Eco-Design and Product Carbon Footprint Use in the Packaging Sector

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Abstract Packaging products are common in all industrial sectors and in the market place. However, packaging design needs to be optimized while avoiding superfluous designs that do not consider the environment in their design. Directive 94/62/EC established a framework in order to harmonize the environmental requirements for packaging as well as to determine targets for recycling and recovering packaging waste. In this chapter, the eco-design projects of different sectors are presented in order to show the different strategies that are used to improve the environmental performance of packaging products. The carbon footprint of the products is quantified and used as an environmental indicator. Common strategies to reduce the carbon footprint of packaging are optimizing the volume (and therefore reducing the transportation requirements), using renewable materials, and optimizing the end-of-life management.

Keywords Eco-design · Carbon footprint · Industrial ecology · Packaging · Sustainable manufacturing

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1 Introduction

Packaging has an extended presence in markets because they have turned into basic elements for distributing and selling products. Packaging has the function of protecting and maintaining the product during the distribution and retail processes. Moreover, packaging has evolved as a new piece of the product, in which design and marketing play an important role. However, the environmental burdens of products are sometimes increased due to the packaging design (Fig. 1). For example, an informatics device can have different types of packaging (multi-packaging systems) that can increase the product volume more than 20 times, therefore increasing the environmental impact of the distribution stage. Moreover, multimaterial packaging are common in stores, such as in food retail or multi-packaging systems.

For example, packaging has an important role in the food sector, where it helps to avoid product losses during distribution and increases the lifespan of the product during the consumption stage. According to the Food and Agriculture Organization of the United Nations (FAO), an important part of food waste is generated during distribution in developing countries, whereas in Western Europe food distribution has low values of food waste, partly because of better food packaging design.

The environmental performance of this sector has recently been analyzed, not only as a product (e.g., Ross and Evans 2003; Zabaniotou and Kassidi 2003) but also as part of the entire lifecycle of a food product (e.g., Koroneos et al. 2005; Sanyé-Mengual et al. 2013; Torrellas et al. 2008). The packaging used for distribution represents one of the highest contributing elements for the life cycle of a tomato consumed in Barcelona (Sanyé-Mengual et al. 2013), as well as for a tomato produced in the Canary Islands (Torrellas et al. 2008). Furthermore, packaging increases the global energy consumption, thus making processed food a highly energy-intensive product (Garnett 2003).

Moreover, food-related packaging is the most common waste in households (Garnett 2003). According to INCPEN (2001), packaging represented a quarter of the household waste production in the UK, and 70 % of this packaging was food-related. This fact is narrowly associated with the retail stage, where packaging is

Fig. 1 Examples of packaging designs that increase the environmental burdens of the product: multipackaging systems, volume increase, and multimaterial packaging

also a key aspect. When comparing different types of food stores, packaging of a standard purchase in a retail park has an impact 2.5 times higher than in a municipal market due to three main reasons: the overuse of primary packaging (overpacking), the total amount of materials, and the higher presence of multi-material packaging (Sanyé et al. 2012).

In this context, EU Directive 94/62/EB and the subsequent directives (European Council 1994, 2004, 2005, 2009a) established a framework for environmental requirements in packaging production, as well as determined recovery and recycling targets for waste packaging. Based on these requirements a new packaging product can enter the market only if the manufacturer has taken all measures to reduce its impact on the environment without degrading its essential functions. Other legislation also aimed to establish a framework for better managing waste packaging, such as Decision 97/129/EC on the identification system for packaging materials (European Council 1997).

The main strategies to optimize packaging design for this legal framework were based on "packaging optimization" in order to reduce the waste packaging. The four strategies most used for this purpose are as follows (Hanssen et al. 2002, 2003):

(1) Optimize packaging to reduce the waste of products
(2) Optimize packaging to maximize the recycling of packaging materials
(3) Optimize packaging to minimize transport work and loss of efficiency in transport and distribution
(4) Optimize packaging by minimizing material consumption

This chapter aims to show the eco-design and product carbon footprint (PCF) methodologies in the packaging sector. The use of eco-design and carbon footprint methodologies are introduced (Sect. 2). Different packaging products from different sectors (Sect. 3) are assessed along with the eco-design and PCF methods in order to improve their environmental performance. The common issues regarding the implementation of PCF accounting in packaging systems and their materials are presented (Sect. 4). The eco-design methodology is applied to five different packaging systems: a multipurpose industrial packaging (Sect. 5), a detergent bottle (Sect. 6), a technical packaging for lighting products (Sect. 7), and two food packaging products (Sects. 8 and 9). Finally, a comparative assessment among the results is performed in order to show the main differences among sectors (Sect. 10).

2 Eco-Design and Carbon Footprint in Packaging

Eco-design is the integration of environmental aspects into the design process in order to improve the environmental performance of the entire lifecycle of a product (EU Directive on Eco-design) (European Council 2009b). This tool provided to be useful in the improvement of packaging products in order to meet the legal requirements. Common eco-design strategies implemented in the packaging sector are related to material selection (e.g., use of renewable or biodegradable

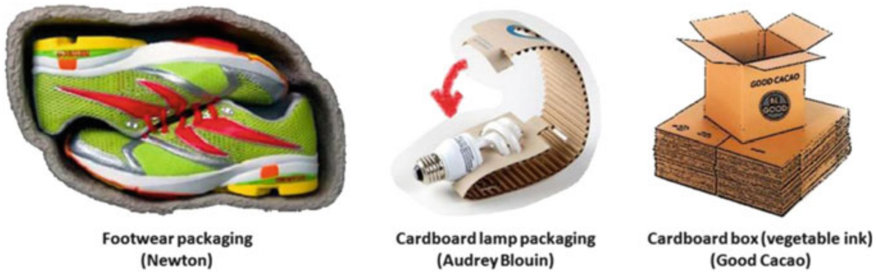

Fig. 2 Case studies for optimizing packaging volume and selecting renewable materials: footwear packaging (Newton), cardboard lamp packaging (Audrey Blouin), and cardboard box printed with vegetable ink (Good Cacao)

materials) (Fig. 2), optimization of the volume (i.e., to decrease the transportation impact) (Fig. 2), and multifunctionality of the packaging in order to increase its lifespan as well as to attract the customer (Fig. 3). As usually applied in eco-design projects, other packaging case studies also focused on consuming local materials (e.g., González-García et al. 2011).

On the other hand, product carbon footprint (CF) (BSI 2011; ISO 14067) is used as a communicative tool for companies to show the customer the environmental performance of their products in terms of greenhouse gas (GHG) emissions. This

Fig. 3 Multifunctional designs for packaging products: **a** Packaging convertible into a spoon (SpoonLidz), **b** cardboard pack convertible into a handle (Hangerpak), and **c** paper bag convertible into a handle for clothes (Muji)

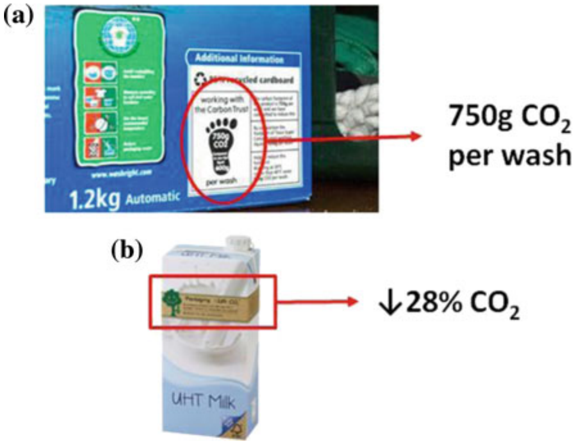

Fig. 4 **a** Packaging used as a communicative channel for consumers: carbon footprint of food products in Tesco supermarkets (UK). **b** Carbon footprint of packaging improvements of the new design Combibloc EcoPlus of the company SIG

tool is useful and understandable by the general public because climate change and global warming issues have been explained by the mass media and CO_2 units are already used in consumable products (e.g., vehicles and emissions per km).

Moreover, packaging can become a communicative channel for the company when used as a platform to inform the customer about eco-labeling, marketing, design, and aspects of the company. In this sense, PCF has been used as a tool for environmental communication to the user not only about the product (Fig. 4a) but also about the packaging itself (Fig. 4b).

3 Case Studies and Methodology

Five eco-design projects in the packaging sector are presented in this chapter. The projects were implemented in different sectors, from industrial to food packaging, and included both primary and distribution packaging (Table 1). All the projects were realized by a collaborative team made of research entities and the company involved.

The projects were performed within the development of the Catalan Ecodesign program (Catalan government). The Catalan Ecodesign program 2004–2006 was a pioneer experience in Catalonia that aimed to disseminate the eco-design methodology among the Catalan business network. The project was driven by the Catalan administration through the Centre for the Enterprise and the Environment, jointly the collaboration of the association from the business confederation of the county of Terrassa, the involved companies, and the Institute of Environmental

Table 1 Characterization of the case studies: economic sector, packaging, and type of packaging

Sector	Packaging	Type of packaging
Industrial	Multiuse packaging	Distribution
Chemical products	Detergent packaging	Primary
Technical products	Lighting packaging	Distribution
Food	Meat tray	Primary
Food retail	Delicatessen	Primary—distribution

Science and Technology). Therefore, it is an interdisciplinary project developed by a cooperative network within the administration, companies, and the university.

The goals of the Catalan Eco-design project are to encourage eco-design as an eco-efficient and innovative tool, to facilitate the incorporation of eco-design strategies in the business processes, to develop eco-design tools for economic sectors (such as guides and software), to train professional in product environmental prevention techniques, to communicate and to disseminate the program results in order to boost environmental improvements in the Catalan industry, and to create the Catalan agency of eco-products in cooperation with other administrations and institutions.

The eco-design methodology is detailed in González-García et al. (2011). The main steps are definition of the product, evaluation of the product, definition and selection of the strategies, and design and validation of the prototype. Regarding the qualitative assessment of life cycle criteria (QALCC) (CPRAC 2012) stage, the lifecycle stages included and the aspects evaluated are described in Table 2.

The quantitative evaluation method used was the life cycle assessment (LCA) (ISO 2006). Three indicators were used to assess the environmental performance of the product. First, the normalized CML value was used to show the global environmental performance of the product and its improvements. This indicator is obtained through the CML 2 Baseline method (Guinée et al. 2000) for the classification and characterization steps. This method includes 10 indicators that assess different environmental aspects: abiotic depletion potential, acidification potential, eutrophication potential, global warming potential (GWP), ozone layer depletion potential, human toxicity potential, ecotoxicity (fresh water, marine, and terrestrial) and photochemical oxidation.

Second, the product carbon footprint (BSI 2011; ISO 14067 2013) was used to show the contribution to the GWP of each product (see Sect. 4). This indicator was chosen as a well-known and understandable indicator for companies (i.e., CO_2 trade, climate change awareness, mass media publications, and eco-labeling). Finally, the cumulative energy demand (CED, MJ) (Hischier et al. 2010) showed the global energy consumption. Moreover, the packaging improvements were also evaluated through some indicators related to packaging design. The weight, the volume of the packaging, and the transport volume (number of units per truck capacity) were assessed as design aspects.

Regarding the PCF implementation, the PCF methodological specifications were followed in this chapter. According to the PAS 2050 (BSI 2011) method, the time

Table 2 Life cycle stages and aspects of the packaging products included in the qualitative assessment of life cycle criteria

Life cycle stage	Evaluated environmental aspect
Concept	Dematerialization
	Multifunctionality
	Optimization of the function
Materials	Elimination of the toxic compounds
	Use of recycled material
	Reduction of material use
	Reused material
	Use of renewable resources
Processing	Optimization of waste generation
	Reduction of water and energy consumption
	Energy savings
	Use of renewable energy
Distribution	Optimization of volume
	Use of recycled materials in secondary packaging
	Use of reusable secondary packaging
	Use of low-impact fuel
Use	Communication to user
	Information about the material
	Durability
End of Life	Reutilization potential
	Recyclability potential
	Energy valorization potential
	Reduction of the final waste volume

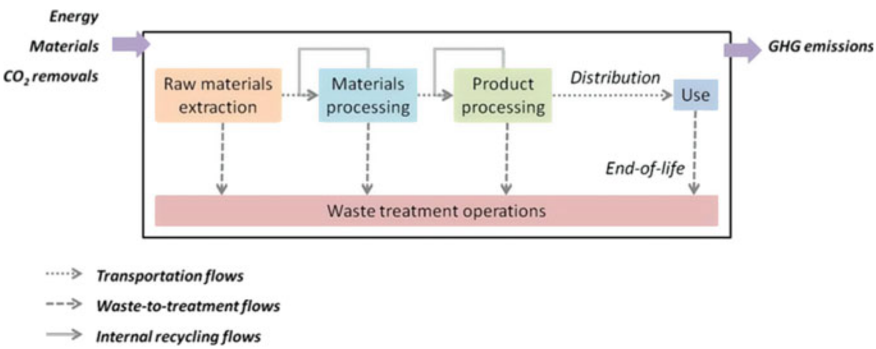

Fig. 5 Life cycle stages of a packaging product from a cradle-to-cradle approach. Processes and flows considered in the product carbon footprint accounting

period chosen for the assessment was 100 years. The last IPCC coefficients were used for the conversion from air emissions to CO_2 equivalent units. A cradle-to-cradle approach was considered for the PCF accounting. The system boundaries and the common processes of the packaging materials are described below (Fig. 5).

4 Overview of the PCF of Packaging Systems

The PCF is commonly used in the market (see Sect. 1). However, LCA and indicators such as GWP are more broadly used in the literature when accounting for the environmental burdens of packaging products. Two main packaging sectors are found in the literature: industrial packaging and food packaging.

Gasol et al. (2008) quantified the environmental burdens of two different options for distributing electrical cable or optic fiber. A wood pallet and a wood spool were analyzed from a cradle-to-grave perspective following the IPCC (2007) method for accounting the GWP. The GWP value obtained for a wood pallet was of 8.18 kg CO_2 eq, whereas the wood spool accounted for 87.1 kg CO_2 eq. Manuilova (2003) analyzed the direct emissions of industrial packaging for chemicals from a life cycle perspective. Considering a functional unit of 1.000 L of chemicals contained, the direct emissions for the different products were 61 kg CO_2 for a bulk container, 70 kg CO_2 for a composite drum, 53 kg CO_2 for a plastic drum, and 52 kg CO_2 for a steel drum.

In the field of food packaging, several studies have included the packaging as part of the life cycle of a food product, such as for beer (Hospido et al. 2005) or the banana supply chain (Svanes and Aronsson 2013). In table 3 recent studies about food packaging are compiled in order to show the GWP of different packaging systems. Most of them apply the LCA methodology for the calculations, apart from Svanes and Aronsson (2013), in which the PCF (ISO 14067) is followed. Also related to the food sector, Sanyé et al. (2012) analyzed the packaging related to food purchases, comparing two different retail options: municipal markets and commercial parks.

In a previous work, the common materials of packaging products (e.g., thermoplasts) were analyzed and their PCF accounted in order to address the use of certain materials. The PCF per kilogram of the material (in terms of CO_2 equivalent) was obtained for polyethylene (PE) (high density—HDPE, and low density—LDPE), polypropylene (PP), polyvinylchloride (PVC), polyethylene terephthalate (PET), corrugated cardboard, and wood (softwood). For each material, the largest GHG emitted and the main contributing processes were identified (Table 3). Local data from companies and the Spanish mix were used as foreground data, whereas background data were obtained from the Ecoinvent 2.2 database (Ecoinvent 2007; Frischknecht et al. 2004).

The PCF of the materials analyzed ranged from 0.065 to 3.77 kg CO_2 equivalents. The least impact materials are the renewable ones: wood and cardboard. Both are mainly used for secondary packaging purposes, although in some sectors they have a higher presence (e.g., industrial packaging). Thermoplasts are largely used in the packaging sector. PCF depends mainly on the country because electricity is the main contributing process to the environmental burdens. Within them, polyethylene and polypropylene are the least impacting materials (Table 4).

Table 3 Recent studies on the global warming potential of food packaging products by study, packaging, global warming potential (GWP), approach, and method

Study	Packaging	GWP (g CO_2 eq)	Approach	Method
Pasqualino et al. (2011)	Juice 1L aseptic carton	113	Cradle-to-grave	IPCC (2007)
	Beer 330 mL aluminum can	826	Cradle-to-grave	IPCC (2007)
	Water 1.5L PET bottle	78	Cradle-to-grave	IPCC (2007)
González-García et al. (2011)	Wine—wood box	314	Cradle-to-gate	IPCC (2007)
Madival et al. (2009)	Strawberries—PLA clamshell	171	Cradle-to-grave	IMPACT 2002+
	Strawberries—PET clamshell	198	Cradle-to-grave	IMPACT 2002+
	Strawberries—PS clamshell	165	Cradle-to-grave	IMPACT 2002+
Toniolo et al. (2013)	Sliced meat—PET tray	78.3	Cradle-to-grave	ReCiPe 2008
	Sliced meat—Multilayer tray	82.4	Cradle-to-grave	ReCiPe 2008
Humbert et al. (2009)	Baby food—glass jar	174	Cradle-to-grave	IMPACT2002+
	Baby food—glass pot A	125	Cradle-to-grave	IMPACT2002+
	Baby food—glass pot B	149	Cradle-to-grave	IMPACT2002+
Svanes and Aronsson (2013)	Banana packaging	80	Cradle-to-grave	Product carbon footprint ISO 14067
Albrecht et al. (2013)	Wood box for fruit and vegetables (15 kg)	2920	Cradle-to-grave	CML method
	Cardboard box for fruit and vegetables (15 kg)	3250	Cradle-to-grave	CML method
	Reusable plastic tray for fruit and vegetables (15 kg)	430	Cradle-to-grave	CML method

Table 4 Product carbon footprint (PCF) of different packaging materials, most emitted greenhouse gases, and main contributing processes to global warming

	PCF (kg CO_2 eq/kg)	Greenhouse gases	Main contributing processes
HDPE	1.65	CO_2, CH_4	Electricity consumption
LDPE	2.27	CO_2, CH_4	Electricity consumption
PP	2.02	CO_2, CH_4	Electricity consumption
PVC	2.66	CO_2, CH_4	Electricity consumption
PET	3.77	CO_2, CH_4	Electricity consumption
Corrugated cardboard	0.957	CO_2, CH_4	Raw material obtaining
Wood	0.065	CO_2, CH_4	Electricity consumption

5 Packaging for the Industrial Sector

An industrial box for different purposes was selected as a representative product of the industrial sector. A company produces and distributes packaging products and their designs may accomplish conditions for containing different products (e.g., weight resistance). The TriBox industrial box is mainly made of two materials (Fig. 6): cardboard and wood. The box is made of triple-channel cardboard that makes an envelope, and it is reinforced with wood pieces. The box is also reinforced with two wood pieces in the cover. Finally, the set is integrated with a pallet. This product was designed for processing, internal logistics, storing, and distribution purposes.

The company proposed a design briefing based on two key objectives: to obtain a monomaterial product and to facilitate the end-of-life management of the product. The quantitative assessment highlighted the importance of the end-of-life stage due to the difficulty for disassembling both materials (i.e., for recycling, reusing), which accounts for more than the 60 % of the CML normalized impact. Materials extraction and processing had also an important role in the carbon footprint ($\approx$50 %) and energy ($\approx$85 %) indicators, where the cardboard processing was the main contributing process. The PCF of the initial Tribox is of 16.13 kg of CO_2 (Fig. 7).

According to that, the implemented strategies were based on design for disassembly, to reduce the amount of materials and the number of different materials. These strategies aimed to facilitate the end-of-life management while optimizing the environmental impact of the materials selected. The new Tribox design is composed of the following main elements (Fig. 7): a cardboard box made of DC cardboard, a cardboard cover for the box (DC cardboard), corner reinforcement pieces (DC cardboard), and a nonintegrated pallet (wood). Although wood and cardboard are also the materials used for this design, the box can be easily disassembled and, therefore, the materials can be separated for being recycled or recovered at the end of life. Moreover, the wood pallet can now be reused while

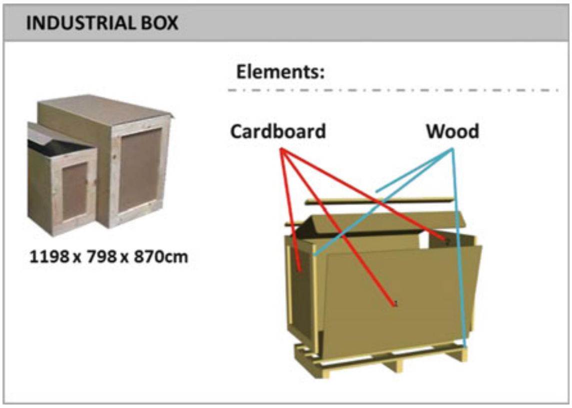

Fig. 6 Initial product, image, and elements of the industrial packaging (*Source* Emabamat)

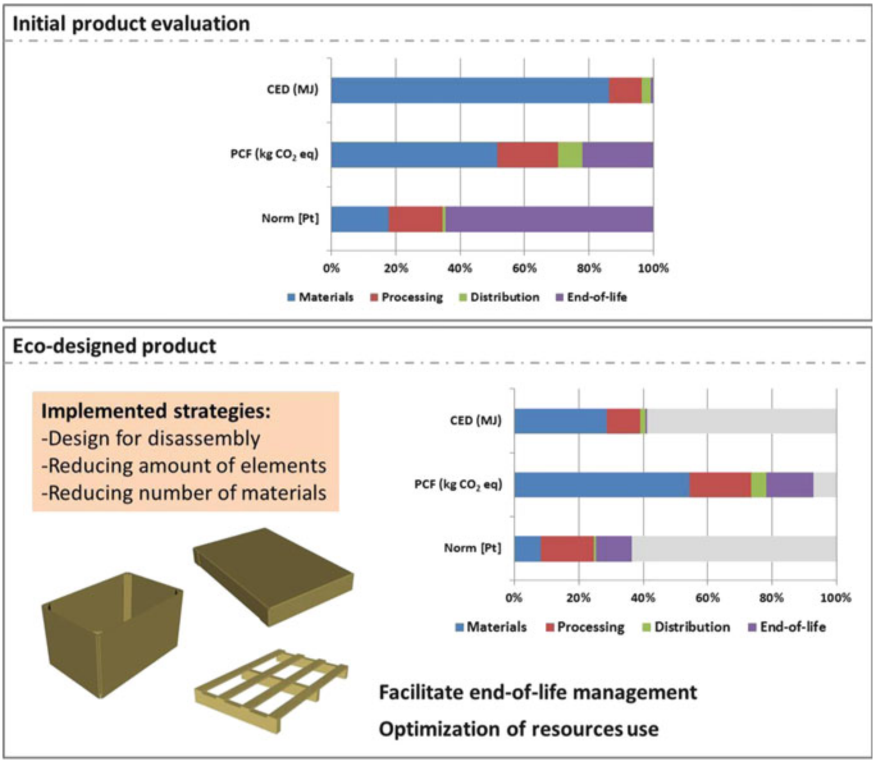

Fig. 7 Initial product evaluation of the industrial packaging: Quantitative assessment by life cycle stage. Eco-design product: implemented strategies and qualitative validation (*gray* shows the reduced amount for each indicator). The cumulative energy demand (CED), product carbon footprint (PCF) and normalized CML impact (Norm) are assessed as indicators

enlarging its lifespan. Finally, the amount of materials and the number of elements were optimized for reducing the environmental impact of the materials extraction and processing stage.

The weight of the product is reduced by almost 35 % due to the optimization of materials used in the box design. This positively affects the environmental issues of the product because the transportation requirements are reduced. The environmental indicators showed reductions from 7.2 % (carbon footprint) to 63.5 % (CML normalized). The facilitation of the end-of-life management contributes significantly to the reduction of the environmental impact (Table 5).

Table 5 Quantitative indicators for the eco-designed industrial packaging regarding design (weight, volume, and transport volume) and environmental improvements (CML norm, product carbon footprint [PCF], and cumulative energy demand [CED])

	Design	Environmental		
	Weight [kg]	CML norm [Pt]	PCF [kg CO_2eq]	CED [MJ]
Initial	25.57	2.01E−11	16.13	603.02
Eco-design	16.71	7.31E−12	14.96	247.73
Variance (%)	−34.65	−63.5	−7.2	−58.9

6 Packaging for Chemical Products

For the case study of chemical product packaging, a detergent bottle was selected. The company aims to improve the environmental performance of the packaging as well as to differentiate the product from their competitors. Moreover, the resulting eco-design strategies are expected to be implemented in other products of the company.

The packaging is a standard bottle for detergent with a volume of 2 L. There are three elements that compose the packaging: a cap (PP), which includes a measuring cup; a bottle (HDPE), with an oval base that includes a handle to facilitate its transportation and usage; and a label (PP) that includes advertising and information about use, toxicology, and environmental issues (Fig. 8). The bottle is obtained through a blowing molding, while the processing used for the cap is injection molding and flexography for the label.

As a result of the qualitative assessment, the distribution and the concept stages were identified as the critical ones. First, there is a need to optimize the packaging for distribution. Second, the packaging is not considered to be innovative in their sector. On the other hand, the technologies used for the processing are identified as optimal for the design and the materials used. However, the quantitative

Fig. 8 Initial product, image, and elements of the technical packaging for a detergent bottle (*Source* KH Lloreda)

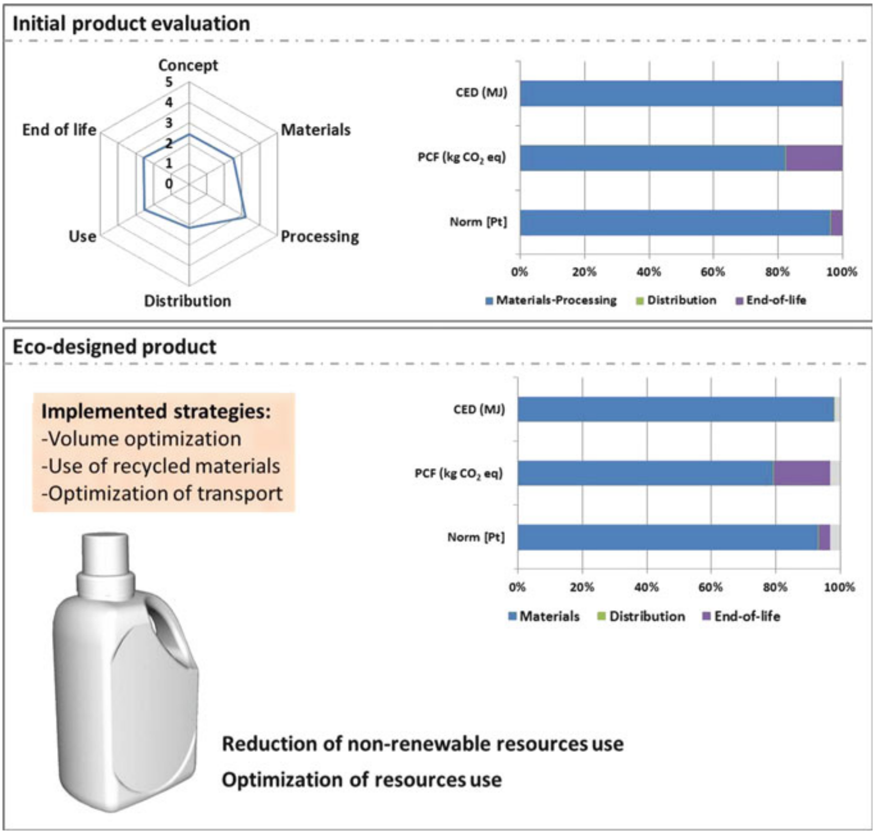

Fig. 9 Initial product evaluation of the detergent bottle: Qualitative and quantitative assessment, by lifecycle stage. Eco-design product: implemented strategies and qualitative validation (*gray* shows the reduce amount for each indicator). The cumulative energy demand (CED), product carbon footprint (PCF), and normalized CML impact (Norm) are assessed as indicators

assessment focused the attention on the materials and processing stages, which accounted for more than the 80 % of the environmental burdens. The environmental impact corresponds mainly to the HDPE bottle, which has the highest weight of the entire packaging. However, the carbon footprint of the packaging highlighted also the contribution of the disposal of the product in a sanitary landfill to the GHG emissions. The detergent packaging obtained a carbon footprint of 322.57 g of CO_2 (Fig. 9).

The resulting strategies for the eco-designed products, therefore, focused on optimizing the use of materials and improving the distribution issue. First, the shape and design of the bottle was modified. The volume was changed into a smaller but wider bottle (volume reduction of 20 %), with a functional handle that occupies less space. Second, the HDPE for the bottle is changed to recycled HDPE

Table 6 Quantitative indicators for the eco-designed detergent bottle regarding design (weight, volume, and transport volume) and environmental improvements (CML norm, product carbon footprint [PCF], and cumulative energy demand [CED])

	Design			Environmental		
	Weight [g]	Unit volume [cm^3]	Transport volume [u/truck]	CML norm [Pt]	PCF [g CO_2eq]	CED [MJ]
Initial	80	3917	36	5.58E−14	322.57	10.45
Eco-design	80	3132	48	5.41E−14	312.49	10.28
Variance (%)	0	−20	+25	−3.1	−3.1	−1.6

in order to reduce the consumption of nonrenewable materials. Finally, the design modification resulted in an optimization of the distribution stage (Fig. 9).

Although the weight and materials use is not reduced, the other design indicators resulted in positive outcomes. First, the volume of the product is optimized (20 % lower). As a result, the transportation is optimized as 25 % more product can be transported per truck. On the other hand, the environmental impacts were reduced up to 3.1 %, both for the global indicator (normalized CML) and the PCF, while the energy consumption was reduced by 1.6 % (Table 6).

7 Packaging for Technical Products (Lighting Sector)

As packaging for technical products, the packaging system for a lighting product was selected. The product was chosen as representative of the packaging used in the company as well as a multipackaging system for a lighting compounded by various parts.

The selected packaging is composed of three different packaging related to each part of the lighting: screen, mast, and base (Fig. 10). The screen is blocked by six pieces (expanded PE) situated in the corners and the sides of the screen. Then, the product is thermo-shrink-wrapped and packed in a cardboard box. Second, the mast is protected with longitudinal block pieces (expanded PE) and thermo-shrink-wrapped. Finally, the base is protected with two block pieces in the sides and is packed in a cardboard box. The main function of the packaging is to protect the different elements of the lighting during the transportation and storage of the product. Moreover, the packaging is expected to differentiate the products of the company from the competitors, and the logo in the different pieces is used for this purpose.

The use and materials lifecycle stages were the least rated in the qualitative assessment. First, the lifespan of the packaging should be adapted to the product, and more information about the materials should be provided to the customer. Second, the use of different materials is perceived as a negative environmental aspect of the product. On the other hand, the processing and the distribution are

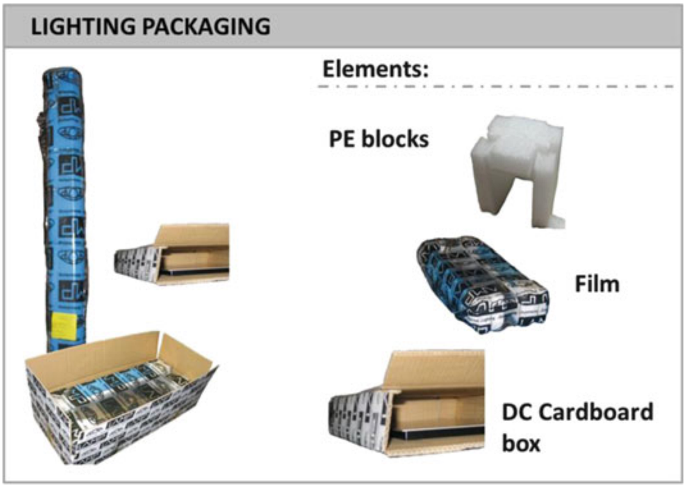

Fig. 10 Initial product, image, and elements of the technical packaging for a lighting product (*Source* Lamp)

considered the most environmentally friendly stages due to the optimization of the process and the fact that secondary packaging is avoided.

The materials extraction and their processing is pointed out as the most contributing lifecycle stage of the packaging (>72 %). Specifically, the PE blocks and film are the most impacting elements, even though cardboard is the most used material. Despite its low contribution to the carbon footprint and the energy consumption indicators, the end-of-life stage has an important role in the global environmental indicator by accounting for approximately 25 % of the impact. Finally, the PCF of the packaging is 4.61 kg of CO_2 and the distribution of the product contributes with 7 % (Fig. 11).

The strategies implemented in the new design are focused on reducing the amount of resources used, reducing the number of materials, and reducing the consumption of nonrenewable materials. The most impacting elements (PE blocks) were eliminated and substituted by elements made of renewable materials (cardboard). The new design is mainly composed of cardboard elements, and the different materials can be disassembled easily while facilitating end-of-life management (Fig. 11).

Regarding the design aspects, the weight of the packaging was reduced by 4 % and the volume by 36 %. Moreover, the facing area was increased by 8 % (in the eco-design product, it was 2.11 m^2). These improvements optimized the environmental requirements of the distribution stage as well as the use of resources in the packaging itself. The environmental indicators obtained important reductions, from 35.3 to 52.8 %. The energy consumption is the most reduced indicator; the change from plastic to cardboard implies a reduction of fuel consumption. The PCF is reduced by 35.3 % and the distribution is still the second most contributing lifecycle stage (Table 7).

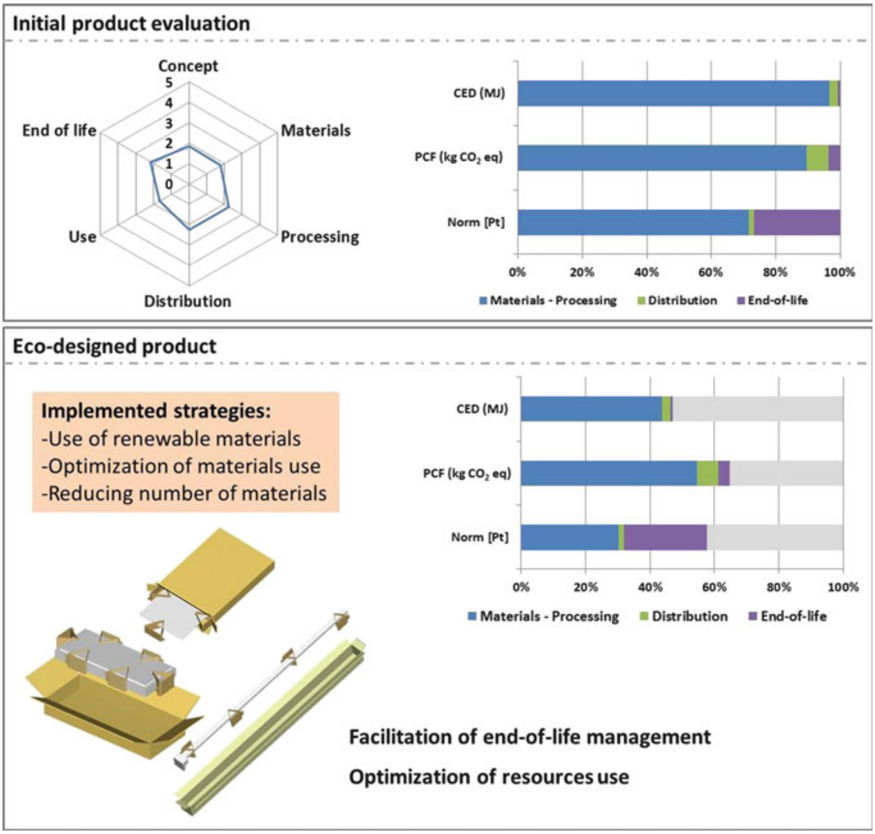

Fig. 11 Initial product evaluation of the technical packaging for a lighting product: Qualitative and quantitative assessment, by lifecycle stage. Eco-design product: implemented strategies and qualitative validation (*gray* shows the reduce amount for each indicator). The cumulative energy demand (CED), product carbon footprint (PCF), and normalized CML impact (Norm) are assessed as indicators

Table 7 Quantitative indicators for the eco-designed lighting packaging regarding design (weight, volume, and transport volume) and environmental improvements (CML norm, product carbon footprint [PCF], and cumulative energy demand [CED])

	Design		Environmental		
	Weight [kg]	Unit volume [cm^3]	CML norm [Pt]	PCF [kg CO_2eq]	CED [MJ]
Initial	2.30	43875	2.57E − 12	4.61	162.70
Eco-design	2.21	28080	1.48E − 12	2.98	76.75
Variance (%)	−4	−36	−42.3	−35.3	−52.8

8 Packaging for the Food Sector

A minced meat tray was selected for the food sector packaging case study. The company produces meat products and retails to supermarkets within Spain and Portugal. Prior to the study, the enterprise changed some cardboard packaging to trays in order to reduce the material amount per product while maintaining the functionality.

The minced meat tray was selected among different products as a representative multilayer product. The multilayer tray has a volume of 740 mL, of which 370 mL are controlled atmosphere gases; it contained 400 g of minced meat. The packaging is made of a transparent material composed of three layers: PET, EVOH, and PE. The packaging is composed of three elements (Fig. 12). First, a film (multilayer O-PET/PE/EVOH/PE) seals the tray, holding the protective atmosphere until the caducity of the product. Second, the tray itself is a transparent multilayer plastic made of PET (80 %), which gives shape to the product; EVOH (3 %), which seals; and PE, which guarantees the sealing of the film. Finally, a label made of coated paper contains information about the product, the logotype of the enterprise and quality labels.

The function of the packaging is to maintain the product in perfect condition for 12 days, 2 days of which correspond to the transportation stage and the other 10 days to the retail and use stages. Unlike traditional packaging, this type of packaging has the particularity that it almost doubles the lifespan of the packed meat. The packaging uses controlled atmosphere technology for improving the quality conditions of the product. For this purpose, the internal air of the packaging is eliminated and substituted by injected gases (CO_2 and O_2) that conserve the content beyond the normal lifespan of other refrigerated products. For an effective

Fig. 12 Initial product, volume, image, and elements of the minced meat tray (*Source* Arcadié)

protective atmosphere packaging, the material used should be as impermeable as possible to gases and water vapors to prevent migration.

In the qualitative assessment of the packaging (QALCC), the materials, use, and end-of-life lifecycles stages obtained the lowest punctuation. The multilayer materials, the longer lifespan of the packaging compared to the product, and the difficulties for its end-of-life management are the critical points. Regarding concept, attention is paid to the need for reducing the resource use of the packaging. Processing is the most rated stage due its optimal design. On the other hand, the quantitative assessment (LCA) highlighted that the most contributing lifecycle stages of the minced meat tray are the materials extraction and transportation (89 % of the normalized impact). The distribution of the product is the second most important stage, with contributions of approximately 25 % in the energy indicator and the carbon footprint. Within the distribution, the distribution packaging for the trays (cardboard boxes) is the main contributor. The amount of material per functional unit is high due to the low capacity of this secondary packaging. The PCF of the initial product accounts for 178.4 g of CO_2 per product (Fig. 13, Table 6).

According to the assessment results, eco-design strategies focus on the materials selection and design (e.g., optimization of materials use in relation to the lifespan of the packaging). The feasibility assessment and the potential compatibility of strategies resulted in a prototype design that included two of the proposed improvements. The new design varies the characteristics of the multilayer tray, while maintaining the other elements in order to ensure the function of the packaging (i.e., product production and sealing, and communication of the product). Moreover, with this selection, the company maintains the image of the product. The new tray has a new design that gives structure to the product while reducing the materials amount. This strategy accounts for a reduction of 15 % of the plastic. Second, the plastic is substituted by recycled material (Fig. 13).

The analyzed indicators showed that the strategies implemented account for a reduction between 8.6 and 50.9 %. Main reductions are done in energy consumption as the use of recycled plastic avoids the extraction of raw plastic from oil sources. The PCF is improved by 35.9 %, mainly due to the reduction of nonrenewable materials use. However, other environmental indicators obtained lower reductions than the PCF, and the normalized CML value decreases only 8.6 %. Regarding design, the eco-design packaging is 12 % lighter (Table 8).

9 Packaging for Food Retail

A delicatessen product was chosen for the food retail case study. Candy Glam Rings are candy jewelry created and sold by a specialized patisserie. The product was selected because it is a referent of the company image.

The rings are presented in a transparent box (like a showcase) and encapsulated in a case. The aspect of the packaging resembles that used in jewelry and

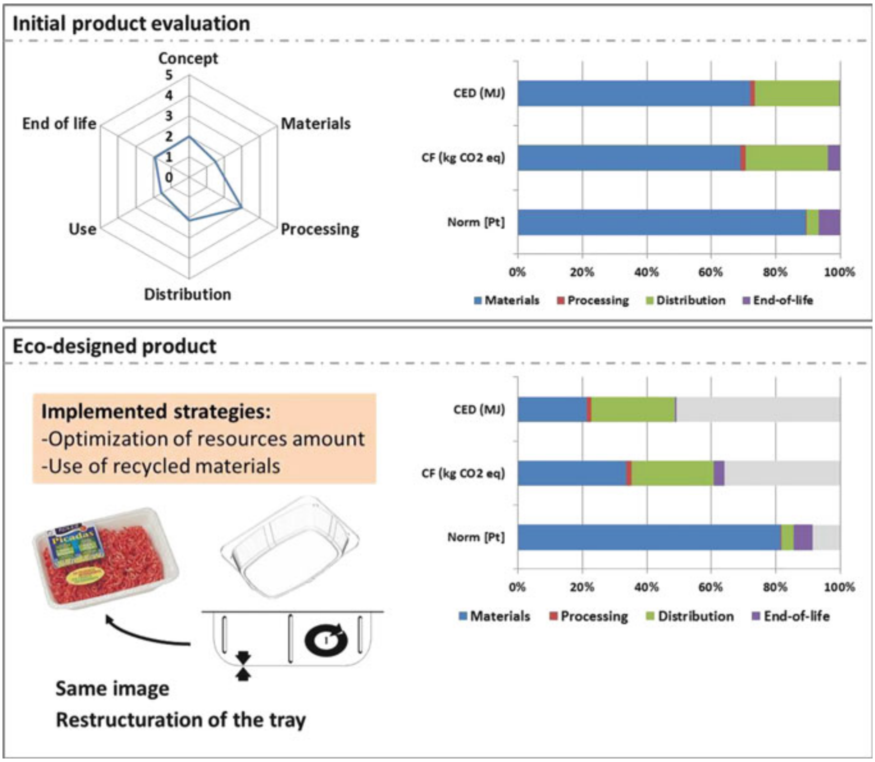

Fig. 13 Initial product evaluation of the minced meat packaging: qualitative and quantitative assessment, by lifecycle stage. Eco-design product: implemented strategies and qualitative validation (*gray* shows the reduce amount for each indicator). The cumulative energy demand (CED), product carbon footprint (PCF), and normalized CML impact (Norm) are assessed as indicators (*Source* Arcadié)

Table 8 Quantitative indicators for the eco-designed minced meat packaging regarding design (weight, volume, and transport volume) and environmental improvements (CML norm, product carbon footprint [PCF], and cumulative energy demand [CED])

	Design	Environmental		
	Weight [g]	CML norm [Pt]	PCF [g CO_2eq]	CED [MJ]
Initial	20.36	8.59E−13	178.4	4.50
Eco-design	17.92	7.85E−13	114.4	2.21
Variance (%)	−12	−8.6	−35.9	−50.9

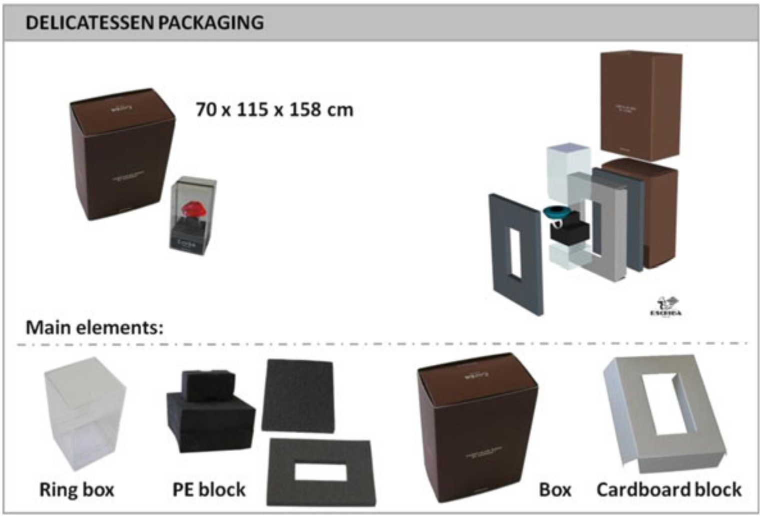

Fig. 14 Initial product, volume, image, and elements of the delicatessen packaging (*Source* Escribà)

perfumery, in order to differentiate the image of the product from other products of the company. The packaging is composed of multiple elements and made by different materials (Fig. 14). There are two main parts of the packaging: the showcase for the ring and the external case. The ring is placed in a soft block (PE) that fits in the transparent box (PS). This internal box is labeled (paper) and is sealed (PE). The external case is made of cardboard and has different block pieces made of cardboard and polyethylene (PE) in order to protect the ring showcase. The functions of the packaging are to protect the product and to show a high-end product image.

The worst result of the qualitative assessment was given to the concept of the packaging because it is not multifunctional despite its lifespan. Moreover, the materials and distribution stages were identified as potential areas to implement strategies. Regarding material, although the use of renewable materials is extended (cardboard), the amount of resources is large considering the product. Second, the transportation requirements of the product are considered as an important contributor to the environmental impacts (Fig. 15).

In the quantitative assessment, the materials extraction and processing were also identified as the most contributing lifecycle stages (40–65 %). Regarding materials, the polystyrene of the transparent box and the polyethylene blocks of the ring are the most impacting materials. Moreover, the processing of the cardboard (external case) has an important role due to the presence of this material in the packaging. The PCF of the product accounts for 708 g of CO_2 and most of the emissions are produced during distribution, mainly by airplane, as the product is sold around the world (Fig. 15).

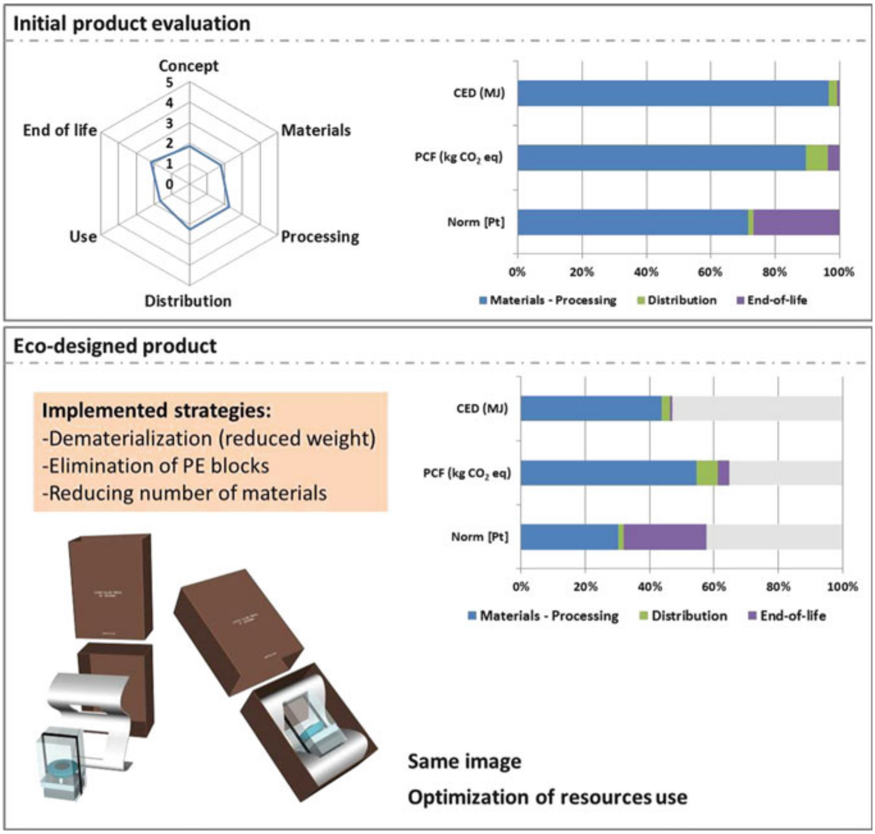

Fig. 15 Initial product evaluation of the delicatessen packaging: Qualitative and quantitative assessment, by lifecycle stage. Eco-design product: implemented strategies and qualitative validation (*gray* shows the reduce amount for each indicator). The cumulative energy demand (CED), product carbon footprint (PCF), and normalized CML impact (Norm) are assessed as indicators

The eco-design product was based on the optimization of the resource use (Fig. 15). First, the most impacting elements (PE blocks) were eliminated. Second, the packaging was dematerialized in order to reduce the weight of the product. This strategy was applied to the external cardboard case, which was lightened. Third, attention was paid to the reduction of the number of materials implemented in the design. In this sense, the internal blocks were changed for one mono-material block. Finally, the strategies aimed also to facilitate the end-of-life management of the product. However, some strategies were rejected as the luxurious image of the product must be maintained.

From the design perspective, the unit volume was optimized and reduced by 11.4 %, although the weight of the product was only reduced by 0.51 %. However, considering the small weight and volume of the packed product, the design could be more optimized. Regarding the environmental burdens, the global impact

Table 9 Quantitative indicators for the eco-designed delicatessen packaging regarding design (weight, volume, and transport volume) and environmental improvements (CML norm, product carbon footprint [PCF], and cumulative energy demand [CED])

	Design		Environmental		
	Weight [g]	Unit volume [m^3]	CML norm [Pt]	PCF [g CO_2eq]	CED [MJ]
Initial	118.67	1271.9	4.31E−13	709.46	16.28
Eco-design	118.06	1126.5	4.26E−13	699.37	16.50
Variance (%)	−0.51	−11.42	−1.1	−1.4	+1.3

(CML) is reduced 1.1 % while the energy consumption is increased by 1.3 %, as the use of cardboard is also accounted as renewable energy. The PCF is the indicator with highest reductions due to the optimization of the volume for transportation (Table 9).

10 Conclusions

The eco-design implementation in different packaging products resulted in a better environmental performance of the packaging. Regarding the design parameters, most of the case studies reduced their weight and volume. As a result, when quantifying the transport capacity, this was increased significantly and, consequently, the transport requeriments also decreased. Second, all of the case studies achieved a reduced PCF (from 1.4 to 35.9 % of reduction), a reduced environmental impact (CML norm, from 1.1 to 63.5 %), and a reduced energy consumption (from 1.6 to 58.9 %, apart from food retail case study) (Table 10).

Among the sectors analyzed, the size and weight of the packaging determine the absolute values of the PCF. Packaging systems for larger products obtained the greatest values: industrial packaging (16 kg CO_2 eq.) and technical packaging (4.6 kg CO_2 eq.). However, both packaging types had a longer lifespan related to the other case studies analyzed. First, industrial packaging is a multipurpose

Table 10 Improvement indicators [variance, %] for the eco-designed products regarding design (weight, volume, and transport volume) and environmental improvements (CML norm, product carbon footprint [PCF], and cumulative energy demand [CED])

	Design			Environmental		
Variance [%]	Weight	Unit volume	Transport volume	CML norm	PCF	CED
Industrial	−34.65	–	–	−63.5	−7.2	−58.9
Chemical	0	−20	+25	−3.1	−3.1	−1.6
Technical	−4	−36	–	−42.3	−35.3	−52.8
Food product	−12	–	–	−8.6	−35.9	−50.9
Food retail	−0.51	−11.42	–	−1.1	−1.4	+1.*3*

packaging that can be re-used in different areas of the company. Second, the technical packaging is designed not only for distribution but also for storage. However, the PCF of the single-use packaging cases primarily depends on the design and the materials used. The food retail packaging got the highest PCF value (709 g CO_2 eq.), even though it contained the smallest product (a candy ring). The design of the box is presumptuous in order to show a high-end product image and to make it similar to real jewelry. Therefore, a higher amount and variety of materials are used than what is actually needed for protection purposes.

In relative values (PCF per mass unit), food packaging accounted for the largest PCF results. First, the meat tray's PCF was of 8.8 g CO_2 eq. per gram of packaging, due to mainly the technical materials of the multilayer for food preservation. Second, the PCF of the food retail packaging resulted in 6.0 g CO_2 eq. per gram of packaging because of the luxurious design and the use of different materials, as mentioned above. Regarding the other sectors, differences depend on the type of material used in the packaging. The chemical packaging analyzed is made of thermoplasts and obtained a PCF per gram of packaging of 4 g CO_2 eq., while the technical packaging combined both plastic and renewable materials and had a PCF of 2.0 g CO_2 eq. per gram of packaging. Finally, the PCF of the industrial packaging resulted in the lowest value per gram of packaging (0.6 g CO_2 eq.), as most of the materials are from renewable sources (cardboard and wood).

Regarding the affectation of the eco-design process, the PCF is mainly reduced due to the optimization of the volume and therefore the improvement in transportation requirements, as the GHG emissions of transportation are the most contributing ones. The PCF is also largely improved when changing from plastic or nonrenewable materials (e.g., high density polyethylene, HDPE) to renewable ones (e.g., cardboard or wood), as the oil consumption is reduced. Lastly, the optimization of the end-of-life management of packaging products also decreased the PCF significantly due to the emissions in landfilling.

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