Introduction to the Eco-Design Methodology and the Role of Product Carbon Footprint

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Abstract Eco-design is used as a tool in the manufacturing and services sectors for improving the sustainability of products by integrating environmental aspects into the design stage, where most of the product impacts are determined. Laws (e.g., EU eco-design directive) and international schemes (e.g., ISO 14006) have encouraged the use of eco-design by companies; in addition, the literature has reported advances in methodology and widespread case studies in different economic sectors. This chapter aims to show a combined design for environment (DfE) and life cycle assessment (LCA) methodology for the implementation of eco-design by companies. The steps and tools of the methodology, as well as the most common strategies, are described. Product carbon footprint (PCF) plays an important role in the methodology in two main ways. First, PCF is one of the indicators that can be calculated with LCA, which has become a common environmental indicator used by companies, not only as quantitative data of the current environmental performance but also as a benchmark for further improvements. Second, PCF is used as a strategy for environmental communication to consumers through eco-labeling. The main strength of the carbon footprint is that stakeholders (business and consumers) are aware of and understand its meaning due to the presence of carbon emissions and global warming in mass media and public science studies.

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1 Introduction

Design for environment (DfE) or eco-design has been increasingly used in sustainable manufacturing during recent decades. The design step of a product has been identified as an important life cycle stage in which 80 % of the environmental burdens are determined (Tischner et al. 2000).

The first EU Directive on eco-design was directive 2005/32/EC on Eco-design of energy-used products (European Council 2005a). This directive replaced former energy efficiency directives for hot-water boilers (Directive 92/42/EEC) (European Council 1992), household appliances (Directive 96/57/EC) (European Council 1996), and fluorescent lighting (Directive 2000/55/EC) (European Council 2000a). In this context, the focus of the directive was on reducing energy consumption and enhancing product efficiency. Moreover, at the same time the European Climate Change Program encouraged energy saving and energy efficiency as key points to achieve the objectives of greenhouse gas (GHG) emissions. These environmental aspects became the main goals of the 2005 eco-design directive (Fig. 1).

The current Directive 2009/125/EC on eco-design requirements for energy-related products (European Council 2009a) emphasizes the assessment of the entire life cycle of a product. This is mainly based on a growing policy-making concern about the environmental impact of products and services and the development of life cycle thinking, particularly since the Integrated Product Policy was implemented (European Commission 2003). Furthermore, other environmental policies also positively influenced the development of eco-design, such as Directive 94/32CE on packaging and packaging waste and the later amending documents (European Council 1994, 2004, 2005b, 2009b) and Directive 2000/53/CE on end-of-life vehicles (European Council 2000b) (Fig. 1).

Finally, international schemes were designed in order to address environmental management and eco-design in companies. The ISO14006 (2011) standards (Environmental management systems—guidelines for incorporating eco-design) provide guidance for working on eco-design as part of an environmental management system. Finally, ISO/TR 14062 (2002) (Environmental management—integrating environmental aspects into product design and development) describes eco-design concepts and practices related to the integration of environmental aspects into product design and development (European Council 2009c, 2010) (Fig. 1).

This chapter introduces the eco-design methodology that is used to integrate the environment into the design stage in order to improve the environmental performance of a product. First, the benefits and opportunities of implementing eco-design in companies are reviewed (Sect. 2), as well as the scope and the implementation of

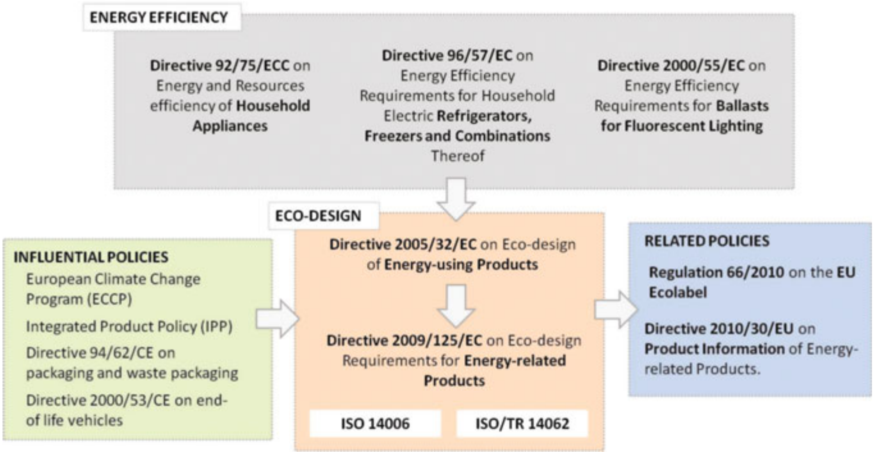

Fig. 1 Legal framework of eco-design in EU countries

eco-design in different sectors (Sects. 2.1 and 2.2). Second, an overview of the methodology is presented (Sect. 3) while showing the different steps and tools employed. In the following sections, attention is paid to qualitative tools (Sect. 4), quantitative tools (Sect. 5), the determination of the design requirements through the eco-briefing (Sect. 6), the definition of eco-design strategies (Sect. 7), and the final prototype design (Sect. 8). The chapter also focuses on the product carbon footprint (PCF) as a quantitative tool (Sect. 5.2) and as a communication-to-user strategy (Sect. 7.3) within the eco-design methodology.

2 Benefits and Opportunities of Eco-Design Implementation

Eco-design offers different benefits and opportunities to companies, not only environmental but also economic and social (Boks 2006; Borchardt et al. 2011; Brezet and van Hemel 1997; Clarimón et al. 2009; CPRAC 2012; Esty and Winston 2006; Knight and Jenkins 2008; Plouffe et al. 2011; Rieradevall et al. 2005; Rupérez et al. 2008; van Hemel and Cramer 2002) (Table 1).

The environmental performance of a product improves (i.e., there is a footprint reduction) by optimizing inputs and outputs of the production process, which reduces resource consumption (i.e., energy, materials, water), and, consequently, the environmental impact (e.g., emissions, waste) and increases the efficiency of the system. Moreover, the implementation of eco-design methodologies might promote the application of environmental management systems (EMS). As external drivers, environmental data can be used for communication-to-user and marketing purposes while expanding the presence of the environment as a

Table 1 Internal and external drivers for eco-design in companies for environmental, economic and social aspects

	Internal drivers	External drivers
Environmental	Decrease of resource consumption	Use of environmental communication
	Decrease of environmental impact	Compliance with environmental legislation
	Increase of efficiency	Contribution to global sustainability
	Enhanced environmental management systems	
	Continuous improvement	
Economic	Variable cost savings	Market differentiation
	Fixed cost reduction	Green purchasing
	Introduction into new markets	Supply for new green market demands
	Development of new products	Enhanced supply chain information
	Improved product quality	
Social	Improved company image	Environmental awareness
	Enhance of innovation and entrepreneurship	Environmental responsibility
	Increased staff motivation	

Adapted from Boks 2006; Borchardt et al. 2011; Brezet and van Hemel 1997; Clarimón et al. 2009; CPRAC 2012; Esty and Winston 2006; Knight and Jenkins 2008; Plouffe et al. 2011; Rieradevall et al. 2005; Rupérez et al. 2008; van Hemel and Cramer 2002

decision-making criterion during purchase. Moreover, improved environmental profiles comply with current regulations but also anticipate more restrictive normative conditions. Finally, eco-design contributes to the global sustainability along with current legislation to establish a framework for promoting continuous environmental improvement (i.e., ISO 14006).

Thanks to the application of efficient production systems, both variable and fixed costs can be reduced (e.g., less demand for the cleaning treatment of outflows by internal recycling and lower demand for resources by energy efficiency). Companies have the opportunity to differentiate themselves from competitors, enter into new markets, and develop new products. Finally, the image of the product is usually improved with the incorporation of environment criteria into its design. Apart from differentiation, companies can benefit from green procurement and from new green market demands. Further, the application of eco-design enhances environmental information along the supply chains.

The social image of the company is also upgraded by the inclusion of environmental criteria and reporting environmental responsibility. Companies generally turn out to be more innovative and entrepreneurial than their competitors when promoting eco-design; the staff motivation also increases. Lastly, environmental communication and marketing can promote environmental knowledge and awareness among customers and consumers.

2.1 The Scope of Eco-Design

DfE or eco-design is defined as the integration of environmental aspects in the product design process during its life cycle (Directive 2009/125/EC). Eco-design can be applied pursuing different objectives depending on the product life cycle stage that must be improved. In this sense, different "Design for X" tools were developed.

- Design for remanufacture (Borchardt et al. 2011; Okumura et al. 2001; Pigosso et al. 2010) focuses on the redesign of an existing product.
- Design for manufacture and assembly (Boothroyd et al. 1994) addresses the improvement of the production process.
- Design for disassembly (Cser and István 1996) aims to optimize the lifespan of the product (e.g., substitution of pieces and reparation) and enhance product recyclability.
- Design for reuse (Hoffmann et al. 2001) aims to optimize the lifespan of the product.
- Design for recycling (Seliger et al. 1999; Oyasato et al. 2001) enhances the product recyclability by avoiding end-of-life treatments with higher impacts.

2.2 Eco-Design Implementation

Eco-design has been applied to different types of products. Several guides have been developed, not only about methodology (IHOBE 2000) but also for specific sectors: urban furniture (e.g., streetlight, bin, bench) (Fundació La Caixa 2007), household products (e.g., appliances) (Rieradevall et al. 2003), electric appliances and electronic devices (Rodrigo and Castells 2002), and packaging (Rieradevall et al. 2000).

Furthermore, the implementation of eco-design in different product sectors has been also analyzed in the literature through case studies, such as wooden products (González-García et al. 2011a, 2012a, b, c), electronics (Unger et al., 2008; Mathieux et al. 2001; Aoe 2007), lighting (Gottberg et al. 2006; Casamayor and Su 2013), automobiles (Alves et al. 2010, Muñoz et al. 2006), packaging (Almeida et al. 2010), and printing (Tischner and Nickel 2003).

Finally, some entities and private companies has developed guidelines and procedures focused on eco-design. For example, Philips published the eco-design manual for electronic products (Cramer 1997; Stevels 1997). Volvo wrote an environmental guidance for car designers (Westerlund 1999). The British Marine Industries Federation made an environmental code of practice for boats (BMIF 2000). The Institute for Product Development (DTU Denmark) published a general eco-design guide (DTU 2005). In Sweden, different handbooks were published by the public administration, such as the guide for electronic products (Bergendahl et al. 1994), or by private companies, such as the construction handbook (AutolivSverige 1999).

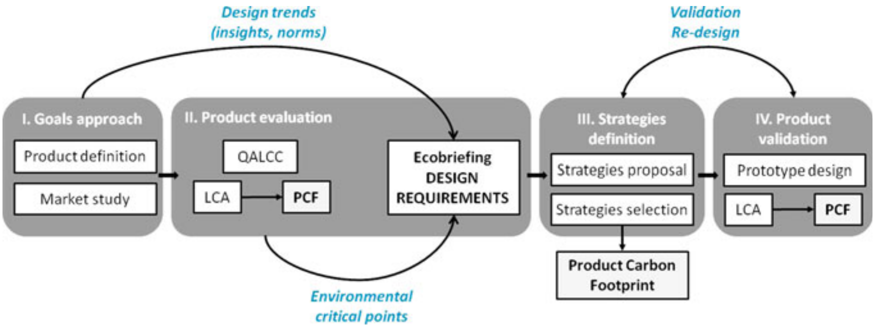

Fig. 2 Steps and tools of the eco-design methodology and role of the product carbon footprint

3 Overview of the Eco-Design Methodology

The presented methodology is based on the combined eco-design and life cycle assessment (LCA) procedure described by González-García et al. (2011b). However, qualitative tools were incorporated for the product evaluation. Although several tools were developed to implement eco-design (Bovea and Perez-Belis 2012; Le Pochat et al. 2007; Pigosso et al. 2010), this methodology was used and improved during the development of real pilot projects and, therefore, was optimized for the participation of companies.

The methodology is divided into four main steps (Fig. 2). First, the product is defined in order to approach the goals of the eco-design process (step I). During this first step, a market study is also completed to detect the design trends (insights and norms) that can contribute to the design requirements. Then, a product evaluation (step II) is performed through the application of the qualitative assessment of life cycle criteria (QALCC) (CPRAC 2012) and a quantitative analysis by means of LCA (ISO 2006a) and carbon footprint (ISO14067, PAS2050). The outputs of both tools are compiled in an eco-briefing (Smith and Wyatt 2006) of the critical points in the life cycle. As a result, the proposal of eco-design strategies (step III) can be defined and selected by the company after a technological, social, and economic assessment. Finally, the prototype is determined by the company with the integration of the chosen strategies (step IV) and the product is validated (step V) through LCA and PCF. These last stages usually interact with each other. The new design is validated and redesigned until it is optimized.

PCF (PAS 2050, ISO 14067) can be used during the eco-design process in different steps and for pursuing different purposes. First, PCF can be used as environmental indicator in the quantitative assessment (steps II and IV). Second, PCF can be used as strategy for environmental communication to the consumer (step III).

4 Qualitative Tools for the Environmental Assessment

4.1 Qualitative Assessment of Life Cycle Criteria

QALCC (CPRAC 2012) is a qualitative methodology that aims to obtain a first environmental assessment of the product at the life cycle stage scale (i.e., the different stages are analyzed separately). Through the interpretation of the QALCC results, the stages that have the largest potential to be environmentally improved are detected. The QALCC is a basis to create an eco-briefing or checklist of the environmental requirements for the eco-design process.

The QALCC methodology consists of three main steps (Fig. 3). First, the life cycle stages of the product are identified to define the system. Second, environmentally relevant criteria are determined for each life cycle stage. Finally, the assessment is performed by the creation of an expert team that evaluates the criteria in order to obtain a spider diagram, in which the valuation of each life cycle stage is represented.

In the system definition, the different life cycle stages of the product are specified. Usually, the life cycle stages are divided into concept, materials, production, packaging, distribution, use, and end-of-life. The life cycle stages considered depend on the LCA perspective: cradle-to-gate, cradle-to-consumer, or cradle-to-cradle.

As second step, various environmentally relevant criteria are defined for each life cycle stage. Criteria for the concept of the product can be the optimization of the function and timeless design. When considering the materials and packaging life cycle stages, the amount and variety of materials should be considered. In the case of the processing of products, the number of production steps and the amount of production wastes are common criteria for the QALCC analysis. Regarding the distribution stage, the distance requirements or logistics optimization can be evaluated as criteria that show the potential environmental contribution of this stage. Communication-to-user about maintenance or resource consumption during maintenance can be criteria for the use stage. Finally, for the end-of-life stage, criteria can be the presence of separable components or separable materials.

For the assessment, a multidisciplinary team must be created. The team may involve the largest number of departments of the company. Therefore, it is recommended to engage employees ranging from directors to workers and from the design department to the sales department. The team can also be complemented by eco-design experts, such as research entities involved in pilot projects. The role of

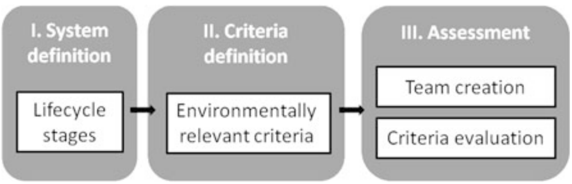

Fig. 3 Steps of the Qualitative Assessment of Life Cycle Criteria (based on CPRAC 2012)

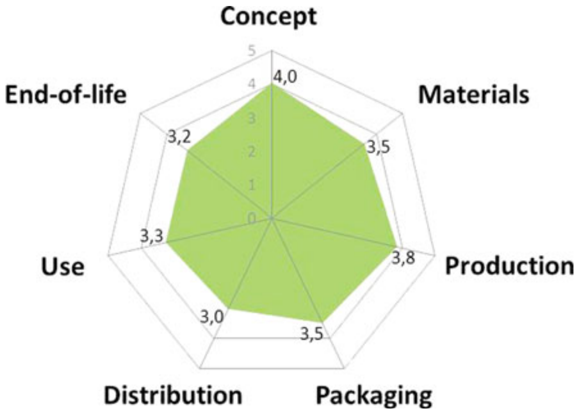

Fig. 4 Example of a QALCC spider diagram. In this case, the perception is that distribution and end-of-life stages are the least environmentally friendly ones, whereas concept and production are the most valued stages

the team is evaluating the criteria according to their possibilities in order to make them more environmentally friendly, grading them on a scale from “enormous room for improvement” (1) to “no room for improvement” (5).

After this evaluation, punctuation is averaged per criteria and per life cycle stage. Results may be represented in a spider diagram that enables the identification of the worst and best life cycle stages and, therefore, those stages where more efforts and strategies should be focused. The area represents the environmental impact: the lower the potential impact, the larger the area (closer to 5: no room for improvement) (Fig. 4).

As an example, the QALCC method was applied to an indoor chair for its entire life cycle (Fig. 4). The highest rated aspects of the design were the multipurpose design (4.5, concept), the use of local materials (4.2, materials), the low number of processing steps (4.1, production), the use of renewable materials (3.7, packaging), the reduced distance for raw materials extraction (4.7, transport), the low consumption of resources during maintenance (4.1, use), and the easy disassembly of materials (4.3, end-of-life). On the other hand, the lowest rated issues were low eco-innovation of the product (2.8, concept), non-use of recycled materials (2.1, materials), large amount of leftovers (3.4, production), non-use of reusable packaging systems (2.1, packaging), no hiring of low impacting transportation (2.6, transport), and no communication about either the maintenance (2.2, use) or the end-of-life management (1.9, end-of-life). The global values highlighted that eco-design strategies should focus on the distribution, use, and end-of-life stages (Fig. 4).

The QALCC tool has some advantages compared to other assessment methods. First, it is comprehensive and accessible to professionals who are not familiar with environmental tools. This enables the involvement of the different departments of a company. Second, the representation of the results facilitates interpretation by professionals who are not familiar with the tool. Third, the application of the tool and the results extraction steps are quick. Fourth, the life cycle concept is introduced to the company and the professionals involved in the project. Finally, this tool facilitates the communication of the environmental profile of the product as well as potential improvements.

However, QALCC should be complemented with a quantitative method due to its disadvantages. First, only qualitative data can be obtained. Second, the contribution of each life cycle stage to the product impact is not measurable, as each stage is assessed separately. Finally, results are linked to the expertise of the professionals who perform the assessment. For this reason, the presented methodology combines QALCC as a qualitative tool and LCA and PCF as quantitative assessment methods for hotspot identification in the eco-briefing.

5 Quantitative Tools for the Environmental Assessment

The quantitative assessment may complement the result of the qualitative assessment to complete the final eco-briefing. As because the entire life cycle of a product is considered, the LCA methodology is used. The PCF can be used as environmental indicator to assess a product's impact on global warming.

5.1 Life Cycle Assessment

LCA (ISO 2006a) is a methodology that allows systematizing the compilation and generation of information to establish objective criteria in the decision-making process for a sustainable development. The LCA method is defined by the ISO 14040 series [Environmental Management—Life Cycle Assessment—Principles and framework] (ISO 2006a). Moreover, this tool efficiently detects the improvement opportunities of an entire system.

The consideration of the environmental impacts of a product, process, or service along its life cycle has been performed since the 1960s and has been expanded in recent years. According to the ISO 14040, the LCA methodology is used for:

- identifying opportunities to improve the environmental performance of products at various points in their life cycle
- informing decision-makers in industry, government, or non-government organizations (e.g., for the purpose of strategic planning, priority setting, product or process design, or redesign)
- selecting relevant indicators of environmental performance, including measurement techniques
- marketing (e.g., implementing an eco-labeling scheme, making an environmental claim, or producing an environmental product declaration)

The depth and range of an LCA study can considerably vary depending on the specific goal of an study (Baumann and Tillman 2004). However, the current standard practice of LCA (ISO 2006a) includes four steps (Fig. 5):

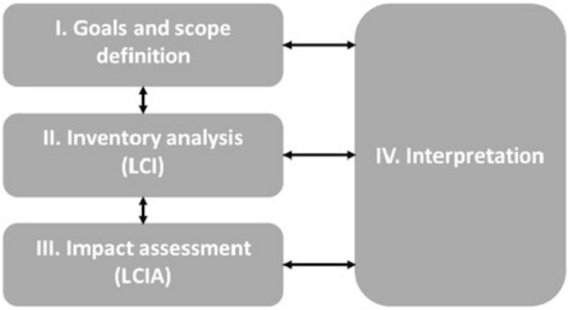

Fig. 5 Steps of the Life Cycle Assessment Methodology (ISO 2006). LCI, life cycle inventory; LCIA, life cycle impact assessment

- *Definition of the goal and scope of a project*. The objectives of the study, the intended audience, and the scope are defined. The last one includes the system that must be analyzed, the functional unit, the system boundaries, and the assumptions as the main items. The functional unit is a measure of the function of the system under study that provides a reference to which the inputs and outputs are related.
- *Inventory analysis* (or life cycle inventory) involves the data collection stage of the method. The objective is to quantify the relevant inputs and outputs of the product system (i.e., energy and raw material requirements, atmospheric emissions, waterborne emissions, solid wastes, and other releases for the entire life cycle of a system).
- *Impact assessment* The life cycle impact assessment is aimed at evaluating the significance of potential environmental impacts using the life cycle inventory results. The process relates the inventory data to specific environmental impact categories (e.g., climate change, ozone depletion).
- *Interpretation* of the significance of impacts. Interpretation is the phase of LCA in which the findings from the inventory analysis and the impact assessment are considered together.

5.2 Product Carbon Footprint as an Assessment Tool

The carbon footprint (CF) is a globally accepted tool for quantifying the environmental burdens of products. This indicator can be obtained through the implementation of an LCA analysis, like other environmental impact categories. The CF is an estimation of the GHG emissions from business activities. The goal of the method is to quantify the global GHG emissions related to the entire life cycle of a product, process, or service. This quantification is expressed in CO_2 equivalent (a unit for expressing the irradiative forcing of a GHG to carbon dioxide) and has become a common indicator for environmental assessment.

This calculation has increasingly more relevance for organizations as customers and consumers perceive and increasingly support environmentally responsible firms. Carbon footprint can be performed at different levels (BSI 2011):

- Organizational carbon footprint, at the company level
- PCF, which includes:

(a) an activity performed on a consumer-supplied tangible product (e.g., automobile to be repaired)
(b) an activity performed on a consumer-supplied intangible product (e.g., the income statement needed to prepare a tax return)
(c) the delivery of an intangible product (e.g., the delivery of information in the context of knowledge transmission)
(d) the creation of ambience for the consumer (e.g., in hotels and restaurants)
(e) software, which consists of information and is generally intangible and can be in the form of approaches, transactions, or procedures

At the organizational level, the international standard family ISO 14064 describes the specifications and guidance for the certification: ISO 14064-1 (ISO 2006b) Greenhouse gases—Part 1: Specification, establish the basic specifications and guidance for certification, ISO 14064-1 (ISO 2006c) Greenhouse gases—Part 2: Specification with guidance at the project level for quantification, monitoring, and reporting of greenhouse gas emission reductions or removal enhancements, and ISO 14064-3 (ISO 2006d) Greenhouse gases—Part 3: Specification with guidance for the validation and verification of greenhouse gas assertions.

The calculation of the PCF is standardized by the specification PAS 2050 (BSI 2011), where a method is provided for accounting for the GHG emissions in the life cycle of goods and services (products). The international standard ISO 14067 (ISO 2013) has recently been published and provides the standard for the application of this method (Carbon footprint of products—Requirements and guidelines for quantification and communication).

PCF quantification follows the LCA stages (Fig. 5). The approach of the method can be cradle-to-grave or cradle-to-gate, based on the system boundaries of the analysis (i.e., the emissions and removals considered arise from the full life cycle of the product or up to the point at which the product leaves the organization) (BSI 2011). PCF aims to measure the overall GHG emissions of a product by considering both emissions to the atmosphere and removals from the atmosphere and by assessing both carbon and biogenic carbon sources (BSI 2011) (Fig. 6).

PCF might characterize the energy use, combustion processes, chemical reactions, loss to atmosphere of refrigerants and other fugitive GHGs, process operations, service provision and delivery, land use and land use change, livestock production, and other agricultural processes and waste management. The assessment of GHG emissions and removals should be performed in a 100-year assessment period. The global warming potential (GWP) of the emissions is calculated according to the latest Intergovernmental Panel on Climate Change coefficients. Multiplier factors for aircraft emissions should not be applied and the

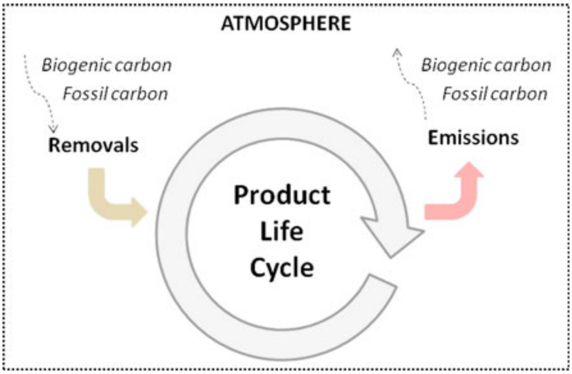

Fig. 6 Flows considered in the product carbon footprint (BSI 2011)

carbon that will not be emitted within this time period (100 years) should be treated as carbon storage (BSI 2011).

In the case of eco-design, the PCF can play two main roles as environmental indicator or assessment tool. First, PCF is used for the quantitative assessment of the initial product because it shows the contribution to global warming of a product in order to be considered in its design (Jeong and Lee 2009). Therefore, the source of GHG emissions and the related environmental impact can be detected within the life cycle of the product. Second, as other environmental indicators, PCF can also be used to define eco-design goals (e.g., reduce 20 % the PCF of the product) and to establish thresholds.

Moreover, PCF is a useful indicator in the realization of projects in companies, such as:

- PCF is an indicator of an increasing importance for reporting the environmental performance of products and organizations (CPRAC 2012)
- PCF has an important role as an eco-label, which has already presence in the market (e.g., Carbon Trust)
- The consumer has knowledge about the topic and can understand the meaning of the PCF, because:

– There is environmental awareness regarding global warming and climate change (e.g., development of laws and standards)
– These topics are covered by mass media (e.g., documentaries, press)
– Environmental laws have already been developed for domestic consumables and marketing has been done regarding carbon emissions (e.g., cars)

Therefore, PCF can be used as a quantitative assessment tool and as indicator to show the environmental burdens of the initial product (step II), the potential improvement of the strategies (step III), and to validate the environmental performance of the prototype design (step IV).

6 Eco-Briefing: Design Requirements Definition

The eco-briefing (Smith and Wyatt 2006) shows, in a concise and clear way, the environmental critical points where attention must be paid to minimize their contribution to the environmental burdens through the eco-design methodology, as well as to observe the life cycle stages where they are concentrated.

The eco-briefing may compile data from the environmental assessment (both qualitative and qualitative). In this case, eco-briefing collects the results from the QALCC and LCA tools. The main requirements for a conventional briefing are contextualization (general description, market trends), product (objective, range of product), design aims and conditioning (available technology, cost, time), project definition, and expected results. An eco-briefing complements this information with the identified environmental critical points in the different life cycle stages (Table 2).

Following the same example, the eco-briefing of an indoor chair included impacts from the QALCC and LCA analysis (Table 2). First, the multidisciplinary team of the QALCC pointed out that the chair design was not innovative and, therefore, it might be a requirement for the prototype definition. Second, both methods noted that some materials were high-impacting and that minimal recycled materials were used. However, the quantitative assessment also highlighted the significant contribution of the energy consumption and paint to the environmental impact. The low efficiency of the volume for distribution was identified in the qualitative assessment and confirmed with the high impact of the distribution in the LCA. Finally, packaging and communication requirements were mainly determined in the qualitative assessment.

Table 2 Example of eco-briefing of an indoor chair

	Life cycle stages						
Critical points	C	M	P	D	P	U	EoL
Lack of innovation	●						
High impact of the wood board		●			●		
Low use of recycled materials		●			●		
High impact of the energy consumption during processing			●				
High impact of the paint			●				
Low efficiency of the volume for distribution	●			●	●		
High impact distribution				●			
Multi-material packaging					●		
Insufficient environmental communication of the maintenance	●					●	
Insufficient environmental communication of the end-of-life	●						●

C Concept, *M* Materials, *P* Production, *D* Distribution, *P* Packaging, *U* Use, *EoL* End-of-life

7 Definition and Selection of Strategies

Once the design requirements for each life cycle stage are identified in the product evaluation, eco-design strategies are proposed in order to improve the product profile by solving the main issues. As a second step, the strategies are selected by the company for designing the prototype.

7.1 Strategies Definition

The first life cycle stage of a product is the conception, where several environmental aspects can be approached and different life cycle stages can be improved at the same time (Table 3). Strategies regarding this life cycle stage improve the design of the product by considering concepts such as functionality, temporality, and lifespan. However, other stakeholders can be involved in this stage, such as consumers (when providing environmental information) and suppliers (when demanding environmental information of production inputs).

The materials of a product (Table 4) can be improved through different ways. The amount of resources can be reduced or optimized (e.g., dematerialization, reused components). Materials can be switched to more environmentally friendly options: renewable materials, recyclable materials, or low-impact materials. Moreover, material selection can be done based on other life cycle stages. A single material design can enhance the recyclability of the product, materials with low maintenance requirements can reduce the contribution of the use stage to the environmental burdens, and materials associated with low-impact end-of-life options can improve this stage of the product. Finally, the selection of local suppliers for the material inputs reduces the transport requirements.

Table 3 Main strategies regarding concept (based on CPRAC 2012)

Life cycle stage	Strategy	Environmental aspect
Concept	Dematerialization	Reduction of resource consumption
	Product sharing	Maximization of product use
	Multifunctional product	Reduction of resource use per function
	Timeless design	Increased lifespan
	Design for updating	
	Environmental information (e.g., carbon footprint)	Market differentiation
	Demand for suppliers' environmental information	Environmental impact of products Environmental responsibility
	Design for assembly and disassembly	Reduction of environmental impact of other life cycle stages of the product

Table 4 Main strategies regarding materials (based on CPRAC 2012)

Life cycle stage	Strategy	Environmental aspect
Materials	Dematerialization	Reduction of resource consumption
	Single material design	Enhanced recycle options
	Recyclable materials	
	Renewable/natural resources	Decoupling of non-renewable resources
	Low-impact materials	Product impact reduction
	Use of abundant materials	
	Local resources	Local positive impacts and distribution impact reduction
	Materials with easy end-of-life management (biodegradable)	Reduced product end-of-life impact
	Materials with low maintenance	Reduced product use impact
	Reused components	Reduced resources extraction

Table 5 Main strategies regarding production (based on CPRAC 2012)

Life cycle stage	Strategy	Environmental aspect
Production	Internal recycling closed-loop production	Waste and emissions reduction
	Optimize production processes	Reduced production impact
	Choose cleaner production processes	Enhanced efficiency
	Use of low-impact energy sources	Reduced energy consumption impact
	Local production	Reduction of logistics requirements

Production strategies commonly address efficiency (Table 5). Material inputs and their environmental impact can be reduced by enhancing internal recycling processes (e.g., waste flows from the production can become a resource for the same or other products). Attention is also paid to the energy flow, where the consumption can be reduced and the energy source may be as clean as possible (e.g., renewable energy systems). Finally, the production process can be revised to optimize and invest in cleaner production systems while reducing the environmental impact of this life cycle stage.

Although packaging is a secondary life cycle of the analyzed product, it is an important stage to assess and it can result into transversal environmental actions (i.e., some products have the same packaging) (Table 6). Main strategies focus on the reduction of resource consumption and the associated impacts, and they also consider the volume of the design, which affects other life cycle stages. The lifespan of the product can be enlarged by designing a reusable or multifunctional packaging.

The transportation of the material inputs and the finalized product can be improved in different ways (Table 7). First, the design of the product can be

Table 6 Main strategies regarding packaging (based on CPRAC 2012)

Life cycle stage	Strategy	Environmental aspect
Packaging	Avoid superfluous packaging	Reduction of resource consumption
	Dematerialization	
	Reusable packaging	Increased lifespan
	Multifunctional packaging	
	Low-impact materials	Reduced of product packaging impact
	Recyclable materials	Enhanced recycle options
	Volume reduction	Optimization of product distribution

Table 7 Main strategies regarding distribution (based on CPRAC 2012)

Life cycle stage	Strategy	Environmental aspect
Distribution	Optimization of product weight	Reduction of transportation energy consumption
	Local distribution	Reduction of transportation environmental impact
	Biofuels transportation	
	Efficient transportation	

Table 8 Main strategies regarding use (based on CPRAC 2012)

Life cycle stage	Strategy	Environmental aspect
Use	Optimization of resources consumption during use	Reduction of product use impact
	Easy installation/assembly	Reduction of resources consumption
	Easy maintenance	
	Easy reparation	Increased lifespan
	Modular design	
	Availability of spares	
	Design for customize	
	Product reliability and durability	
	Communication-to-user (e.g., best practices)	Reduction of product use impact

optimized to reduce the product weight and, thereby, to reduce the environmental burdens of transportation. Second, transportation requirements can be diminished by looking for local suppliers and retailers. Finally, more environmentally friendly means of transport (i.e., biofuels, efficient systems) reduce the environmental impact.

Regarding the use stage (Table 8), strategies may focus on an optimized use of resources (e.g., design for an easy installation and maintenance), an enlargement of the lifespan of the product (e.g., design for disassembly and easy reparation), and communication-to-user to boost best practices by reducing the environmental impact of this stage.

Table 9 Main strategies regarding end-of-life (based on CPRAC 2012)

Life cycle stage	Strategy	Environmental aspect
End-of-life	Simplification of disassembly	Enhanced recycle and reuse options
	Component disassembly	
	Recyclability	
	Material identification	
	Reusability	Increased lifespan
	Biodegradability	Reduction of product impact
	Communication-to-user (e.g., end-of-life options)	Reduction of product end-of-life impact

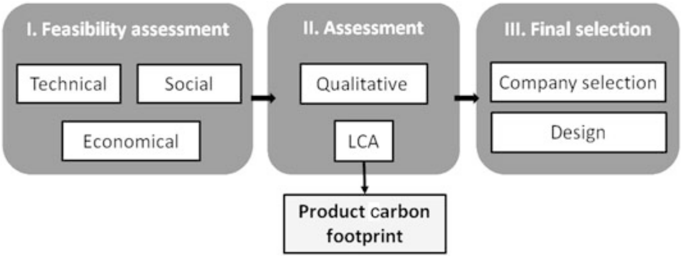

Fig. 7 Steps of the eco-design strategies selection process. LCA, life cycle assessment

Finally, different strategies can be used to improve the end-of-life stage (Table 9). Materials can be recyclable or can be biodegradable to reduce the environmental impact of the disposal process. The design can be performed for disassembly (facilitate end-of-life management) or for reusability (increase the lifespan). Finally, communication-to-user strategies can enhance best practices regarding end-of-life treatments to reduce their impact.

7.2 Strategy Selection

Once the strategies are defined, two selective steps are done in order to determine the eco-design strategies that should be integrated in the prototype (Fig. 7). First, a feasibility assessment is performed by the company to observe technical, economic, and social constrains. This step leads to a first selection of the most potential strategies. Second, the selected strategies are assessed (both quantitative and qualitative) to observe their potential improvements. Finally, the company picks some of the strategies to be incorporated in the prototype design.

The feasibility assessment (Table 10) is performed for each proposed strategy. The technical, economic, and social feasibility are determined as “Feasible” (F+), “Feasible at mid-term” (F-), “Unfeasible” (U) or “Not applicable” (NA) when the

Table 10 Example of the feasibility assessment of potential concept strategies

Id	Strategy	Criterion	Feasibility				Priority
			F+	F−	U	NA	
Concept	Increase of functionality	T		X			Low
		E	X				
		S	X				
	Design for customize	T	X				Medium
		E	X				
		S	X				
	Volume reduction	T			X		Low
		E			X		
		S				X	

T technical, *E* economic, and *S* social

criterion is not considered. Finally, a priority value is defined as "High," "Medium," or "Low" in order to establish a classification for the strategies selection.

For the feasible eco-design strategies, a quantitative assessment (LCA and/or PCF) is used to show the potential environmental improvement of the strategy. For those conceptual strategies (e.g., multifunctional product, communication) the assessment is carried out from a qualitative perspective (e.g., description of the potential benefits and involvement of stakeholders). After the assessment, the company selects the final strategies for defining the prototype.

7.3 Product Carbon Footprint as a Communication Tool

Environmental communication is the process of sharing environmental information, not only with suppliers but also with customers. The main goal is to generate confidence, credibility, and association as well as to increase the environmental awareness during decision-making processes.

Labeling for environmental communication is used for showing the environmental contribution of products to human health and sustainability. With this standard labeling system, the company shows their reliability and becomes competitive in their sector.

For environmental communication, the PCF is a useful and understandable indicator to show the environmental aspects of a product. This can be used within a set of indicators, such as a part of an Environmental Product Declaration (Eco-label type III, norm ISO 14025) (ISO 2006e) or as a unique indicator. In this second case, the PCF can be done through the standard certification (following the PAS 2050) and by means of an official entity (e.g., Carbon Trust), or through a self-declared environmental claim (eco-label type II, norm ISO 14021 (ISO, 1999)) (Fig. 8).

Fig. 8 Examples of the use of product carbon footprint as a communication-to-user tool: **a** environmental product declaration (EPD) of a chair (©Arper), **b** Carbon Trust declaration of a wine (©Mobiu), and **c** Self-declared product carbon footprint of an eco-designed knife by ARCOS (©Sostenipra)

Moreover, environmental communication can be done through different pathways. As mentioned before, labels can be used in the product or packaging. However, this communication can also be integrated in the company's functions (e.g., marketing, advertisement, events, customers, suppliers, and website). For example, the ISO 14063 (ISO 2006f; on Environmental Management—Environmental communication of the company) establishes guidance on the communication of the environmental policy (general, strategy, and activities) of the company, based on the EMS ISO 14001 (ISO, 2000).

8 Design of the Prototype

The final step of the presented eco-design methodology is the design of the prototype. The selected strategies are integrated and combined to obtain a more environmentally friendly product with environmental aspects as added value.

The final prototype is obtained as a result of two interactive steps: prototype design and validation (Fig. 9). First, the company designs the prototype as a result of integrating eco-design strategies but also adapting them to the technical and economic constraints. Second, the environmental performance of the new product is validated through a quantitative method (LCA) in order to assess the environmental improvement of the entire eco-design process. Both steps interact in order to optimize the outputs of the eco-design efforts by considering the company context (e.g., technical availability, economic costs) and the aimed environmental

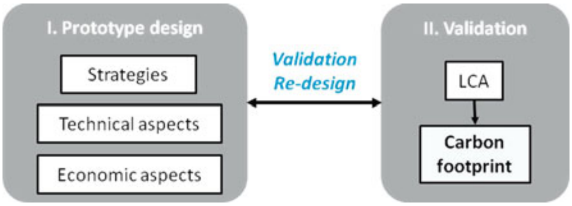

Fig. 9 Steps of the prototype design and validation. LCA, life cycle assessment

improvements. The PCF can be used in this step as an environmental indicator for the quantitative validation. Moreover, it can also be used as goal of the eco-design process (e.g., minimum reduction of the PCF value), as mentioned before.

9 Conclusions

The presented eco-design method is a comprehensive way to assess the potential environmental improvement of products, processes, and services. It combines qualitative (VEA) and quantitative (LCA) methods for the assessment of product as well as for analyzing the strategies. As a life cycle-based method, each life cycle stage is assessed in detail in order to optimize the impact contribution of the product. The eco-briefing method establishes the design requirements and results in a complete basis for defining eco-design strategies and for transferring complex environmental information to the design team. The strategies selection method combines two selection steps, where the company is involved, and optimizes the efforts for defining the new prototype design.

Finally, the PCF may have an important role in the eco-design methodology because it can be used in different steps and for achieving diverse targets. Carbon footprint is a well-known and understandable communication tool, not only from companies to consumer but also between businesses. Moreover, PCF can be a pioneer indicator in the implementation of quantitative environmental communication in products and services. For communicative purposes, the use of PCF can be also complemented with other life cycle environmental indicators in order to show different environmental aspects of the product (e.g., LCA indicators, water footprint).

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