552:2020 - General method for the assessment of the durability of energy-related products.*
- CEN/CENELEC. (2021). *SIST EN 203-2-1:2022 - Gas heated catering equipment - Part 2-1: Specific requirements - Open burners and wok burners.*
- Center for Global Workers' Rights. (2023). *Labour Rights Indicators.* Retrieved 2023, from <http://labour-rights-indicators.la.psu.edu/>
- Cespi, D., Passarini, F., Ciacci, L., Vassura, I., Castellani, V., Collina, E., . . . Morselli, L. (2014). Heating systems LCA: Comparison of biomass-based appliances. *The International Journal of Life Cycle Assessment, 19*, 88-99. doi:10.1007/s11367-013-0611-3
- chemsec. (n.d.). *SIN LIST.* Retrieved 2023, from <https://sinlist.chemsec.org/>
- Chen, R. W., Navin-Chandra, D., & Print, F. B. (1994). A cost-benefit analysis model of product design for recyclability and its application. *IEEE Transactions on Components, Packaging, and Manufacturing Technology: Part A, 17*(4), 502-507.
- Chen, X., & Lee, J. (2021). The identification and selection of good quality data using pedigree matrix. *Sustainable Design and Manufacturing 2020: Proceedings of the 7th International Conference on Sustainable Design and Manufacturing (KES-SDM 2020)*, 13-25. doi:https://doi.org/10.1007/978-981-15-8131-1_2
- Chocontá Bernal, D., Muñoz, E., Manente, G., Sciacovelli, A., Ameli, H., & Gallego-Schmid, A. (2021). Environmental assessment of latent heat thermal energy storage technology system with phase change material for domestic heating applications. *Sustainability, 13*(20), 11265. doi:10.3390/su132011265

- Ciroth, A., Muller, S., Weidema, B., & Lesage, P. (2016). Empirically based uncertainty factors for the pedigree matrix in ecoinvent. *The International Journal of Life Cycle Assessment*, 21, 1338-1348. doi:<https://doi.org/10.1007/s11367-013-0670-5>
- Classen, S. (2021, May 24). *Core Sustainability: Triple Bottom Line – Equity*. Retrieved 2023, from <https://cascadiaupdates.wordpress.com/2021/05/24/core-sustainability-triple-bottom-line-equity/>
- Compromiso RSE. (2020, 02 17). *El 61% de los millennials, dispuestos a pagar más por productos sostenibles y ecológicos*. Retrieved 2023, from <https://www.compromisorse.com/rse/2020/02/17/el-61-de-los-millennials-dispuestos-a-pagar-mas-por-productos-sostenibles-y-ecologicos/>
- Cong, L., Zhao, F., & Sutherland, J. W. (2019). A design method to improve end-of-use product value recovery for circular economy. *Journal of Mechanical Design*, 141(4), 044502. doi:10.1115/1.4041574
- Consumer reports. (2019, 06 20). *Most Common Appliance Problems and Repairs*. Retrieved 2023, from <https://www.consumerreports.org/appliances/most-common-appliance-problems-and-repairs-a5550122416/>
- Cordella, M., Alfieri, F., & Sanfelix Forner, J. V. (2019). *Analysis and development of a scoring system for repair and upgrade of products*. JRC Technical Report. Luxembourg: Publications Office of the European Union. doi:10.2760/725068
- Cordella, M., Sanfelix, J., & Alfieri, F. (2018). Development of an Approach for Assessing the Reparability and Upgradability of Energy-related Products. *Procedia Cirp*, 69, 888-892.
- Cradle to Cradle Products Innovation Institute. (2016). *Cradle to Cradle Certified - Product Standard - Version 3.1*. Retrieved from https://s3.amazonaws.com/c2c-website/resources/certification/standard/C2CCertified_ProductStandard_V3.1_160107_final.pdf

- Cullen, J. M., & Allwood, J. M. (2009). The role of washing machines in life cycle assessment studies the dangers of using lca for prioritization. *Journal of Industrial Ecology*, 13(1), 27-37. doi:10.1111/j.1530-9290.2009.00107.x
- Dahlstrøm, O., Sørnes, K., Eriksen, S. T., & Hertwich, E. G. (2012). Life cycle assessment of a single-family residence built to either conventional- or passive house standard. *Energy and buildings*, 54, 470-479. doi:10.1016/j.enbuild.2012.07.029
- Dangal, S., Faludi, J., & Balkenende, R. (2022). Design Aspects in Repairability Scoring Systems: Comparing Their Objectivity and Completeness. *Sustainability*, 14(14), 8634. doi:10.3390/su14148634
- Dangal, S., van den Berge, R., Pozo Arcos, B., Faludi, J., & Balkenende, R. (2021). Perceived capabilities and barriers for do-it-yourself repair. *Proceedings of the 4th PLATE 2021 Conference, Virtual*, 26-28.
- Das, S. K., Yedlarajiah, P., & Narendra, R. (2000). An approach for estimating the end-of-life product disassembly effort and cost. *International journal of production research*, 38(3), 657-673. doi:10.1080/002075400189356
- De Felice, F., Elia, V., Gnoni, M. G., & Petrillo, A. (2014). Comparing environmental product footprint for electronic and electric equipment: a multi-criteria approach. *International Journal of Sustainable Engineering*, 7(4), 360-373. doi:10.1080/19397038.2013.865811
- De Pascale, A., Arbolino, R., Szopik-Depczyńska, K., Limosani, M., & Ioppolo, G. (2021). A systematic review for measuring circular economy: The 61 indicators. *Journal of cleaner production*, 281, 124942. doi:doi.org/10.1016/j.jclepro.2020.124942
- Dekoninck, E. A., Domingo, L., O'Hare, J. A., Pigosso, D. C., Reyes, T., & Troussier, N. (2016). Defining the challenges for ecodesign implementation in companies: Development and consolidation of a framework. *Journal of Cleaner Production*, 135, 410-425.

- Den Hollander, M. (2018). *Design for managing obsolescence: A design methodology for preserving product integrity in a circular economy*. Delft, The Netherlands: Ph.D. Thesis, Delft University of Technology.
- Denzinger, C., Berkemeier, G., Winter, O., Worsham, M., Labrador, C., Willard, K., . . . Ciric, A. C. (2021). Toward sustainable refrigeration systems: Life cycle assessment of a bench-scale solar-thermal adsorption refrigerator. *International Journal of Refrigeration*, 121, 105-113. doi:10.1016/j.ijrefrig.2020.09.022
- Dewhurst, P. (1993). Product design for manufacture: Design for disassembly. *Industrial Engineering*, 25, 26-28.
- Di Maio, F., & Rem, P. C. (2015). A robust indicator for promoting circular economy through recycling. *Journal of Environmental Protection*, 6(10), 1095. doi:10.4236/jep.2015.610096
- Di Maio, F., Rem, P. C., Baldé, K., & Polder, M. (2017). Measuring resource efficiency and circular economy: A market value approach. *Resources, Conservation and Recycling*, 122, 163-171.
- ECODESIGN PILOT. (n.d.). Retrieved 2023, from <http://pilot.ecodesign.at/pilot/ONLINE/ENGLISH/INDEX.HTM>
- Eco-indicator 99 Manual for Designers - A damage oriented method for Life Cycle Impact Assessment*. (2000). The Netherlands: Ministry of Housing, Spatial Planning and the Environment.
- Eklund, J. A. (1995). Relationships between ergonomics and quality in assembly work. *Applied Ergonomics*, 26(1), 15-20. doi:10.1016/0003-6870(95)95747-N
- Elkington, J. (1994). Towards the Sustainable Corporation: Win-Win-Win Business Strategies for Sustainable Development. *California management review*, 36(2), 90-100.
- ELLEN MACARTHUR FOUNDATION. (2019a). *Circularity Indicators: An Approach to Measuring Circularity - Methodology*.

- ELLEN MACARTHUR FOUNDATION. (2019b). *The butterfly diagram: visualising the circular economy*. Retrieved 2023, from <https://ellenmacarthurfoundation.org/circular-economy-diagram>
- ELLEN MACARTHUR FOUNDATION. (2021a). *Circular economy glossary*.
- ELLEN MACARTHUR FOUNDATION. (2021b). *Circular Example - How tool sharing could become a public utility: Toronto Tool Library and Makerspace*. Retrieved 2023, from <https://ellenmacarthurfoundation.org/circular-examples/how-tool-sharing-could-become-a-public-utility>
- Ellram, L. M. (1995). Total cost of ownership: an analysis approach for purchasing. *International Journal of Physical Distribution & Logistics Management*, 25(8), 4-23.
- European Commission - Directorate-General for Environment; Ricardo-AEA Ltd. (2015). *The durability of products – Standard assessment for the circular economy under the eco-innovation action plan*. Publications Office. Retrieved from <https://data.europa.eu/doi/10.2779/37050>
- European Commission. (2015). *COMMUNICATION FROM THE COMMISSION TO THE EUROPEAN PARLIAMENT, THE COUNCIL, THE EUROPEAN ECONOMIC AND SOCIAL COMMITTEE AND THE COMMITTEE OF THE REGIONS Closing the loop - An EU action plan for the Circular Economy - COM/2015/0614 final*. Brussels.
- European Commission. (2019a). *COMMUNICATION FROM THE COMMISSION - The European Green Deal - COM(2019) 640 final*. Brussels. Retrieved 2023, from <https://eur-lex.europa.eu/legal-content/EN/TXT/HTML/?uri=CELEX:52019DC0640>
- European Commission. (2019b). *Product database - European Product Registry for Energy Labelling*. Retrieved 2023, from https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/product-database_en

- European Commission. (2020). *COM/2020/98 final - A new Circular Economy Action Plan - For a cleaner and more competitive Europe*. Brussels.
- European Commission. (2023, October 9). *Commission welcomes completion of key 'Fit for 55' legislation, putting EU on track to exceed 2030 targets*. Retrieved 2023, from https://ec.europa.eu/commission/presscorner/detail/en/ip_23_4754
- European Commission. (n.d. a). *About the energy label and ecodesign*. Retrieved 2023, from https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign/about_en
- European Commission. (n.d. b). *Delivering the European Green Deal*. Retrieved 2023, from https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en
- European Commission. (n.d. c). *Ecodesign for Sustainable Products Regulation*. Retrieved 2023, from https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/sustainable-products/ecodesign-sustainable-products-regulation_en
- European Commission. (n.d. d). *EU Ecolabel*. Retrieved 2023, from https://environment.ec.europa.eu/topics/circular-economy/eu-ecolabel-home_en
- European Commission. (n.d. e). *Waste Framework Directive*. Retrieved 2023, from https://environment.ec.europa.eu/topics/waste-and-recycling/waste-framework-directive_en
- European Parliament. (2009a). *Consolidated text: Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries and amending Directive 2004/35/EC*. Retrieved from <http://data.europa.eu/eli/dir/2006/21/2009-08-07>

- European Parliament. (2009b). *Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (recast)*.
- European Parliament. (2009c). *DIRECTIVE 2009/125/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 October 2009 establishing a framework for the setting of ecodesign requirements for energy-related products (recast)*. Retrieved from https://commission.europa.eu/energy-climate-change-environment/standards-tools-and-labels/products-labelling-rules-and-requirements/energy-label-and-ecodesign_en
- European Parliament. (2017). *Consolidated text: Regulation (EU) 2017/1369 of the European Parliament and of the Council of 4 July 2017 setting a framework for energy labelling and repealing Directive 2010/30/EU (Text with EEA relevance)Text with EEA relevance*. Retrieved from <http://data.europa.eu/eli/reg/2017/1369/2021-05-01>
- European Parliament. (2018). *Consolidated text: Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance)*. Retrieved from <http://data.europa.eu/eli/dir/2008/98/2018-07-05>
- European Parliament. (2018a). *Commission notice on technical guidance on the classification of waste (C/2018/1447)*. Retrieved from https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv:OJ.C_.2018.124.01.0001.01.ENG
- European Parliament. (2018b). *Consolidated text: Council Directive 1999/31/EC of 26 April 1999 on the landfill of waste*. Retrieved from <http://data.europa.eu/eli/dir/1999/31/2018-07-04>
- European Parliament. (2018c). *Consolidated text: Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives (Text with EEA relevance)*. Retrieved from <http://data.europa.eu/eli/dir/2008/98/2018-07-05>
- European Parliament. (2018d). *Consolidated text: Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical*

and electronic equipment (WEEE) (recast) (Text with EEA relevance).
 Official Journal of the European Union. Retrieved from
<http://data.europa.eu/eli/dir/2012/19/2018-07-04>

European Parliament. (2018e). *Consolidated text: European Parliament and Council Directive 94/62/EC of 20 December 1994 on packaging and packaging waste.* Retrieved from
<http://data.europa.eu/eli/dir/1994/62/2018-07-04>

European Parliament. (2018f). *Consolidated text: Regulation (EU) No 1257/2013 of the European Parliament and of the Council of 20 November 2013 on ship recycling and amending Regulation (EC) No 1013/2006 and Directive 2009/16/EC (Text with EEA relevance).* Retrieved from
<http://data.europa.eu/eli/reg/2013/1257/2018-07-04>

European Parliament. (2021). *Consolidated text: Regulation (EC) No 1013/2006 of the European Parliament and of the Council of 14 June 2006 on shipments of waste.* Retrieved from
<http://data.europa.eu/eli/reg/2006/1013/2021-01-11>

European Parliament. (2022). *Consolidated text: Council Directive of 12 June 1986 on the protection of the environment, and in particular of the soil, when sewage sludge is used in agriculture (86/278/EEC).* Retrieved from
<http://data.europa.eu/eli/dir/1986/278/2022-01-01>

European Parliament. (2023a). *Consolidated text: Directive 2000/53/EC of the European Parliament and of the Council of 18 September 2000 on end-of-life vehicles.* Retrieved from
<http://data.europa.eu/eli/dir/2000/53/2023-03-30>

European Parliament. (2023b). *Consolidated text: Directive 2011/65/EU of the European Parliament and of the Council of 8 June 2011 on the restriction of the use of certain hazardous substances in electrical and electronic equipment (recast) (Text with EEA relevance)Text with EEA relev.* Retrieved from
<http://data.europa.eu/eli/dir/2011/65/2023-09-01>

European Parliament. (2023c). *Regulation (EU) 2023/1542 of the European Parliament and of the Council of 12 July 2023 concerning batteries and waste batteries, amending Directive 2008/98/EC and Regulation (EU)*

- 2019/1020 and repealing Directive 2006/66/EC (Text with EEA relevance). Retrieved from <http://data.europa.eu/eli/reg/2023/1542/oj>
- Eurostat. (2023, September 26). *Electricity price statistics*. Retrieved from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics#Electricity_prices_for_household_consumers
- Eurostat. (n.d.). *Circular Economy - Monitoring framework*. Retrieved 2023, from <https://ec.europa.eu/eurostat/web/circular-economy/monitoring-framework>
- Evans, J., & Bocken, N. M. (2013). *CE toolkit*. Retrieved 2022, from <http://circulareconomytoolkit.org/>
- Fair Trade International. (n.d.). *Get Certified*. Retrieved 2023, from <https://www.fairtrade.net/act/get-certified>
- Fajilla, G., Borri, E., De Simone, M., Cabeza, L. F., & Bragança, L. (2021). Effect of climate change and occupant behaviour on the environmental impact of the heating and cooling systems of a real apartment. A parametric study through life cycle assessment. *Energies*, 14(24), 8356. doi:10.3390/en14248356
- Favi, C. (2013). *Toward eco-design: an integrated lifecycle engineering system to develop sustainable mechatronic products and services*. (Doctoral dissertation), Università Politecnica delle Marche.
- Favi, C., Formentini, G., & Boix Rodríguez, N. (2020). Eco-design of cooking appliances based on food habits and diets. *Procedia CIRP*, 90, 372-376. doi:10.1016/j.procir.2020.02.054
- Favi, C., Germani, M., Landi, D., Mengarelli, M., & Rossi, M. (2018). Comparative life cycle assessment of cooking appliances in Italian kitchens. *Journal of Cleaner Production*, 180, 430-449. doi:10.1016/j.jclepro.2018.03.140
- Favi, C., Germani, M., Luzi, A., Mandolini, M., & Marconi, M. (2017). A design for EoL approach and metrics to favour closed-loop scenarios for products. *International Journal of Sustainable Engineering*, 10(3), 136-146. doi:10.1080/19397038.2016.1270369

- Favi, C., Germani, M., Mandolini, M., & Marconi, M. (2016). Includes Knowledge of Dismantling Centers in the Early Design Phase: A Knowledge-based Design for Disassembly Approach. *Procedia CIRP*, 48, 401-406. doi:10.1016/j.procir.2016.03.242
- Favi, C., Marconi, M., Germani, M., & Mandolini, M. (2019). A design for disassembly tool oriented to mechatronic product demanufacturing and recycling. *Advanced Engineering Informatics*, 39, 62-79. doi:10.1016/j.aei.2018.11.008
- Figge, F., Thorpe, A. S., Givry, P., Canning, L., & Franklin-Johnson, E. (2018). Longevity and Circularity as Indicators of Eco-Efficient Resource Use in the Circular Economy. *Ecological Economics*, 150, 297-306. doi:10.1016/j.ecolecon.2018.04.030
- Fiore, S., Ibanescu, D., Teodosiu, C., & Ronco, A. (2019). Improving waste electric and electronic equipment management at full-scale by using material flow analysis and life cycle assessment. *Science of The Total Environment*, 659, 928-939. doi:10.1016/j.scitotenv.2018.12.417
- Flipsen, B., Huisken, M., Opsomer, T., & Depypere, M. (2019). Smartphone reparability scoring: Assessing the self-repair potential of mobile ICT devices. *PLATE 2019*, 18-20.
- Formentini, G., & Ramanujan, D. (2023). Design for circular disassembly: Evaluating the impacts of product end-of-life status on circularity through the parent-action-child model. *Journal of Cleaner Production*, 405, 137009. doi:10.1016/j.jclepro.2023.137009
- Formentini, G., Favi, C., Cuiller, C., Dereux, P. E., Bouissiere, F., & Cédric, J. (2021). Conceptual design for assembly in aerospace industry: sensitivity analysis of mathematical framework and design parameters. *Proceedings of the Design Society*, 1, 731-740. doi:10.1017/pds.2021.73
- Franklin-Johnson, E., Figge, F., & Canning, L. (2016). Resource duration as a managerial indicator for Circular Economy performance. *Journal of Cleaner Production*, 133, 589-598. doi:10.1016/j.jclepro.2016.05.023

- Freedom House. (2023). *Freedom in the World 2023 - Methodology - Questions*. Retrieved from https://freedomhouse.org/sites/default/files/2023-03/FITW_2023%20MethodologyPDF.pdf
- Fregonara, E., Giordano, R., Ferrando, D. G., & Pattono, S. (2017). Economic-Environmental Indicators to Support Investment Decisions: A Focus on the Buildings' End-of-Life Stage. *Buildings*, 7(3), 65. doi:10.3390/buildings7030065
- Fridays for future. (n.d.). *Who we are*. Retrieved 2023, from <https://fridaysforfuture.org/what-we-do/who-we-are/>
- Frizziero, L., Donnici, G., & Freddi, M. (2022). Design for Disassembly combined with augmented reality for optimization of maintenance processes. *Frontiers in Sustainability*, 3, 1066448. doi:10.3389/frsus.2022.1066448
- Frizziero, L., Leon Cardena, C., Freddi, M., Grassoni, A., & Liverani, A. (2023). Augmented reality applied to design for disassembly assessment for a volumetric pump with rotating cylinder. *Production & Manufacturing Research*, 11(1). doi:10.1080/21693277.2023.2199815
- Frizziero, L., Liverani, A., Caligiana, G., Donnici, G., & Chinaglia, L. (2019). Design for Disassembly (DfD) and Augmented Reality (AR): Case Study Applied to a Gearbox. *Machines*, 7(2), 29. doi:10.3390/machines7020029
- Gabriel, C., Boix Rodríguez, N., Gaha, R., Mio, A., & Favi, C. (2023). Design metrics to normalize and compare LCA results in household appliance sector: outcomes from literature analysis. *Procedia CIRP*, 116, 612-617.
- Gagnon, B., Leduc, R., & Savard, L. (2012). From a conventional to a sustainable engineering design process: different shades of sustainability. *Journal of Engineering Design*, 23(1), 49-74. doi:10.1080/09544828.2010.516246
- Gaha, R., Benamara, A., & Yannou, B. (2018). Proposition of Eco-Feature: A New CAD/PLM Data Model for an LCA Tool. *Design and Modeling*

of Mechanical Systems – III: Proceedings of the 7th Conference on Design and Modeling of Mechanical Systems, 763-770. doi:10.1007/978-3-319-66697-6_74

- Gao, H., & Shi, X. (2013). Research on Household Electrical Appliances' Supply Chain Based on the LCA Method in the Situation of Low-Carbon Product Certification. *LTLGB 2012: Proceedings of International Conference on Low-carbon Transportation and Logistics, and Green Buildings*, 691-698. doi:10.1007/978-3-642-34651-4_94
- Garrido Azevedo, S., Godina, R., & de Oliveira Matias, J. C. (2017). Proposal of a Sustainable Circular Index for Manufacturing Companies. *Resources*, 6(4), 63.
- Gasparis-Wieloch, H. (2019). Project Net Present Value estimation under uncertainty. *Central European Journal of Operations Research*, 27, 179-197. doi:10.1007/s10100-017-0500-0
- German Federal Government. (n.d.). *Blue Angel - The german ecolabel*. Retrieved 2023, from <https://www.blauer-engel.de/en>
- Go, T. F., Wahab, D. A., Rahman, M. N., & Ramli, R. (2010). A design framework for end-of-life vehicles recovery: Optimization of disassembly sequence using genetic algorithms. *American Journal of Environmental Sciences*, 6, 350-356. doi:10.3844/ajessp.2010.350.356
- Greening, B., & Azapagic, A. (2014). Domestic solar thermal water heating: A sustainable option for the UK? *Renewable Energy*, 63, 23-36. doi:10.1016/j.renene.2013.07.048
- Grignon-Masse, L., Riviere, P., & Adnot, J. (2011). Strategies for reducing the environmental impacts of room air conditioners in Europe. *Energy Policy*, 39(4), 2152-2164. doi:10.1016/j.enpol.2011.02.004
- Guinée, J. B. (2002). *Handbook on life cycle assessment: operational guide to the ISO standards* (Vol. 7). Springer Science & Business Media.
- Guna, V. K., Murugesan, G., Basavarajaiah, B. H., Ilangovan, M., Olivera, S., Krishna, V., & Reddy, N. (2016). Plant-based completely biodegradable printed circuit boards. *IEEE Transactions on Electron Devices*, 63(12), 4893-4898. doi:10.1109/TED.2016.2619983

- Gungor, A., & Gupta, S. M. (2001). Disassembly sequence plan generation using a branch-and-bound algorithm. *Int. J. Prod. Res.*, 39, 481-509. doi:10.1080/00207540010002838
- Gutierrez, E., Adenso-Diaz, B., Lozano, S., & Barba-Gutierrez, Y. (2009). Visualisation of LCA environmental impacts of electrical and electronic products using multidimensional scaling. *International Journal of Product Lifecycle Management*, 4(1-3), 166-185. doi:10.1504/IJPLM.2009.031672
- Hamrol, A., Pawelczak, M., & Osiński, F. (2022). Household Appliance Lifecycle and Sustainable Development. *International Scientific-Technical Conference MANUFACTURING*, 203-213. doi:10.1007/978-3-031-00218-2_17
- Hazen, B. T., Cegielski, C., & Hanna, J. B. (2011). Diffusion of green supply chain management: Examining perceived quality of green reverse logistics. *The International Journal of Logistics Management*, 22(3), 373-389. doi:10.1108/09574091111181372
- Hischier R., W. B.-J. (2010). *Implementation of Life Cycle Impact Assessment Methods*. Dübendorf: Swiss Centre for Life Cycle Inventories.
- Hischier, R., Reale, F., Castellani, V., & Sala, S. (2020). Environmental impacts of household appliances in Europe and scenarios for their impact reduction. *Journal of cleaner production*, 267, 121952. doi:10.1016/j.jclepro.2020.121952
- Holl, H. J., Horwath, I., Cojocar, E. C., Hehenberger, P., & Ernst, W. (2018). Integration of gender in the design process of mechatronic products: an interdisciplinary approach. *Materials Today: Proceedings*, 5(13), 26673-26679.
- Hua, Z., Yang, J., Coulibaly, S., & Zhang, B. (2006). Integration TRIZ with problem-solving tools: a literature review from 1995 to 2006. *International journal of business innovation and research*, 1(1-2), 111-118.
- Huang, G. O., Lee, S. W., & Mak, K. L. (1999). Web-based product and process data modelling in concurrent "design for X". *Robotics and Computer-Integrated Manufacturing*, 15, 53-63.

- Huijbregts, M., Steinmann, Z., Elshout, P., Stam, G., Verones, F., Vieira, M., . . . van Zelm, R. (2016). *ReCiPe 2016: A harmonized life cycle impact assessment method at midpoint and endpoint level. Report I: Characterization*. The Netherlands: National Institute for Public Health and the Environment.
- Huysman, S., De Schaepmeester, J., Ragaert, K., Dewulf, J., & De Meester, S. (2017). Performance indicators for a circular economy: A case study on post-industrial plastic waste. *Resources, conservation and recycling*, 120, 46-54. doi:10.1016/j.resconrec.2017.01.013
- Huysman, S., Debaveye, S., Schaubroeck, T., De Meester, S., Ardente, F., Mathieux, F., & Dewulf, J. (2015). The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastic recycling in Flanders. *Resources, Conservation and Recycling*, 101, 53-60. doi:10.1016/j.resconrec.2015.05.014
- Huysman, S., Debaveye, S., Schaubroeck, T., De Meester, S., Ardente, F., Mathieux, F., & Dewulf, J. (2015). The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastic recycling in Flanders. *Resources, Conservation and Recycling*, 101, 53-60. doi:10.1016/j.resconrec.2015.05.014
- IDEALO&CO Explore. (2016). Retrieved 2022, from Circularity Calculator: <https://circularitycalculator.com/>
- IFIXIT. (n.d.). Retrieved 2023, from <https://www.ifixit.com/>
- ILO - International Labour Organization. (2022). *ILO Declaration on Fundamental Principles and Rights at Work (1998), as amended in 2022*. Retrieved from https://www.ilo.org/dyn/normlex/en/f?p=1000:62:0::NO:62:P62_LIST_ENTRIE_ID:2453911:NO
- International Health Facility Guidelines. (2023). *International Health Facility Guidelines: Part C - Access, Mobility and OH&S. Version 6.0*. Retrieved from https://www.healthfacilityguidelines.com/ViewPDF/ViewIndexPDF/iHFG_part_c_complete

- International Organization for Standardization. (2000). *Hammers – Technical specifications concerning steel hammer heads – Test procedures (ISO 15601:2000)*.
- International Organization for Standardization. (2004a). *Assembly tools for screws and nuts – Screwdrivers for cross-recessed head screws – Part 1: Driver tips (ISO 8764-1:2004)*.
- International Organization for Standardization. (2004b). *Assembly tools for screws and nuts – Screwdrivers for slotted-head screws – Part 1: Tips for hand- and machine-operated screwdrivers (ISO 2380-1:2004)*.
- International Organization for Standardization. (2004c). *Pliers and nippers – Diagonal cutting nippers – Dimensions and test values (ISO 5749:2004)*.
- International Organization for Standardization. (2004d). *Pliers and nippers – Engineer's and "Lineman's" pliers – Dimensions and test values (ISO 5746:2004)*.
- International Organization for Standardization. (2004e). *Pliers and nippers – Pliers for gripping and manipulating – Dimensions and test values (ISO 5745:2004)*.
- International Organization for Standardization. (2006a). *Environmental management – Life cycle assessment – Requirements and guidelines (ISO 14044:2006)*.
- International Organization for Standardization. (2006b). *Environmental Management – Life Cycle Assessment – Principle and Framework (ISO 14040:2006)*.
- International Organization for Standardization. (2014a). *Assembly tools for screws and nuts – Hexagon socket screw keys (ISO 2936:2014)*.
- International Organization for Standardization. (2014b). *Hexalobular internal driving feature for bolts and screws (ISO 10664:2014)*.
- International Organization for Standardization. (2015). *Assembly tools for screws and nuts – Combination wrenches – Lengths of wrenches and maximum thickness of heads (ISO 7738:2015)*.

- International Organization for Standardization. (2020). *Environmental management systems – Guidelines for incorporating ecodesign (ISO 14006:2020)*.
- International Organization for Standardization. (2021). *Pliers and nippers – Multiple slip joint pliers – Dimensions and test values (ISO 8976:2021)*.
- Iraldo, F., Facheris, C., & Nucci, B. (2017). Is product durability better for environment and for economic efficiency? A comparative assessment applying LCA and LCC to two energy-intensive products. *Journal of Cleaner Production*, 140(3), 1353-1364. doi:10.1016/j.jclepro.2016.10.017
- Istituto Nazionale di Statistica. (2023, 06 06). *Comunicato stampa - Le prospettive per l'economia italiana nel 2023-2024*. Retrieved 2023, from <https://www.istat.it/it/archivio/285241>
- Javani, N., Abraham, F., Dincer, I., & Rosen, M. A. (2013). Comparative environmental impact assessment of residential HVAC systems. *Systems. Causes, Impacts and Solutions to Global Warming*, 1143-1158. doi:10.1007/978-1-4614-7588-0_61
- Jelsma, J., & Knot, M. (2002). Designing environmentally efficient services; a 'script' approach. *The Journal of Sustainable Product Design*, 2(3-4), 119-130.
- Jun, H. B., Park, J. Y., & Suh, H. W. (2006). Lead time estimation method for complex product development process. *Concurrent Engineering*, 14, 313-328.
- Kankanamge, N., Yigitcanlar, T., Goonetilleke, A., & Kamruzzaman, M. (2019). Can volunteer crowdsourcing reduce disaster risk? A systematic review of the literature. *International journal of disaster risk reduction*, 35, 101097. doi:10.1016/j.ijdr.2019.101097
- Keoleian, G., & Menerey, D. (1993). *Life cycle design guidance manual: environmental requirements and the product system*. Risk Reduction Engineering Laboratory, Office of Research and Development, US Environmental Protection Agency.

- Kheder, M., Trigui, M., & Aifaoui, N. (2015). Disassembly sequence planning based on a genetic algorithm. *J. Mech. Eng. Sci.*, 229, 2281-2290. doi:10.1177/0954406214557340
- Kirchherr, J., Reike, D., & Hekkert, M. (2017). Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling*, 127, 221-232. doi:10.1016/j.resconrec.2017.09.005
- Klöpffer, W., & Ciroth, A. (2011). Is LCC relevant in a sustainability assessment? *The International Journal of Life Cycle Assessment*, 16(2), 99-101.
- Kucera, D., & Sari, D. (2019). New labour rights indicators: Method and trends for 2000-15. *International Labour Review*, 158(3), 419-446.
- Kuo, T. C., Huang, S. H., & Zhang, H. C. (2001). Design for manufacture and design for 'X': concepts, applications, and perspectives. *Computers & industrial engineering*, 41, 241-260.
- Landi, D., Consolini, A., Germani, M., & Favi, C. (2019). Comparative life cycle assessment of electric and gas ovens in the Italian context: An environmental and technical evaluation. *Journal of Cleaner Production*, 221, 189-201. doi:10.1016/j.jclepro.2019.02.196
- Laroche, M., Bergeron, J., & Barbaro Forleo, G. (2001). Targeting consumers who are willing to pay more for environmentally friendly products. *Journal of Consumer Marketing*, 18(6), 503-520.
- Larrain, M., Van Passel, S., Thomassen, G., Van Gorp, B., Nhu, T. T., Huysveld, S., . . . Billen, P. (2021). Techno-economic assessment of mechanical recycling of challenging post-consumer plastic packaging waste. *Elsevier*, 170, 105607. doi:10.1016/j.resconrec.2021.105607
- Le Pochat, S., Bertoluci, G., & Froelich, D. (2007). Integrating ecodesign by conducting changes in SMEs. *Journal of Cleaner Production*, 15(7), 671-680.
- Le Pochat, S., Bertoluci, G., & Froelich, D. (2007). Integrating ecodesign by conducting changes in SMEs. *Journal of Cleaner Production*, 15(7), 671-680.

- Leadership Council of the SDSN. (2014). *An Action Agenda for Sustainable Development - Report for the UN secretary-general*.
- Lee, H. M., Lu, W. F., & Song, B. (2014). A framework for assessing product End-Of-Life performance: reviewing the state of the art and proposing an innovative approach using an End-of-Life Index. *Journal of Cleaner Production*, 66, 355-371. doi:10.1016/j.jclepro.2013.11.001
- Lin, H., Clavreul, J., Jeandaux, C., Crawley, J., & Butnar, I. (2021). Environmental life cycle assessment of heating systems in the UK: Comparative assessment of hybrid heat pumps vs. condensing gas boilers. *Energy and Buildings*, 240, 110865. doi:10.1016/j.enbuild.2021.110865
- Linder, M., Sarasini, S., & van Loon, P. (2017). A Metric for Quantifying Product-Level Circularity. *Journal of Industrial Ecology*, 21(3), 545-558. doi:10.1111/jiec.12552
- Luttropp, C., & Lagerstedt, J. (2006). EcoDesign and The Ten Golden Rules: generic advice for merging environmental aspects into product development. *Journal of cleaner production*, 14, 1396-1408. doi:10.1016/j.jclepro.2005.11.022
- Marconi, M., Germani, M., Mandolini, M., & Favi, C. (2019). Applying data mining technique to disassembly sequence planning: a method to assess effective disassembly time of industrial products. *International Journal of Production Research*, 57(2), 599-623. doi:10.1080/00207543.2018.1472404
- Marosky, N., Dose, J., Fleischer, G., & Ackermann, R. (2007). Challenges of data transfer between CAD and LCA software tools. *Proceedings of the 3rd International Conference on Life Cycle Management, University of Zurich, Irchel, Switzerland*.
- Mathieux, F., Froelich, D., & Moszkowicz, P. (2008). ReSICLED: a new recovery-conscious design method for complex products based on a multicriteria assessment of the recoverability. *Journal of Cleaner Production*, 16(3), 277-298. doi:10.1016/j.jclepro.2006.07.026

- Mendoza, J. M., Gallego-Schmid, A., Rivera, X. C., Rieradevall, J., & Azapagic, A. (2019). Sustainability assessment of home-made solar cookers for use in developed countries. *Science of the total environment*, 648, 184-196. doi:10.1016/j.scitotenv.2018.08.125
- Mengarelli, M., Zamagni, A., Buttol, P., Cortesi, S., Nanfitò, S., & Porta, P. L. (2015). Simplification strategies for mechatronic products: A methodology proposal. *Matériaux & Techniques*, 103(1). doi:10.1051/mattech/2015003
- Menzies, G. F., & Roderick, Y. (2010). Energy and carbon impact analysis of a solar thermal collector system. *International Journal of Sustainable Engineering*, 3(1), 9-16. doi:10.1080/19397030903362869
- Merschak, S., & Hehenberger, P. (2019). Ecodesign Methods for Mechatronic Systems: A Literature Review and Classification. *20th International Conference on Research and Education in Mechatronics (REM)*, 1-8. doi:10.1109/REM.2019.8744105
- Mesa, J., Esparragoza, I., & Maury, H. (2018). Developing a set of sustainability indicators for product families based on the circular economy model. *Journal of Cleaner Production*, 196, 1429-1442. doi:10.1016/j.jclepro.2018.06.131
- Mihelcic, J. R., Paterson, K. G., Phillips, L. D., Zhang, Q., Watkins, D. W., Barkdoll, B. D., . . . Hokanson, D. R. (2008). Educating engineers in the sustainable futures model with a global perspective. *Civil Engineering and Environmental Systems*, 25(4), 255-263. doi:10.1080/10286600802002981
- Ministère de la Transition écologique et de la Cohésion des territoires. (n.d.). *Indice de réparabilité*. Retrieved 2023, from <https://www.ecologie.gouv.fr/indice-reparabilite>
- Mio, A., Fermeglia, M., & Favi, C. (2022). A critical review and normalization of the life cycle assessment outcomes in the naval sector. *Journal of Cleaner Production*, 370, 133476. doi:10.1016/j.jclepro.2022.133476
- Mohamed Sultan, A. A., Lou, E., & Mativenga, P. T. (2017). What should be recycled: An integrated model for product recycling desirability.

Journal of Cleaner Production, 154, 51-60.
doi:10.1016/j.jclepro.2017.03.201

Moss, M. A. (1985). *Designing for minimal maintenance expense: the practical application of reliability and maintainability* (Vol. 1). CRC press.

Nakamura, S., & Kondo, Y. (2006). Hybrid LCC of appliances with different energy efficiency. *The International Journal of Life Cycle Assessment*, 11, 305-314. doi:10.1065/lca2006.05.244

Nakamura, S., & Yamasue, E. (2010). Hybrid LCA of a design for disassembly technology: Active disassembling fasteners of hydrogen storage alloys for home appliances. *Environmental Science & Technology*, 44(12), 4402-4408. doi:10.1021/es903340h

Nakano, K., Aoki, R., Yagita, H., & Narita, N. (2007). Evaluating the reduction in green house gas emissions achieved by the implementation of the household appliance recycling in Japan. *The International Journal of Life Cycle Assessment*, 12, 289-298. doi:10.1065/lca2006.11.281

Nas, T. F. (2016). *Cost-benefit analysis: Theory and application*. Lexington Books.

Naumann, G., Schropp, E., & Gaderer, M. (2022). Life Cycle Assessment of an Air-Source Heat Pump and a Condensing Gas Boiler Using an Attributional and a Consequential Approach. *Procedia CIRP*, 105, 351-356. doi:10.1016/j.procir.2022.02.058

Nelen, D., Manshoven, S., Peeters, J. R., Vanegas, P., D'Haese, N., & Vrancken, K. (2014). A multidimensional indicator set to assess the benefits of WEEE material recycling. *Journal of Cleaner Production*, 83, 305-316. doi:10.1016/j.jclepro.2014.06.094

Nitkiewicz, A., & Sekret, R. (2014). Comparison of LCA results of low temperature heat plant using electric heat pump, absorption heat pump and gas-fired boiler. *Energy Conversion and Management*, 87, 647-652. doi:10.1016/j.enconman.2014.07.032

Nordic Council of Ministers. (n.d.). *The Nordic Swan Ecolabel*. Retrieved 2023, from <https://www.nordic-swan-ecolabel.org/>

- Ong, N. S., & Wong, Y. (1999). Automatic subassembly detection from a product model for disassembly sequence generation. *Int. J. Adv. Manuf. Technol.*, 15, 425-431. doi:10.1007/s001700050086
- Osti, F., Ceruti, A., Liverani, A., & Caligiana, G. (2017). Semi-automatic Design for Disassembly Strategy Planning: An Augmented Reality Approach. *Procedia Manufacturing*, 11, 1481-1488. doi:10.1016/j.promfg.2017.07.279
- Pahl, G., Beitz, W., Feldhusen, J., & Grote, K. H. (2007). *Engineering Design: A Systematic Approach* (3 ed.). Springer London. doi:10.1007/978-1-84628-319-2
- Papetti, A., Germani, M., & Mandolini, M. (2014). Product innovations and eco-sustainability: An approach to evaluate the relationships. *Key Engineering Materials*, 572, 74-77. doi:10.4028/www.scientific.net/KEM.572.74
- Papetti, A., Germani, M., Marconi, M., & Favi, C. (2017). Lifecycle tools as a support for the eco-design innovation of domestic appliances. *International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*, V004T05A043. doi:10.1115/DETC2017-68141
- Park, J. Y., & Chertow, M. R. (2014). Establishing and testing the “reuse potential” indicator for managing wastes as resources. *Journal of Environmental Management*, 137, 45-53. doi:10.1016/j.jenvman.2013.11.053
- Park, P. J., Tahara, K., Jeong, I. T., & Lee, K. M. (2006). Comparison of four methods for integrating environmental and economic aspects in the end-of-life stage of a washing machine. *Resources, conservation and recycling*, 48(1), 71-85. doi:10.1016/j.resconrec.2006.01.001
- Peeters, J. R., Tecchio, P., & Vanegas, P. (2018). *eDIM: Further Development of the Method to Assess the Ease of Disassembly and Reassembly of Products: Application to Notebook Computers*. Luxembourg: Publications Office of the European Union.

- Pelletier, C., Rogaume, Y., Dieckhoff, L., Bardeau, G., Pons, M. N., & Dufour, A. (2019). Effect of combustion technology and biogenic CO₂ impact factor on global warming potential of wood-to-heat chains. *Applied energy*, 235, 1381-1388. doi:10.1016/j.apenergy.2018.11.060
- Perera, H. S. (1999). Component part standardization: A way to reduce the life-cycle costs of products. *International journal of production economics*, 60, 109-116.
- Peruzzini, M., & Germani, M. (2013). Investigating the Sustainability of Product and Product-Service Systems in the B2C Industry. *Product-Service Integration for Sustainable Solutions: Proceedings of the 5th CIRP International Conference on Industrial Product-Service Systems*, 421-434. doi:10.1007/978-3-642-30820-8_36
- Peruzzini, M., Germani, M., & Marilungo, E. (2014). Product-Service Lifecycle Management in Manufacturing: An Industrial Case Study. *Product Lifecycle Management for a Global Market. PLM 2014. IFIP Advances in Information and Communication Technology*, 442, 445-454. doi:10.1007/978-3-662-45937-9_44
- Pigosso, D. C., Rozenfeld, H., & McAloone, T. C. (2013). Ecodesign maturity model: a management framework to support ecodesign implementation into manufacturing companies. *Journal of Cleaner Production*, 59, 160-1723.
- Pina, C., Elduque, D., Javierre, C., Martínez, E., & Jiménez, E. (2015). Influence of mechanical design on the evolution of the environmental impact of an induction hob. *Journal of Life Cycle Assessment*, 20, 937-946. doi:10.1007/s11367-015-0890-y
- Piontek, F. M., Rapaport, M., & Müller, M. (2019). One year of clothing consumption of a German female consumer. *Procedia CIRP*, 80, 417-421. doi:10.1016/j.procir.2019.01.055
- Pozo Arcos, B., Bakker, C. A., Flipsen, B., & Balkenende, R. (2020). Practices of Fault Diagnosis in Household Appliances: Insights for Design. *Journal of Cleaner Production*, 265, 121812.

- Pozo Arcos, B., Bakker, C. A., Flipsen, B., & Balkenende, R. (2021). Faults in consumer products are difficult to diagnose, and design is to blame: A user observation study. *Journal of Cleaner Production*, 319, 128741.
- Pulikottil, T., Boix Rodríguez, N., & Peeters, J. R. (n.d.). Robotic ease of Disassembly Metric (Re-DiM) for human robot collaborative disassembly: A case study for vacuum cleaner. *Submitted to Procedia CIRP*.
- Rey Martínez, F. J., Velasco Gómez, E., Martín García, C., Sanz Requena, J. F., Navas Gracia, L., Hernández Navarro, S., . . . Martín Gil, J. (2011). Life cycle assessment of a semi-indirect ceramic evaporative cooler vs. a heat pump in two climate areas of Spain. *Applied Energy*, 88(3), 914-921. doi:10.1016/j.apenergy.2010.08.025
- Right to Repair. (n.d.). *Europe, let's reuse, refurbish, repair*. Retrieved 2023, from <https://repair.eu/>
- Rinne, S., & Syri, S. (2013). Heat pumps versus combined heat and power production as CO2 reduction measures in Finland. *Energy*, 57, 308-318. doi:10.1016/j.energy.2013.05.033
- Rodríguez, E., & Boks, C. (2005). How design of products affects user behaviour and vice versa: the environmental implications. *2005 4th International Symposium on Environmentally Conscious Design and Inverse Manufacturing*, 54-61.
- Rossi, M., Germani, M., & Zamagni, A. (2016). Review of ecodesign methods and tools. Barriers and strategies for an effective implementation in industrial companies. *Journal of Cleaner Production*, 129, 361-373. doi:10.1016/j.jclepro.2016.04.051
- Rossi, M., Papetti, A., Marconi, M., & Germani, M. (2019). A multi-criteria index to support ecodesign implementation in manufacturing products: benefits and limits in real case studies. *International Journal of Sustainable Engineering*, 12(6), 376-389. doi:10.1080/19397038.2019.1575926

- Russo, D., Bersano, G., Birolini, V., & Uhl, R. (2011). European testing of the efficiency of TRIZ in eco-innovation projects for manufacturing SMEs. *Procedia engineering*, 9, 157-171.
- Saccani, N., Perona, M., & Bacchetti, A. (2017). The total cost of ownership of durable consumer goods: A conceptual model and an empirical application. *International Journal of Production Economics*, 183, 1-13.
- SAI - Social Accountability International. (2014). *SA8000:2014 Standard*. Retrieved from <https://sa-intl.org/resources/sa8000-standard/>
- Sakao, T., & Brambila Macias, S. A. (2018). Do we share an understanding of transdisciplinarity in environmental sustainability research? *Journal of Cleaner Production*, 170, 1399-1403. doi:10.1016/j.jclepro.2017.09.226
- Sala, S., & Castellani, V. (2019). The consumer footprint: Monitoring sustainable development goal 12 with process-based life cycle assessment. *Journal of Cleaner production*, 240, 118050. doi:10.1016/j.jclepro.2019.118050
- Santos, R., Abreu, A., Soares, J., Mendes, F., & Calado, J. M. (2020). A soft computing framework to support consumers in obtaining sustainable appliances from the market. *Applied Sciences*, 10(9), 3206. doi:10.3390/app10093206
- Saoud, A., Harajli, H., & Manneh, R. (2021). Cradle-to-grave life cycle assessment of an air to water heat pump: Case study for the Lebanese context and comparison with solar and conventional electric water heaters for residential application. *Journal of Building Engineering*, 44, 103253. doi:10.1016/j.job.2021.103253
- Säynäjoki, A., Heinonen, J., Junnila, S., & Horvath, A. (2017). Can life-cycle assessment produce reliable policy guidelines in the building sector? *Environmental Research Letters*, 12, 013001. doi:10.1088/1748-9326/aa54ee
- Scheepens, A. E., Vogtländer, J. G., & Brezet, J. C. (2016). Two life cycle assessment (LCA) based methods to analyse and design complex (regional) circular economy systems. Case: making water tourism

- more sustainable. *Journal of Cleaner Production*, 114, 257-268. doi:10.1016/j.jclepro.2015.05.075
- Singh, V. K., Henriques, C. O., & Martins, A. G. (2019). A Multiperspective Assessment of Best Available Energy End-Use Technologies in India's Households. *Process Integration and Optimization for Sustainability*, 3, 89-99. doi:10.1007/s41660-018-0054-1
- Skorup, D., Rozing, G., Heffer, G., & Vidaković, I. (2022). Product Life Cycle Analysis on the Example of a Home Appliance. *Proceedings of 30th International Conference on Organization and Technology of Maintenance*, 217-227. doi:10.1007/978-3-030-92851-3_16
- Smith, S., Hsu, L. Y., & Smith, G. C. (2016). Partial disassembly sequence planning based on cost-benefit analysis. *Journal of Cleaner Production*, 139, 729-739. doi:10.1016/j.jclepro.2016.08.095
- Soh, S. L., Ong, S. K., & Nee, A. Y. (2016). Design for assembly and disassembly for remanufacturing. *Assembly Automation*, 36(1), 12-24. doi:10.1108/AA-05-2015-040
- Sohlenius, G. (1992). Concurrent engineering. *CIRP annals*, 41, 645-655.
- Spreafico, C., & Russo, D. (2020). Assessing domestic environmental impacts through LCA using data from the scientific literature. *Journal of Cleaner Production*, 266, 121883. doi:10.1016/j.jclepro.2020.121883
- State of Alaska - Department of Education & Early Development. (2018). *Life Cycle Cost Analysis Handbook* (2 ed.). Juneau, Alaska.
- Sudheshwar, A., Malinverno, N., Hischier, R., Nowack, B., & Som, C. (2023). The need for design-for-recycling of paper-based printed electronics - a prospective comparison with printed circuit boards. *Resources, Conservation and Recycling*, 189, 106757. doi:10.1016/j.resconrec.2022.106757
- Sutherland, J. W. (2016). The role of manufacturing in affecting the social dimension of sustainability. *CIRP Annals*, 65(2), 689-712. doi:10.1016/j.cirp.2016.05.003

- Swenson, M. R., & Wells, W. D. (2018). Useful correlates of pro-environmental behavior. *Social marketing*, 91-109.
- Tao, J., & Yu, S. (2011). Implementation of energy efficiency standards of household refrigerator/freezer in China: Potential environmental and economic impacts. *Applied Energy*, 88(5), 1890-1905. doi:10.1016/j.apenergy.2010.11.015
- Tasaki, T., Motoshita, M., Uchida, H., & Suzuki, Y. (2013). Assessing the Replacement of Electrical Home Appliances for the Environment: An Aid to Consumer Decision Making Tasaki et al. Replacement of Home Appliances for the Environment. *Journal of Industrial Ecology*, 17(2), 290-298. doi:10.1111/j.1530-9290.2012.00551.x
- Tomislav, K. (2018). The concept of sustainable development: From its beginning to the contemporary issues. *Zagreb International Review of Economics & Business*, 21(1), 67-94.
- Törngren, M., Qamar, A., Biehl, M., Loiret, F., & El-Khoury, J. (2014). Integrating viewpoints in the development of mechatronic products. *Mechatronics*, 24(7), 745-762.
- Tseng, K. C., & Abdalla, H. (2006). A novel approach to collaborative product design and development environment. *Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture*, 220, 1997-2020.
- Ulrich, K. T., & Eppinger, S. D. (2015). *Product Design and Development* (6 ed.). Mc Graw Hill Education.
- UNEP. (2009). *Guidelines for Social Life Cycle Assessment of Products*.
- UNESCO & ICEE. (2021). *Engineering for Sustainable Development - Executive summary*. Retrieved from <https://unesdoc.unesco.org/ark:/48223/pf0000375634?2=null&queryId=93649919-12f6-4efa-aafc-b9c022d9d756>
- United Nations. (2012). *The future we want, our common vision - Outcome document of the Rio+20 Conference (A/CONF.216/L.1)*. Rio de Janeiro, Brazil. Retrieved from

<https://wedocs.unep.org/bitstream/handle/20.500.11822/13662/N1238164.pdf?sequence=1&am%3BisAllowed=>

- United Nations. (2015). *Transforming our world: the 2030 Agenda for Sustainable Development - Resolution adopted by the General Assembly on 25 September 2015*. Retrieved from <https://documents-dds-ny.un.org/doc/UNDOC/GEN/N15/291/89/PDF/N1529189.pdf?OpenElement>
- United Nations. (2023). *The Sustainable Development Goals Report - Special editions*. Retrieved from <https://unstats.un.org/sdgs/report/2023/>
- United Nations. (n.d.). *SDGs - Communications materials*. Retrieved 2023, from <https://www.un.org/sustainabledevelopment/news/communications-material/>
- Van Marrewijk, M. (2003). Concepts and definitions of CSR and corporate sustainability: Between agency and communion. *Journal of business ethics*, 44, 95-105.
- van Schaik, A., & Reuter, M. A. (2016). Recycling indices visualizing the performance of the circular economy. *World Metall. Erzmetall*, 69(4).
- Vanegas, P., Peeters, J. R., Cattrysse, D., Tecchio, P., Ardente, F., Mathieux, F., . . . Duflou, J. R. (2018). Ease of disassembly of products to support circular economy strategies. *Resources, Conservation and Recycling*, 135, 323-334. doi:<https://doi.org/10.1016/j.resconrec.2017.06.022>
- Wan, Q., Kanth, R. K., Yang, G., Chen, Q., & Zheng, L. R. (2015). Environmental impacts analysis for inkjet printed paper-based bio-patch. *Journal of Multidisciplinary Engineering Science and Technology (JMEST)*, 2(4).
- Wang, Q., Ploskić, A., Song, X., & Holmberg, S. (2016). Ventilation heat recovery jointed low-temperature heating in retrofitting - An investigation of energy conservation, environmental impacts and indoor air quality in Swedish multifamily houses. *Energy and Buildings*, 121, 250-264. doi:[10.1016/j.enbuild.2016.02.050](https://doi.org/10.1016/j.enbuild.2016.02.050)
- Wang, Y., Cai, L., Shao, X., Jin, G., & Zhang, X. (2013). Analysis on energy-saving effect and environmental benefit of a novel hybrid-power gas

- engine heat pump. *International Journal of Refrigeration*, 36(1), 237-246. doi:10.1016/j.ijrefrig.2012.09.021
- Wang, Z., Song, Q., You, Y., Duan, H., Yuan, W., & Li, J. (2021). Identifying the lifecycle ODP and GWP effects of the refrigerants from household air-conditioners in Macau. *Environmental Impact Assessment Review*, 90, 106639. doi:10.1016/j.eiar.2021.106639
- Wasserbaur, R., Sakao, T., & Milios, L. (2022). Interactions of governmental policies and business models for a circular economy: A systematic literature review. *Journal of Cleaner Production*, 337, 130329. doi:10.1016/j.jclepro.2021.130329
- Weidema, B., Wenzel, H., Petersen, C., & Hansen, K. (2004). *The product, functional unit and reference flows in LCA*. Environmental News.
- Wenzel, H., Hauschild, M. Z., & Alting, L. (1997). *Environmental Assessment of Products: Volume 1 Methodology, tools and case studies in product development* (Vol. 1). Springer Science & Business Media.
- Willems, B., Dewulf, W., & Duflou, J. (2005). Design for active disassembly (DfAD): an outline for future research. *Proceedings of the 2005 IEEE International Symposium on Electronics and the Environment*, 129-134.
- World Commission on Environment and Development (WCED). (1987). *Our Common Future*. New York.
- Xiao, R., Zhang, Y., Liu, X., & Yuan, Z. (2015). A life-cycle assessment of household refrigerators in China. *Journal of Cleaner Production*, 95, 301-310. doi:10.1016/j.jclepro.2015.02.031
- Xie, H., Cui, Q., & Li, Y. (2022). Net Present Value Method: A Method Recommended by ISO 15686-5 for Economic Evaluation of Building Life Cycle Costs. *World Journal of Engineering and Technology*, 10(2), 224-229.
- Yang, C. J., & Chen, J. L. (2012). Forecasting the design of eco-products by integrating TRIZ evolution patterns with CBR and Simple LCA methods. *Expert Systems with Applications*, 39(3), 2884-2892.

- Yang, X., Li, F., Wang, X., & Wang, L. (2012). A green-feature based LCA backtracking mechanism. *2012 Electronics Goes Green 2012+*, 1-6.
- Yaping, R., Xingchen, Z., Lu, L., Yao, C., & Yiwei, S. (2016). Life cycle cost analysis of urban rail transit vehicle. *2016 Eighth International Conference on Measuring Technology and Mechatronics Automation (ICMTMA)*, 375-378.
- Yuan, Z., Zhang, Y., & Liu, X. (2016). Life cycle assessment of horizontal-axis washing machines in China. *The International Journal of Life Cycle Assessment*, 21, 15-28. doi:10.1007/s11367-015-0993-5
- Zandin, K. B. (2021). *MOST - Work Measurement Systems* (4 ed.). CRC Press.
- Zero Waste Europe. (n.d.). *About zero waste*. Retrieved 2023, from <https://zerowasteurope.eu/about/about-zero-waste/>
- Zhang, X., & Zhang, S. Y. (2010). Product cooperative disassembly sequence planning based on branch-and-bound algorithm. *J. Adv. Manufact. Technol.*, 19, 91-103. doi:10.1007/s00170-010-2682-7
- Zhifeng, L., Yang, G., Di, H., & Bo, L. (2012). Dishwasher's environmental impact analysis and improvement by addressing EUP directive in China dishwasher manufactures. *International Journal of Environmental Technology and Management*, 15(1), 61-78. doi:10.1504/IJETM.2012.045146
- Zwolinski, P., Lopez-Ontiveros, M. A., & Brissaud, D. (2006). Integrated design of remanufacturable products based on product profiles. *Journal of Cleaner Production*, 14(15-16), 1333-1345. doi:10.1016/j.jclepro.2005.11.028

APPENDICES

APPENDIX I

All the data collected during the Phase II of the methodology is presented in this appendix. Table App. I. 1 focuses on design-related information, Table App. I. 2 on manufacturing processes, Table App. I. 3 on the use and maintenance phase, and Table App. I. 4 on considerations related to the end of the product's life cycle.

Table App. I. 1. Design information collected during the Life Cycle Engineering phase.

ID	Parameter level 0	Parameter level 1	Parameter level 2	Related area		Data source		Uncertainty score [0-5]	Notes
D001	Geometric	Volume	Product	Environmental Manufacturing, Remanufacturing	Impact,	CAD, Engineering Department, Design Department	BoM,	0	The ratio Volume/Area or Volume/Mass will be important for the manufacturing, in order to know how much scraps is present
D002	Geometric	Area	Product	Environmental Manufacturing, Remanufacturing	Impact,	CAD, Engineering Department, Design Department	BoM,	0	
D003	Geometric	Mass	Product	Environmental Manufacturing, Remanufacturing	Impact,	CAD, Engineering Department, Design Department	BoM,	0	
D004	Geometric	Volume	Component	Environmental Manufacturing, Remanufacturing	Impact,	CAD, Engineering Department, Design Department	BoM,	0	
D005	Geometric	Area	Component	Environmental Manufacturing, Remanufacturing	Impact,	CAD, Engineering Department,	BoM,	0	

						Design Department				
D006	Geometric	Mass	Component	Environmental Remanufacturing	Impact,	CAD, Engineering Department, Design Department	BoM,	0		
D007	Composition	Material	Component	Environmental Manufacturing, Remanufacturing &Repair ability &Reuse &Recycling &Upgradability =EoL	Impact, Cost,	CAD, PLM, Design Department, Engineering Department, Research & Development (R&D) Department	BoM, Design	1	Material of each component	
D008	Composition	List of hazardous/s carce materials	Component	Environmental Cost, Remanufacturing &Repair ability &Reuse &Recycling &Upgradability =EoL	Impact,	Public Reports, Scientific Literature		2		
D009	Composition	Origin	Component	Environmental Circularity, Cost	Impact,	PLM, Engineering Department, Design Department, Research & Development (R&D) Department		3	Virgin, recycled, reused, remanufactured	

D010	Composition	Origin	Raw material	Environmental Circularity, aspects	Impact, Cost, Social	PLM, Internal knowledge, PLM, Engineering Department, Design Department, Research & Development (R&D) Department	3	Virgin, recycled, reused, remanufactured The social aspect is due to the origin of the material (it is not suggested to use conflictive materials)
D011	Classification	Category of mechatronic product	Product	Environmental Cost	Impact,	PLM, Public Reports, Standards	0	Defined in <i>Product identification</i>

Table App. I. 2. Manufacturing information collected during the Life Cycle Engineering phase.

ID	Parameter level 0	Parameter level 1	Parameter level 2	Related area	Data source	Uncertainty score [0-5]	Notes
M001	Technology	Manufacturing process	Component	Environmental Impact, Cost, Manufacturing, Remanufacturing&Repairability&Reuse&Recycling &Upgradability =EoL	BoM, PLM, Production Department	0	
M002	Plant consumption	Energy consumption	Component	Environmental Impact, Cost, Manufacturing, Remanufacturing	PLM, Production Department	0	
M003	Plant consumption	Energy consumption	Product	Environmental Impact, Cost, Manufacturing, Remanufacturing	PLM, Production Department	0	
M004	Plant consumption	Water consumption	Component	Environmental Impact, Cost, Manufacturing, Remanufacturing	PLM, Production Department	0	
M005	Plant consumption	Water consumption	Product	Environmental Impact, Cost, Manufacturing, Remanufacturing	PLM, Production Department	0	
M006	Plant consumption	Gas consumption	Component	Environmental Impact, Cost, Manufacturing, Remanufacturing	PLM, Production Department	0	
M007	Plant consumption	Gas consumption	Product	Environmental Impact, Cost, Manufacturing, Remanufacturing	PLM, Production Department	0	
M008	Plant location	Region/Country	Component	Environmental Cost	PLM, Logistics and Supply	0	

						Chain Department			
M009	Plant location	Region/Cou ntry	Product	Environmental Cost	Impact,	PLM, Logistics and Supply Chain Department	0		
M010	Plant location	Working conditions in that country	Component	Social aspects		Public Reports, Statistics, Public Reports, Statistics, Human Resources (HR) Department	4		
M011	Plant location	Working conditions in that country	Product	Social aspects		Public Reports, Statistics, Human Resources (HR) Department	4		
M012	Logistics	Transport of raw materials	Component	Environmental Cost	Impact,	PLM, Logistics and Supply Chain Department, Procurement Department	3		Usually it is based on assumptions (because the impact of this parameter is low)
M013	Logistics	Transport of subassemblies	Component	Environmental Cost	Impact,	PLM, Procurement Department, Logistics and Supply Chain Department	3		Usually it is based on assumptions (because the impact of this parameter is low)

M014	Logistics	Transport of final product	Product	Environmental Cost	Impact,	PLM, Logistics and Supply Chain Department	3	Usually it is based on assumptions (because the impact of this parameter is low)
M015	Importance level	Target components/ Main functional modules	Component	Circularity, Remanufacturing&Repair ability&Reuse&Recycling &Upgradability =EoL		Public Reports, Engineering Department, Design Department, Research & Development (R&D) Department	3	

Table App. I. 3. Use and maintenance information collected during the Life Cycle Engineering phase.

ID	Parameter level 0	Parameter level 1	Parameter level 2	Related area		Data source	Uncertainty score [0-5]	Notes
U001	Durability	Lifespan	Component	Environmental Circularity, Cost	Impact,	Public Reports, Statistics, Engineering Department, Research & Development (R&D) Department, Design Department	3	
U002	Durability	Lifespan	Product	Environmental Circularity, Cost	Impact,	Public Reports, Statistics, Engineering Department, Research & Development (R&D) Department, Design Department	3	
U003	Efficiency	Energy consumption (use phase)	Product	Environmental Cost	Impact,	Public Reports, Statistics, Embedded sensors	5	The energy consumption data available is calculated in a very specific conditions (usually

								differs from the actual consumption) Using DPP the uncertainty would be drastically reduced
U004	Efficiency	Resources consumption (use phase)	Product	Environmental Cost	Impact,	Statistics, Public Reports, Statistics, Embedded sensors	5	Depends a lot on user behaviour (the uncertainty can be reduced using for example the Digital Product Passport or some sensor that allows the collection of this information)
U005	Durability	Failure rate of target components	Component	Circularity, Reuse, Cost	Repairability,	Internal knowledge, Statistics, Public Reports, Statistics, Engineering Department, Research & Development (R&D) Department, Design Department, Quality Assurance (QA) Department	4	Target components or main functional modules

U006	Target market	Region/Country during use	Product	Environmental Cost	Impact,	Statistics, Sales & Marketing Department	3	
U007	Logistics	Transport to the final user	Product	Environmental Cost	Impact,	Statistics, Logistics and Supply Chain Department	3	Usually it is based on assumptions (because the impact of this parameter is low)
U008	Maintenance	Spare parts type	Component	Repairability, Cost, Reuse, Circularity		Standards, Research & Development (R&D) Department, Engineering Department	1	If it is a standard spare part
U009	Maintenance	Spare parts cost	Component	Repairability, Cost, Reuse, Circularity		Statistics, Procurement Department, Engineering Department, Sales & Marketing Department, Customer Support Department	4	
U010	Maintenance	Type of tools needed for the disassembly	Component	EoL, Remanufacturing&Repairability&Reuse&Recycling &Upgradability =EoL		Engineering Department, Design Department, Research &	1	

					Development (R&D) Department		
U011	Maintenance	Type of connectors used	Component	EoL, Remanufacturing&Repair ability&Reuse&Recycling &Upgradability =EoL	Internal knowledge, Engineering Department, Design Department, Research & Development (R&D) Department	1	
U012	Maintenance	Disassembly path	Component	EoL, Remanufacturing&Repair ability&Reuse&Recycling &Upgradability =EoL	Internal knowledge, Engineering Department, Design Department, Research & Development (R&D) Department	3	Number of steps It can vary from one operator doing the analysis to another one. Common rules must be defined
U013	Information	Availability	Product	EoL, Remanufacturing&Repair ability&Reuse&Recycling &Upgradability =EoL, Social aspects	Sales & Marketing Department, Customer Support Department,	3	

					Embedded sensors		
U014	Quality	Commercial guarantee	Product	Cost, Repairability	Public Reports, Quality Assurance (QA) Department	0	
U015	Maintenance	Cost	Product	Cost, Repairability	Customer Support Department, Finance & Accounting Department	4	There are many external factors than can vary the cost (the market uncertainty is very high)
U016	Maintenance	Cost	Component	Cost, Repairability	Customer Support Department, Finance & Accounting Department	4	There are many external factors than can vary the cost (the market uncertainty is very high)
U017	Maintenance	Product status	Product	Remanufacturing&Repairability&Reuse&Recycling &Upgradability =EoL	Embedded sensors, Customer Support Department	5	

Table App. I. 4. EoL information collected during the Life Cycle Engineering phase.

ID	Parameter level 0	Parameter level 1	Parameter level 2	Related area	Data source	Uncertainty score [0-5]	Notes
E001	Logistics	Transport to the disposal plant	Product	Environmental Impact, Cost	Logistics and Supply Chain Department	3	Usually it is based on assumptions (because the impact of this parameter is low)
E002	Location	Region/Country	Product	Environmental Cost, Social aspects	Logistics and Supply Chain Department, Public Reports	3	
E003	Location	Country working conditions	Product	Social aspects	Public Reports, Statistics, Public Reports, Statistics, Human Resources (HR) Department	4	
E004	Recovery	Recovery efficiency (recycling)	Material	Recycling	Scientific Literature, Statistics, Public Reports, Research & Development (R&D) Department	4	
E005	Recovery	Energy recovery (recycling)	Material	Recycling	Statistics, Scientific	3	

					Literature, Public Reports	
E006	Information	Availability for the disposal	Product	Remanufacturing&Repair ability&Reuse&Recycling &Upgradability =EoL, Social aspects	Statistics, Customer Support Department, Sales & Marketing Department	2
E007	Information	Availability for the disposal	Component	Remanufacturing&Repair ability&Reuse&Recycling &Upgradability =EoL, Social aspects	Statistics, Customer Support Department, Sales & Marketing Department	2
E008	Economical	Cost associated to EoL	Component	Cost, Remanufacturing&Repair ability&Reuse&Recycling &Upgradability =EoL	Statistics, Public Reports, & Research & Development (R&D) Department	4
E009	Economical	Residual value	Component	Cost, Remanufacturing&Repair ability&Reuse&Recycling &Upgradability =EoL	Statistics, Public Reports, & Research & Development (R&D) Department	5
E010	Composition	Number of different	Component	Environmental Circularity,	Impact, Cost, CAD, BoM, PLM,	0

materials per component	Remanufacturing&Repair ability&Reuse&Recycling &Upgradability =EoL	Engineering Department, Design Department
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APPENDIX II

The eDiM is one of the methods that can be used to calculate the disassembly time (Vanegas, et al., 2018). This metric relies on assessing disassembly time through the MOST method (Zandin, 2021). Nevertheless, its limitations become apparent when applied to intricate disassembly tasks, as it lacks the adaptability to replicate certain disassembly sequences encountered in real-world scenarios.

For this research work, its structure has been modified to be usable with any type of mechatronic product. One of the critical points identified was the limited flexibility the method offered when calculating tool positioning time. This led to the addition of a column where the type of positioning can be selected according to the specifications outlined in Table App. II. 1. Columns have also been included to select the type of operator's manipulation (see Table App. II. 2) and component removal (see Table App. II. 3). Additionally, as the eDiM database is based on MOST, new sequences had to be created to obtain the time for the newly introduced features (Pulikottil, Boix Rodríguez, & Peeters). This way, the flexibility in time calculation through the eDiM is increased for other categories of mechatronic products.

Table App. II. 1. Types of tool positioning for eDiM database.

Positioning Type	Description	Time [s]	MOST Sequence	Reference
A	Light pressure; frequency=1	1.44	A1 B0 P3 A0	(Peeters, Tecchio, & Vanegas, 2018)
B	Light pressure; frequency>1; distance between fasteners < 5 cm	1.08	A1 B0 (P3 A0)	New
C	Light pressure; frequency>1; distance between fasteners > 5 cm	1.44	A0 B0 (P3 A1)	New
D	Care or precision, heavy pressure; frequency = 1	2.52	A1 B0 P6 A0	(Peeters, Tecchio, & Vanegas, 2018)
E	Care or precision, heavy pressure; frequency>1; distance between fasteners < 5 cm	2.16	A1 B0 (P6 A0)	New
F	Care or precision, heavy pressure; frequency>1; distance between screws > 5 cm	2.52	A0 B0 (P6 A1)	New

Table App. II. 2. Types of operator manipulation.

Manipulation Type	Description	Time [s]	MOST Sequence	Reference
A	Turning the object with one hand	1.80	A1 B0 G1 + L3	(Peeters, Tecchio, & Vanegas, 2018)
B	Turning the object with two hands	3.60	A1 B0 G3 + L6	(Peeters, Tecchio, & Vanegas, 2018)
C	Walking 3 or 4 steps	2.16	A6	New
D	Lifting the object with one hand	1.80	A1 B0 G1 + L3	New
E	Two hands manipulation	2.16	L6	New
F	Disengaging of 1-3 wires	2.52	A1 B0 G3 + L3	New
G	Disengaging of 4-6 wires	3.60	A1 B0 G3 + L6	New

Table App. II. 3. Types of component removal.

Removal Type	Description	Time [s]	MOST Sequence	Reference
A	Light object	1.44	A1 B0 G1 + A1 B0 P1	(Peeters, Tecchio, & Vanegas, 2018)
B	Heavy / interlocked object	2.16	A1 B0 G3 + A1 B0 P1	New
C	2 Light objects	4.32	(A1 B0 G3 + A1 B0 P1) (2)	New
D	3 Light objects	6.48	(A1 B0 G3 + A1 B0 P1) (3)	New
E	4 Light objects	8.64	(A1 B0 G3 + A1 B0 P1) (4)	New

APPENDIX III

Table App. III. 1 provides the inventory with all the necessary data for the LCA analysis of the first case study, the electric oven, including all materials to be considered, types of manufacturing processes, transportation of the raw materials and components, and the end-of-life for each component. On the other hand, Table App. III. 2 provides the LCI for the second case study, the cooker hood.

Table App. III. 1. Life Cycle Inventory - Case study: Electric Oven.

Assembly	Component	Weight [g]	Materialecoinvent	Manufacturingecoinvent	Type of EoL material
Asm. Structure	Side panel left	925	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
	Side panel right	930	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
	Bottom panel	975	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
	Back panel	865	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
	Top panel	755	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
	Cover rear	410	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel

Asm. Door	Door handle	425	Steel, chromium steel 18/8 {GLO} market for Cut-off, U	Metal working, average for steel product manufacturing {GLO} market for Cut-off, U	Steel
	Front glass	2740	Flat glass, coated {RER} market for flat glass, coated Cut-off, U	Tempering, flat glass {GLO} market for Cut-off, U	Glass
		200	Steel, chromium steel 18/8, hot rolled {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel
		80	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
		20	N-olefins {GLO} market for Cut-off, U	NA	Landfill
		1845	Flat glass, coated {RER} market for flat glass, coated Cut-off, U	Tempering, flat glass {GLO} market for Cut-off, U	Glass
	Glass 2	1845	Flat glass, coated {RER} market for flat glass, coated Cut-off, U	Tempering, flat glass {GLO} market for Cut-off, U	Glass
	Glass 3	2000	Flat glass, coated {RER} market for flat glass, coated Cut-off, U	Tempering, flat glass {GLO} market for Cut-off, U	Glass
	Glass 4	180	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
	Top door cover	80	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
Bottom door cover					
Asm. Cooling motor and fan	Motor	33	Aluminium, cast alloy {GLO} market for Cut-off, U	Casting, aluminium, lost-wax {GLO} market for Cut-off, U	Non-steel

		465	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel
		33	Copper, cathode {GLO} market for Cut-off, U	Wire drawing, copper {GLO} market for Cut-off, U	WEEE
	Motor plate	119	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
	Cooling fan wheel	25	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
	Fan wheel disc	30	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
Asm. Hinges	Hinge left	100	Steel, chromium steel 18/8 {GLO} market for Cut-off, U	Wire drawing, steel {GLO} market for Cut-off, U	Steel
		335	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
	Hinge right	75	Steel, chromium steel 18/8 {GLO} market for Cut-off, U	Wire drawing, steel {GLO} market for Cut-off, U	Steel
		175	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel

Asm. Insulation	Insulation	1930	Glass wool mat {GLO} market for Cut-off, U	NA	Landfill	
Asm. Hot air motor	Motor	33	Aluminium, cast alloy {GLO} market for Cut-off, U	Casting, aluminium, lost-wax {GLO} market for Cut-off, U	Non-steel	
		465	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel	
		33	Copper, cathode {GLO} market for Cut-off, U	Wire drawing, copper {GLO} market for Cut-off, U	WEEE	
	Fan	80	Steel, chromium steel 18/8 {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel	
		5	Steel, chromium steel 18/8 {GLO} market for Cut-off, U	Chromium steel removed by turning, average, computer numerical controlled {GLO} market for Cut-off, U	Steel	
Asm. elements	Heating	Top HE	410	Iron-nickel-chromium alloy {GLO} market for Cut-off, U	Drawing of pipe, steel {GLO} market for Cut-off, U	Steel
		Ring HE	225	Iron-nickel-chromium alloy {GLO} market for Cut-off, U	Drawing of pipe, steel {GLO} market for Cut-off, U	Steel
	Bottom HE	230	Iron-nickel-chromium alloy {GLO} market for Cut-off, U	Drawing of pipe, steel {GLO} market for Cut-off, U	Steel	
	Bottom HE support	700	Iron-nickel-chromium alloy {GLO} market for Cut-off, U	Drawing of pipe, steel {GLO} market for Cut-off, U	Steel	
Asm. Cavity	Metal panels	1862	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel	

	Side grids	960	Steel, chromium steel 18/8 {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Wire drawing, steel {GLO} market for Cut-off, U • Welding, arc, steel {GLO} market for Cut-off, U 	Steel
	Cavity	6879	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Powder coat, steel {GLO} market for Cut-off, U 	Steel
	Cables	270	Copper, cathode {GLO} treatment of used cable Cut-off, U	Wire drawing, copper {GLO} market for Cut-off, U	WEEE
		30	Polyvinylchloride, bulk polymerised {GLO} market for Cut-off, U	Injection moulding {GLO} market for Cut-off, U	WEEE
	Lamp	35	Flat glass, coated {RER} market for flat glass, coated Cut-off, U	Tempering, flat glass {GLO} market for Cut-off, U	Glass
		5	Diode, glass-, for through-hole mounting {GLO} market for Cut-off, U	NA	WEEE
Asm. User Interface	Glass	333	Flat glass, coated {RER} market for flat glass, coated Cut-off, U	Tempering, flat glass {GLO} market for Cut-off, U	Glass
	Glue	30	N-olefins {GLO} market for Cut-off, U	NA	Landfill
	UI Box	75	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
	Metal parts	400	Steel, low-alloyed, hot rolled {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel

		132	Steel, chromium steel 18/8, hot rolled {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel
	Electronic components	100	Printed wiring board, surface mounted, unspecified, Pb free {GLO} market for Cut-off, U	NA	WEEE
		45	Glass, for liquid crystal display {GLO} market for Cut-off, U	NA	WEEE
Asm. Motherboard	PCB	225	Printed wiring board, surface mounted, unspecified, Pb free {GLO} market for Cut-off, U	NA	WEEE
Asm. Packaging	Plastic parts	600	Polystyrene foam slab {GLO} market for Cut-off, U	NA	Plastics
	Cardboard parts	100	Solid bleached and unbleached board carton {RER} market for solid bleached and unbleached board carton Cut-off, U	NA	Paper
Asm. Power cord	Cables	185	Copper, cathode treatment of used cable {GLO} Cut-off, U	Wire drawing, copper {GLO} market for Cut-off, U	WEEE
		20	Polyvinylchloride, bulk polymerised {GLO} market for Cut-off, U	Injection moulding {GLO} market for Cut-off, U	WEEE
	Cables support	50	Polycarbonate {GLO} market for Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics

Table App. III. 2. Life Cycle Inventory - Case study: Cooker Hood.

Assembly	Component	Qty.	Weight [g]	Materialecoinvent	Manufacturingecoinvent	Type of EoL material
Asm. Structure	Chassis	1	4009	Steel, chromium steel 18/8, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Welding, arc, steel {GLO} market for Cut-off, U 	Steel
	Crosspiece	2	968	Steel, chromium steel 18/8, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U 	Steel
	Lateral	1	226	Steel, chromium steel 18/8, hot rolled {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U 	Steel
	Blower support	1	239	Steel, low-alloyed {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
	Back platform	1	1477	Steel, low-alloyed {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
	Front platform	1	498	Steel, low-alloyed {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
	Flange	1	50	Polypropylene, granulate {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Injection moulding {GLO} market for Cut-off, U 	Plastics
	Support bracket	1	42	Steel, low-alloyed {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U 	Steel

	Motor box bracket	1	298	Steel, low-alloyed {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Zinc coat, pieces {GLO} market for Cut-off, U • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
Asm. Aesthetic	Front glass	1	562	Flat glass, coated {RER} market for flat glass, coated Cut-off, U	Tempering, flat glass {GLO} market for Cut-off, U	Glass
		1	30	Acrylonitrile-butadiene-styrene copolymer {GLO} market for Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
		2	53	Steel, low-alloyed {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
		1	0.5	N-olefins {GLO} market for Cut-off, U	NA	Landfill
	1	1.65	Epoxy resin, liquid {RER} market for epoxy resin, liquid Cut-off, U	NA	Landfill	
	1	12.68	Silicone product {RER} market for silicone product Cut-off, U	NA	Landfill	
	Back glass	1	560	Flat glass, coated {RER} market for flat glass, coated Cut-off, U	Tempering, flat glass {GLO} market for Cut-off, U	Glass
		2	53	Steel, low-alloyed {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel

		1	1.32	Epoxy resin, liquid {RER} market for epoxy resin, liquid Cut-off, U	NA	Landfill
		1	10.14	Silicone product {RER} market for silicone product Cut-off, U	NA	Landfill
		1	0.50	N-olefins {GLO} market for Cut-off, U	NA	Landfill
	Bracket BG	1	3	Steel, chromium steel 18/8, hot rolled {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel
	Glass bracket	2	139	Steel, chromium steel 18/8, hot rolled {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel
	H2H passive IR receiver	1	10	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
		1	5	Light emitting diode {GLO} market for Cut-off, U	NA	WEEE
Asm. Blower	Motor	1	94	Aluminium, cast alloy {GLO} market for Cut-off, U	Casting, aluminium, lost-wax {GLO} market for Cut-off, U	Non-steel
		1	10	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
		1	43	Aluminium, cast alloy {GLO} market for Cut-off, U	Casting, aluminium, lost-wax {GLO} market for Cut-off, U	Non-steel
		1	10	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
		1	323	Steel, low-alloyed {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel
		1	100	Aluminium alloy, AlMg3 {GLO} market for Cut-off, U	Metal working, average for aluminium product manufacturing {GLO} market for Cut-off, U	Non-steel

		1	1152	Steel, low-alloyed {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel
		1	300	Copper, cathode {GLO} market for Cut-off, U	Wire drawing, copper {GLO} market for Cut-off, U	WEEE
		1	18	Copper, cathode {GLO} market for Cut-off, U	Wire drawing, copper {GLO} market for Cut-off, U	WEEE
		1	2	Polyvinylchloride, bulk polymerised {GLO} market for Cut-off, U	Injection moulding {GLO} market for Cut-off, U	WEEE
		1	20	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
	Capacitor	1	47	Capacitor, auxiliaries and energy use {GLO} market for Cut-off, U	NA	WEEE
	Fan	1	187	Polypropylene, granulate {GLO} market for Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
		1	6	Brass {RoW} market for brass Cut-off, U	Casting, brass {GLO} market for Cut-off, U	Non-steel
	Right cochlea	1	236	Polypropylene, granulate {GLO} market for Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
	Left cochlea	1	259	Polypropylene, granulate {GLO} market for Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
Asm. Chimney	Top structure	1	2500	Steel, low-alloyed {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U • Zinc coat, pieces {GLO} market for Cut-off, U 	Steel
	Bottom structure	1	3530	Steel, low-alloyed {GLO} market for Cut-off, U	<ul style="list-style-type: none"> • Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U 	Steel

	Top tubes	1	2620	Steel, chromium steel 18/8 {GLO} market for Cut-off, U	<ul style="list-style-type: none"> Zinc coat, pieces {GLO} market for Cut-off, U Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel
	Bottom tubes	1	3670	Steel, chromium steel 18/8 {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel
Asm. Grease filters	Grease filter	3	44	Polypropylene, granulate {GLO} market for Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
		3	120	Aluminium alloy, AlMg3 {GLO} market for Cut-off, U	Metal working, average for aluminium product manufacturing {GLO} market for Cut-off, U	Non-steel
Asm. LED lamps	LED	4	4	Light emitting diode {GLO} market for Cut-off, U	NA	WEEE
	Case	4	30	Steel, chromium steel 18/8, hot rolled {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Steel
		4	6	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
	Cables	4	4.2	Copper, cathode {GLO} market for Cut-off, U	Wire drawing, copper {GLO} market for Cut-off, U	WEEE
		4	1.8	Polyvinylchloride, bulk polymerised {GLO} market for Cut-off, U	Injection moulding {GLO} market for Cut-off, U	WEEE
Asm. User Interface	PCB	1	36.6	Printed wiring board, surface mounted, unspecified, Pb free {GLO} market for Cut-off, U	NA	WEEE
	Housing box	1	45	Acrylonitrile-butadiene-styrene copolymer {GLO} market for Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics

Asm. Electronic Components	Electronic box and components	1	102	Printed wiring board, surface mounted, unspecified, Pb free {GLO} market for Cut-off, U	NA	WEEE
		1	60	Aluminium alloy, AlMg3 {GLO} market for Cut-off, U	Deep drawing, steel, 650 kN press, single stroke {GLO} market for Cut-off, U	Non-steel
		1	257	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
		1	78.50	Capacitor, auxiliaries and energy use {GLO} market for Cut-off, U	NA	WEEE
		1	105	Capacitor, auxiliaries and energy use {GLO} market for Cut-off, U	NA	WEEE
		1	6	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
		3	4	Nylon 6-6 {RER} market for nylon 6-6 Cut-off, U	Injection moulding {GLO} market for Cut-off, U	Plastics
Asm. Packaging	Plastic bag	1	56	Polyethylene, high density, granulate {Europe without Switzerland} polyethylene, high density, granulate, recycled to generic market for high density PE granulate Cut-off, U	NA	Plastics
		2	857	Cleft timber, measured as dry mass {Europe without Switzerland} market for Cut-off, U	NA	Wood
		1	7290	Corrugated board box {RER} market for corrugated board box Cut-off, U	NA	Paper
Asm. Power cord	Cables	1	91	Copper, cathode {GLO} treatment of used cable Cut-off, U	Wire drawing, copper {GLO} market for Cut-off, U	WEEE

			39	Polyvinylchloride, bulk polymerised {GLO} market for Cut-off, U	Injection moulding {GLO} market for off, U	WEEE
Asm. Other cables	Wires	1	180	Copper, cathode {GLO} treatment of used cable Cut-off, U	Wire drawing, copper {GLO} market for Cut-off, U	WEEE
			20	Polyvinylchloride, bulk polymerised {GLO} market for Cut-off, U	Injection moulding {GLO} market for off, U	WEEE

APPENDIX IV

The literature review has been carried out for all the appliances related to household chores presented in the introduction of the Section 4. In this way, different normalization indices have been defined for each of them.

The keyword-based search method for each product family is presented in Figure App. IV. 1, along with the Boolean operators (AND / OR) used. After the filtering process based on the title, abstract, and keywords, 595 records were identified (using the *Scopus*, *Springer*, and *Taylor & Francis* databases, as suggested by the methodology).

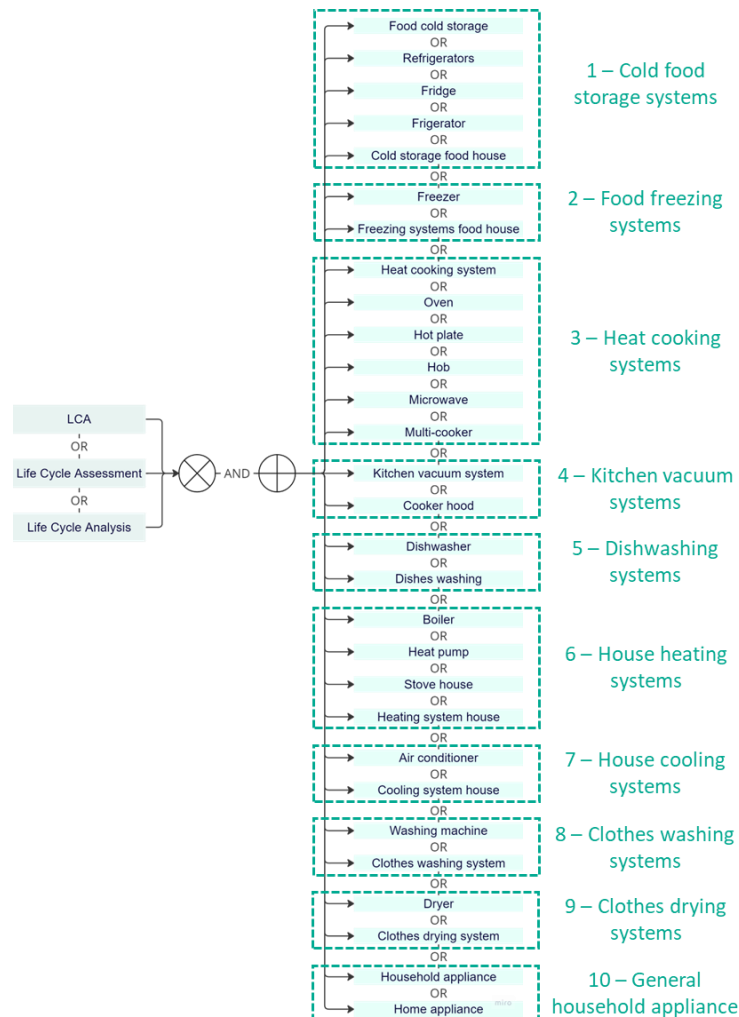


Figure App. IV. 1. Keywords with Boolean search strategy.

After applying the exclusion criteria explained in the methodology, the final portfolio used in this research work encompasses 59 documents (article, conference paper, and book chapters). Figure App. IV. 2 shows an overview of the article refinement and screening process. Table App. IV. 1 summarizes them, indicating the title, year of publication, type of document, and source.

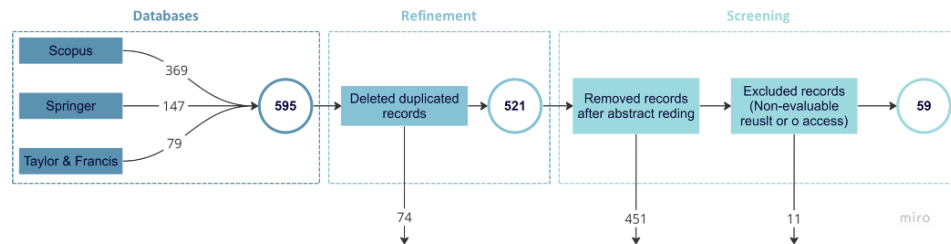


Figure App. IV. 2. Record selection process.

After analysing all the retrieved works, with a focus on the functional units used for the LCA analysis, the different normalization indices can be defined for the different families (see Table App. IV. 2).

Table App. IV. 1. Final portfolio after the literature review.

Title	Year	Type of document	Source	Reference
Material flow, economic and environmental life cycle performances of informal electronic waste recycling in a Thai community	2022	Article	Scopus	(Arain, et al., 2022)
Household Appliance Lifecycle and Sustainable Development	2022	Conference Paper	Scopus	(Hamrol, Pawelczak, & Osiński, 2022)
Product Life Cycle Analysis on the Example of a Home Appliance	2022	Conference Paper	Scopus	(Skorup, Rozing, Heffer, & Vidaković, 2022)
Life Cycle Assessment of an Air-Source Heat Pump and a Condensing Gas Boiler Using an Attributional and a Consequential Approach	2022	Conference Paper	Scopus	(Naumann, Schropp, & Gaderer, 2022)
Identifying the lifecycle ODP and GWP effects of the refrigerants from household air-conditioners in Macau	2021	Article	Scopus	(Wang, et al., 2021)
Quantifying the environmental impact of clustering strategies in waste management: A case study for plastic recycling from large household appliances	2021	Article	Scopus	(Bracquené, et al., 2021)
Toward sustainable refrigeration systems: Life cycle assessment of a bench-scale solar-thermal adsorption refrigerator	2021	Article	Scopus	(Denzinger, et al., 2021)
Cradle-to-grave life cycle assessment of an air to water heat pump: Case study for the Lebanese context and comparison with solar and conventional electric water heaters for residential application	2021	Article	Scopus	(Saoud, Harajli, & Manneh, 2021)
Environmental assessment of latent heat thermal energy storage technology system with phase change material for domestic heating applications	2021	Article	Scopus	(Chocontá Bernal, et al., 2021)
Environmental life cycle assessment of heating systems in the UK: Comparative assessment of hybrid heat pumps vs. condensing gas boilers	2021	Article	Scopus	(Lin, Clavreul, Jeandaux, Crawley, & Butnar, 2021)
Effect of climate change and occupant behaviour on the environmental impact of the heating and cooling systems of a real apartment. A parametric study through life cycle assessment	2021	Article	Scopus	(Fajilla, Borri, De Simone, Cabeza, & Bragança, 2021)
Environmental impacts of household appliances in Europe and scenarios for their impact reduction	2020	Article	Scopus	(Hischier, Reale, Castellani, & Sala, 2020)

Assessing domestic environmental impacts through LCA using data from the scientific literature	2020	Article	Scopus	(Spreafico & Russo, 2020)
A soft computing framework to support consumers in obtaining sustainable appliances from the market	2020	Article	Scopus	(Santos, Abreu, Soares, Mendes, & Calado, 2020)
The consumer footprint: Monitoring sustainable development goal 12 with process-based life cycle assessment	2019	Article	Scopus	(Sala & Castellani, 2019)
Comparative life cycle assessment of electric and gas ovens in the Italian context: An environmental and technical evaluation	2019	Article	Scopus	(Landi, Consolini, Germani, & Favi, 2019)
Improving waste electric and electronic equipment management at full-scale by using material flow analysis and life cycle assessment	2019	Article	Scopus	(Fiore, Ibanescu, Teodosiu, & Ronco, 2019)
A Multiperspective Assessment of Best Available Energy End-Use Technologies in India's Households	2019	Article	Scopus	(Singh, Henriques, & Martins, 2019)
A multi-criteria index to support ecodesign implementation in manufacturing products: benefits and limits in real case studies	2019	Article	Taylor & Francis	(Rossi, Papetti, Marconi, & Germani, 2019)
Sustainability assessment of home-made solar cookers for use in developed countries	2019	Article	Scopus	(Mendoza, Gallego-Schmid, Rivera, Rieradevall, & Azapagic, 2019)
Effect of combustion technology and biogenic CO ₂ impact factor on global warming potential of wood-to-heat chains	2019	Article	Scopus	(Pelletier, et al., 2019)
One year of clothing consumption of a German female consumer	2019	Conference Paper	Scopus	(Piontek, Rapaport, & Müller, 2019)
Comparative life cycle assessment of cooking appliances in Italian kitchens	2018	Article	Scopus	(Favi C. , Germani, Landi, Mengarelli, & Rossi, 2018)
Life Cycle Assessment of Home Smart Objects: Kitchen Hood Cases	2018	Conference Paper	Scopus	(Castorani, Rossi, Germani, Mandolini, & Vita, 2018)
Lifecycle tools as a support for the eco-design innovation of domestic appliances	2017	Conference Paper	Scopus	(Papetti, Germani, Marconi, & Favi, 2017)
Are district heating systems and renewable energy sources always an environmental win-win solution? A life cycle assessment case study in Tuscany, Italy	2017	Review	Scopus	(Bartolozzi, Rizzi, & Frey, 2017)

A multidisciplinary method for sustainability assessment of PSS: Challenges and developments	2016	Article	Scopus	(Allais & Gobert, 2016)
Ventilation heat recovery jointed low-temperature heating in retrofitting - An investigation of energy conservation, environmental impacts and indoor air quality in Swedish multifamily houses	2016	Article	Scopus	(Wang, Ploskić, Song, & Holmberg, 2016)
Life cycle assessment of horizontal-axis washing machines in China	2016	Article	Scopus	(Yuan, Zhang, & Liu, 2016)
The recyclability benefit rate of closed-loop and open-loop systems: A case study on plastic recycling in Flanders	2015	Article	Scopus	(Huysman, et al., 2015)
Simplification strategies for mechatronic products: A methodology proposal	2015	Article	Scopus	(Mengarelli, et al., 2015)
Influence of mechanical design on the evolution of the environmental impact of an induction hob	2015	Article	Springer	(Pina, Elduque, Javierre, Martínez, & Jiménez, 2015)
Product innovations and eco-sustainability: An approach to evaluate the relationships	2014	Article	Scopus	(Papetti, Germani, & Mandolini, 2014)
Comparing environmental product footprint for electronic and electric equipment: a multi-criteria approach	2014	Article	Taylor & Francis	(De Felice, Elia, Gnoni, & Petrillo, 2014)
Product-Service Lifecycle Management in Manufacturing: An Industrial Case Study	2014	Conference Paper	Springer	(Peruzzini, Germani, & Marilungo, 2014)
Domestic solar thermal water heating: A sustainable option for the UK?	2014	Article	Scopus	(Greening & Azapagic, 2014)
Comparison of LCA results of low temperature heat plant using electric heat pump, absorption heat pump and gas-fired boiler	2014	Article	Scopus	(Nitkiewicz & Sekret, 2014)
Heating systems LCA: Comparison of biomass-based appliances	2014	Article	Scopus	(Cespi, et al., 2014)
Annual evaluation of energy, environmental and economic performances of a membrane liquid desiccant air conditioning system with/without ERV	2014	Article	Scopus	(Abdel-Salam & Simonson, 2014)
Comparative environmental impact assessment of residential HVAC systems	2013	Book Chapter	Scopus	(Javani, Abraham, Dincer, & Rosen, 2013)
Research on Household Electrical Appliances' Supply Chain Based on the LCA Method in the Situation of Low-Carbon Product Certification	2013	Conference Paper	Springer	(Gao & Shi, 2013)
Investigating the Sustainability of Product and Product-Service Systems in the B2C Industry	2013	Conference Paper	Springer	(Peruzzini & Germani, 2013)

Heat pumps versus combined heat and power production as CO2 reduction measures in Finland	2013	Article	Scopus	(Rinne & Syri, 2013)
Comparative exergoenvironmental analysis and assessment of various residential heating systems	2013	Article	Scopus	(Abusoglu & Sedeeq, 2013)
Analysis on energy-saving effect and environmental benefit of a novel hybrid-power gas engine heat pump	2013	Article	Scopus	(Wang, Cai, Shao, Jin, & Zhang, 2013)
Assessing the Replacement of Electrical Home Appliances for the Environment: An Aid to Consumer Decision Making Tasaki et al. Replacement of Home Appliances for the Environment	2013	Article	Scopus	(Tasaki, Motoshita, Uchida, & Suzuki, 2013)
Dishwasher's environmental impact analysis and improvement by addressing EUP directive in China dishwasher manufactures	2012	Article	Scopus	(Zhifeng, Yang, Di, & Bo, 2012)
Life cycle assessment of a single-family residence built to either conventional- or passive house standard	2012	Article	Scopus	(Dahlstrøm, Sørnes, Eriksen, & Hertwich, 2012)
Implementation of energy efficiency standards of household refrigerator/freezer in China: Potential environmental and economic impacts	2011	Article	Scopus	(Tao & Yu, 2011)
Life cycle assessment of a semi-indirect ceramic evaporative cooler vs. a heat pump in two climate areas of Spain	2011	Article	Scopus	(Rey Martínez, et al., 2011)
Strategies for reducing the environmental impacts of room air conditioners in Europe	2011	Article	Scopus	(Grignon-Masse, Riviere, & Adnot, 2011)
Hybrid LCA of a design for disassembly technology: Active disassembling fasteners of hydrogen storage alloys for home appliances	2010	Article	Scopus	(Nakamura & Yamasue, 2010)
Energy and carbon impact analysis of a solar thermal collector system	2010	Article	Taylor & Francis	(Menziez & Roderick, 2010)
Life cycle assessment of a domestic cooker hood	2010	Article	Scopus	(Bevilacqua, Caresana, Comodi, & Venella, 2010)
Visualisation of LCA environmental impacts of electrical and electronic products using multidimensional scaling	2009	Article	Scopus	(Gutierrez, Adenso-Diaz, Lozano, & Barba-Gutierrez, 2009)
The role of washing machines in life cycle assessment studies the dangers of using lca for prioritization	2009	Review	Scopus	(Cullen & Allwood, 2009)

Evaluating the reduction in green house gas emissions achieved by the implementation of the household appliance recycling in Japan	2007	Article	Scopus	(Nakano, Aoki, Yagita, & Narita, 2007)
Comparison of four methods for integrating environmental and economic aspects in the end-of-life stage of a washing machine	2006	Article	Scopus	(Park, Tahara, Jeong, & Lee, 2006)
Hybrid LCC of appliances with different energy efficiency	2006	Article	Scopus	(Nakamura & Kondo, 2006)

Table App. IV. 2. Normalized indices for environmental impact assessment of household appliances.

Num.	Household appliance family	Raw Material Index	Manufacturing Index	Use phase Index	EoL Index	Transport Index	Maintenance Index
1	Cold food storage systems	$Ri = \frac{Ei_{RM}}{Vs} \times y$	$Mi = \frac{Ei_M}{w} \times y$	$Ui = \frac{Ei_U}{P} \times Y$			
		Unit [Pt*kg*m ⁻³ *years ⁻¹]	Unit [Pt*kg*m ⁻³ *years ⁻¹]	Unit [Pt*W*m ⁻³ *years ⁻¹]			
2	Food freezing systems (no papers available, work based on the cold food storage systems)	$Ri = \frac{Ei_{RM}}{Vs} \times y$	$Mi = \frac{Ei_M}{w} \times y$	$Ui = \frac{Ei_U}{P} \times Y$	$Ei = \frac{Ei_{EoL}}{w} \times y$	$Ti = \frac{Ei_T}{V \times w} \times y$	$Si = \frac{Ei_S}{ws} \times ys$
		Unit [Pt*kg*m ⁻³ *years ⁻¹]	Unit [Pt*kg*m ⁻³ *years ⁻¹]	Unit [Pt*W*m ⁻³ *years ⁻¹]	Unit [Pt*kg ⁻¹ *years ⁻¹]	Unit [Pt*m ³ *kg*Km ⁻¹ *years ⁻¹]	Unit [Pt*kg*years ⁻¹]
3	Heat cooking systems	$Ri = \frac{Ei_{RM}}{Vc} \times y$	$Mi = \frac{Ei_M}{w} \times y$	$Ui = \frac{Ei_U}{P \times tb} \times h \times Y$			
	3.1. Closed systems	Unit [Pt*kg*m ⁻³ *years ⁻¹]	Unit [Pt*kg*m ⁻³ *years ⁻¹]	Unit [Pt*W*m ⁻³]			
	3.2. Open systems	$Ri = \frac{Ei_{RM}}{A} \times y$	$Mi = \frac{Ei_M}{w} \times y$	$Ui = \frac{Ei_U}{P \times tw} \times h \times Y$			

4	Kitchen systems	vacuum	Unit [Pt*kg*m ⁻² *years ⁻¹] $Ri = \frac{Ei_{RM}}{\frac{A}{w} \times y}$	Unit [Pt*kg*m ⁻² *years ⁻¹] $Mi = \frac{Ei_M}{\frac{A}{w} \times y}$	Unit [Pt*W*m ⁻²] $Ui = \frac{Ei_U}{\frac{Q}{P} \times h \times Y}$
5	Dishwashing systems		Unit [Pt*kg*m ⁻² *years ⁻¹] $Ri = \frac{Ei_{RM}}{\frac{Vw}{w} \times y}$	Unit [Pt*kg*m ⁻² *years ⁻¹] $Mi = \frac{Ei_M}{\frac{Vw}{w} \times y}$	Unit [Pt*W*m ⁻³] $Ui = \frac{Ei_U}{\frac{P \times Wc}{P \times Wc} \times n \times ct \times Y}$
6	House systems	heating	Unit [Pt*kg*m ⁻³ *years ⁻¹] $Ri = \frac{Ei_{RM}}{\frac{P}{w} \times y}$	Unit [Pt*kg*m ⁻³ *years ⁻¹] $Mi = \frac{Ei_M}{\frac{P}{w} \times y}$	Unit [Pt*W*1*m ⁻³ *cycle ⁻¹ *h ⁻¹] $Ui = \frac{Ei_U}{\frac{Hs}{P} \times h \times Y}$
7	House systems	cooling	Unit [Pt*kg*W ⁻¹ *years ⁻¹] $Ri = \frac{Ei_{RM}}{\frac{Q}{w} \times y}$	Unit [Pt*kg*W ⁻¹ *years ⁻¹] $Mi = \frac{Ei_M}{\frac{Q}{w} \times y}$	Unit [Pt*W*m ⁻² *h ⁻¹] $Ui = \frac{Ei_U}{\frac{Q}{P} \times h \times Y}$
8	Clothes systems	washing	Unit [Pt*kg*h*m ⁻³ *years ⁻¹] $Ri = \frac{Ei_{RM}}{\frac{C}{w} \times y}$	Unit [Pt*kg*h*m ⁻³ *years ⁻¹] $Mi = \frac{Ei_M}{\frac{C}{w} \times y}$	Unit [Pt*W*m ⁻³] $Ui = \frac{Ei_U}{\frac{C}{P \times Wc} \times n \times ct \times Y}$
9	Clothes systems	drying	Unit [Pt*years ⁻¹] $Ri = \frac{Ei_{RM}}{\frac{C}{w} \times y}$	Unit [Pt*years ⁻¹] $Mi = \frac{Ei_M}{\frac{C}{w} \times y}$	Unit [Pt*W*1*kg ⁻¹ *cycle ⁻¹ *h ⁻¹] $Ui = \frac{Ei_U}{\frac{C}{P \times Wc} \times n \times h \times Y}$
			Unit [Pt*years ⁻¹]	Unit [Pt*years ⁻¹]	

Unit	[P ^t W ^l year ^{kg} h ^{cycle} h ⁻¹]
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The following parameters were used within the equations:

- Ei_{RM} : environmental impact of raw material phase (e.g., GWP, WCP, SOP, or CED)
- Ei_M : environmental impact of manufacturing phase (e.g., GWP, WCP, SOP, or CED)
- Ei_U : environmental impact of use phase (e.g., GWP, WCP, SOP, or CED)
- Ei_{EoL} : environmental impact of EoL phase (e.g., GWP, WCP, SOP, or CED)
- Ei_T : environmental impact of transportation phase (e.g., GWP, WCP, SOP, or CED)
- Ei_S : environmental impact of maintenance phase (e.g., GWP, WCP, SOP, or CED)
- w : product weight [kg]
- V_s : volume of storage capacity [m³]
- V_c : volume of cooking capacity [m³]
- A : total cooking surface area [m²]
- Q : maximum air flow rate [m³/h]
- V_w : volume washing capacity [m³]
- C : Clothes maximum capacity [kg]
- P : Maximum power [W]
- W_c : maximum water consumption during a cycle [l]
- H_s : surface heated considered in the study [m²]
- n : number of cycles considered per year [cycle/year]
- y : duration of the product [years]
- Y : timeframe considered in the scope of the study [years]
- t_b : time needed to heat up a chilled wet brick from 5°C to 60°C (standard EN15181) (CEN/CENELEC, 2020a) [h]
- t_w : time to heat a pan of water at maximum burner to 70°C (standard EN203-2-1) (CEN/CENELEC, 2021) [h]
- h : time of use per year considered [h/year]
- ct : maximum cycle time [h]
- D : distance for the transport phase [km]
- V : volume of the product during transportation [m³]
- ws : weight of the spare part [kg]
- ys : duration of the spare part [years]

In the equations, the unit "Pt" is used as the unit of measurement for environmental impacts in various phases. It should be noted that it can be replaced with the corresponding unit of measure for the specific LCIA indicators being considered. As a result, the ultimate unit of measurement is determined by the specific environmental impact indicator under analysis.