Sustainable Design of Packaging Materials

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Abstract The development and production of products in a more sustainable way has received special attention in recent years. In particular, packaging products range from single materials with simple designs as well as complex ones that include different materials (cardboard, woody boards, paper, plastics, etc.). A comprehensive assessment of the environmental impacts of a product's life cycle comprises functions from the extraction of raw materials to waste management and disposal (i.e., the life cycle-assessment perspective). Thus, the knowledge of the environmental impacts of packaging products used in a specific production sector is a factor of major importance not only with the aim of improving the environmental performance of products and/or processes but also to fulfill the requirements of the ecological/green products market. One of the most valid tools to assess and reduce the inherent environmental burdens associated with products is ecodesign or Design for the Environment (DfE). This methodology consists of applying environmental criteria to the development of a product and implies a change of how we regard that product. The assessment of environmental

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improvement of the product's entire life cycle is also considered for a comprehensive analysis. To demonstrate the application of DfE in the ecodesign of packaging products, a wooden storage box was assessed. Different types of materials, such as timber, plywood, engineered woods, plastics, brads, hoods, and/or staples, can be considered in the manufacture process. This type of box is often used for packaging when mechanical resistance is required for heavy loads, long-term warehousing, or adequate rigidity. Moreover, when such a box is used in the food sector, its production chain must include fitosanitary thermal treatment. According to the assessment by means of DfE methodology, the relevance of the raw materials chosen, as well as their origin, can greatly influence the associated environmental burdens, which can also be confirmed quantitatively by LCA. Thus, a correct methodological adaptation of the concept of "eco-briefing" as a tool for communication among environmental technicians and designers, includes the simplification of the analytical tool used and the application of the life cycle-assessment methodology, which facilitates the environmental analysis, are required to obtain new formats of packaging materials designed within a sustainable perspective.

Keywords Design for environment · Ecodesign · Environmental performance · Life cycle assessment · Materials selection

1 Introduction

Environmental issues, such as climate change and fossil fuels depletion, have led to a society hat increasingly aware of environmental preservation (Ribeiro et al. 2013). One of the major aspects in the process of product development is the one related to materials selection, which is not only associated with products manufacture but also with packaging (González-García et al. 2011a; Sanyé et al. 2012; Peças et al. 2013). Therefore, the growing concern about products being manufactured in a sustainable manner involves paying special attention to packaging materials. Different investigators have reported the outstanding contribution from environmentally friendly packaging of a wide range of products in the context of global environmental impact (Koreneos et al. 2005; Meyhoff Fry and Edwards 2011; González-García et al. 2011a; Sanyé et al. 2012). According to these studies, a good packaging design could contribute to decreases in the environmental impact of a product as well as lower production costs (Ribeiro et al. 2008).

Packaging products have a strong presence in markets as well because they have turned into essential elements in the life cycle of other products. In fact, packaging has the function of protecting and maintaining products during the distribution and retail processes all the way to the final user (Sanyé-Mengual et al. 2014a). Specifically in the food sector, advances in food packaging play a major role in keeping the food supply safe (Marsh and Bugusu 2007; Meyhoff Fry and Edwards 2011). Packaging technology must balance food protection with other issues including energy and material costs, social and environmental awareness, and compliance with regulations on the disposal of municipal solid waste (Jungbluth et al. 2000; Marsh and Bugusu 2007; Madival et al. 2009).

Multiple examples exist of reporting the environmental impacts of packaging materials in the food sector (Spitzley et al. 1997; Koreneos et al. 2005; Siracusa et al. 2008; Meyhoff Fry and Edwards 2011; Antón et al. 2008; González-García et al. 2013a, b) including a remarkable case study on a sparkling drink[1] regarding the introduction of both new packaging designs and recycling concept (Sanyé-Mengual et al. 2014a). Thus, packaging has evolved into a new integral part of the product where design and marketing play an imperative task. The environmental burdens of products are increased due to not only the amount and type of packaging materials (Jungbluth et al. 2000) but also the packaging-material management approach (Ross and Evans 2003; Büsser and Jungbluth 2009; Sanyé-Mengual et al. 2014a). Therefore, proper management of these packaging wastes is also important in terms of environmental consequences (recycling, reuse, valorization, landfilling, etc.). To comply with the current European legislation on packaging and packaging waste (European Council 1994, 1997, 2004, 2005, 2009), packaging producers must take all possible measures to reduce the environmental impact of packaging products while retaining the functions that existed prior to the admission of the product in the market.

Although numerous studies have quantified the environmental consequences derived from packaging materials, the influence of the packaging during the full life cycle of products is reasonably different depending on the product considered (Jungbluth et al. 2000). Particular attention is being paid to utilizing alternative raw materials specifically for polymers (Siracusa et al. 2009). So far, petroleum-based polymers have been used as packaging materials due to their large availability at relatively low costs as well as good insulating and mechanical properties (Siracusa et al. 2009). Substitutes for plastic packaging (such as steel, aluminum, glass, cardboard, packaging paper) vary depending on the market sector and packaging application. In this sense, cork and rubber are alternatives in the caps and closures category (Franklin Associates 2014). However, plastic packaging also presents disadvantages because they are not completely recyclable and/or biodegradable. In this sense, research is being focused on the development of biodegradable polymers and bioplastics made from renewable raw materials (Siracusa et al. 2009; Moralejo-Gárate et al. 2013; European Bioplastics 2015).

This chapter focuses on the process of applying environmentally friendly strategies in the design of packaging products. First, environmental strategies that can be included in the life cycle of packaging products are proposed. Second, the methodology to improve the design of packaging by combining design for environment (DfE) and life cycle assessment (LCA) is described. Finally, a case study of a wooden storage box is assessed.

[1]http://www.carbontrust.com/media/5888/cts287-coca-cola.pdf.

2 Integration of Environmental Aspects into Packaging Design

In the framework of design for environment (DfE), a large number of ecodesign strategies have been proposed to improve the environmental performance of products. All of them are commonly grouped according the life-cycle stage they affect (Crul and Diehl 2006; van Hemel 1998). This section aims to select and collect those ecodesign strategies than can be applied to the packaging sector where packaging is analyzed as a single product rather than as part of a life-cycle stage. These strategies may be used as a guidance source for designers and policy makers when applying ecodesign to packaging products.

Tables 1 and 2 show the recommended ecodesign strategies for the packaging sector by life-cycle stage. The list of environmental strategies in DfE provided by Sanyé-Mengual et al. (2014c) was combined with a new set of specific strategies for packaging products. The tables include strategies for the following life-cycle stages: concept, materials, production distribution, and end-of-life. Strategies for the use stage were omitted because they do not apply for packaging products or are covered in other stages such as the concept stage.

The concept stage (Table 1) usually has a great potential to reduce the environmental impact of products (van Hemel 1998). However, applying strategies such as dematerialization may sometimes require redesigning a product and generating new concepts. Packaging products have already been optimized during previous years (Bovea and Gallardo 2006; Sanyé-Mengual et al. 2014a). Consequently, achieving strong modifications for dematerialization in packaging products could result in a difficult task for companies. Nevertheless, work can be done with little investment to increase the environmental information included in packaging products.

According to Table 1, strategies for packaging materials have great potential to reduce the environmental impact of these products. In this stage, three specific strategies were added for packaging products: (1) the use of natural printing inks; (2) the avoidance of adhesives or use of natural ones; and (3) the avoidance vinyls and stickers. These strategies are oriented to reduce the environmental impact when integrating packaging into communications support (e.g., the brand or products' properties). Communication within packaging (e.g., use of stickers) could lead to difficulties in separating materials for recycling. Moreover, the use of synthetic inks would increase the environmental impact of packaging at the end-of-life stage.

Table 2 displays the common environmental strategies to improve the production stage for all types of products. These strategies apply for many different production processes. However, their potential environmental benefits are dependent on the best technologies available. The main objectives in this stage are to reduce resource and energy consumption as well as waste generation.

For the distribution stage, strategies are oriented to increase the efficiency of the transportation process and, consequently, to optimize the volume and weight

Table 1 Environmental strategies for the concept and material stages of a packaging product by life-cycle stage and benefit

Strategies	Reduced resources consumption	Reduced environmental impact	Reduced energy consumption	Enhanced recycling/ reusing	Decoupling from non-renewable resources	Increased lifespan	Market differentiation	Improved user behaviour
Concept								
Dematerialization	•	•						
Multifunctionality						•		
Environmental information (e.g. carbon footprint)							•	•
Demand of suppliers' environmental information		•						
Ensure packaging durability if reused		•						
Shared use of packaging (standard packaging)	•	•		•				
Materials								
Dematerialization	•	•						
Monomaterial				•				
Recyclable materials				•				
Renewable/natural resources		•			•			
Low-impact materials		•						
Local resources		•					•	
Reused components	•	•						
Use of natural printing inks		•						
Avoid adhesives or use natural ones		•						
Avoid vinyls and stickers	•	•		•				

Table 2 Environmental strategies for the production, distribution, and end-of-life stages of a packaging product by life-cycle stage and benefit

Strategies	Reduced resources consumption	Reduced environmental impact	Reduced energy consumption	Enhanced recycling/reusing	Decoupling from non-renewable resources	Increased lifespan	Market differentiation	Improved user behaviour
Production								
Internal recycling (closed-loop)	•							
Optimize production process	•	•	•					
Choose cleaner production processes	•		•					
Use of low-impact energy sources		•						
Promote renewable energy sources					•			
Local production		•	•					
Distribution								
Optimization of product weight	•		•					
Optimization of packaging volume		•	•					
Local distribution		•	•					
Bio-fuels transportation		•	•					
Efficient transportation		•	•					
End of life								
Feasibility of components separation				•				
Recyclability				•				
Materials identification				•				
Reusability				•		•		
Biodegradability				•				
Communication-to-user (waste management)		•						•

of the packaging product or to use more energy-efficient transportation vehicles. However, in this case, strategies such as optimizing the volume and weight of the packaging are dependent of the product being packaged. Consequently, these strategies may be developed accordingly with the requirements and properties (e.g., dimensions) of the particular product.

Finally, environmental strategies to improve the end-of-life packaging of products are very similar to all type of products. These are basically oriented to reduce resource consumption by enhancing the reusability of elements or by promoting its recycling. Increasing the use of biodegradable materials, or communicating to the user the optimal ways to manage this product as a waste, aims to reduce the environmental burdens of this stage.

As mentioned previously, the stage with more specific strategies for packaging products is the materials stage due to the requirements of packaging to communicate information. Using inappropriate technologies for adding information on packaging products could result in a significant environmental impact. For the other stages, the strategies mentioned are in common use for different type of products such as furniture or textiles.

3 Design for Environment Methodology

3.1 Introduction

Although LCA methodology is a suitable and valuable tool to assess the environmental impact of materials during their life cycle (Baumann and Tillman 2004), it can also be combined with environmental tools to analyze and reduce the environmental burdens associated with products.

Ecodesign or Design for the Environment (DfE) is receiving special attention as a potential instrument in product-development strategies. Product design is one of the most important production strategies toward global sustainability due to the fact that all products available in markets are the result of a product-development process (Ramani et al. 2010). DfE integrates multifaceted aspects of both design and environmental considerations. It takes into account that the definition of sustainable solutions for products must be based on the minimization of negative consequences in the context of economic, environmental, and social perspectives (Charter and Tischner 2001).

This methodology is composed of applying environmental criteria to the development and design of a product (Ramani et al. 2010). So although many other definitions exist, DfE is considered as the design of and for a sustainable development context (Karlsson and Luttropp 2006). This change in the design process is translated into (1) a reduction of environmental emissions and (2) the improvement of the environmental profile of products throughout the entire life cycle taking all the involved steps into consideration (McDonough et al. 2003; Zust and Wirnmer 2004).

Consequently, LCA and DfE constitute a good relationship because LCA provides the structure for analyzing the environmental impacts associated to a product and DfE can perform the practical application of the assessment (Ramani et al. 2010).

3.2 Stages of Design for Environment

DfE refers to the methodical integration of environmental factors into product design and development, thus playing a crucial role in the development of an integrated product policy (Tukker et al. 2000; Sanyé-Mengual et al. 2014a).

Certain environmental objectives must be set for a proper conceptual development, based on which, and by means of a critical review by a panel of expert participants, the process of ecodesign is initiated with consideration of all the stages of the life cycle (Smith and Wyatt 2006). Thus, a proper and fluid communication between environmental experts and designers is mandatory. Figure 1 displays the different steps to fulfil in an ecodesign strategy.

Step 1. Establishment of the multidisciplinary ecodesign team

An important aspect that must be considered is the creation of a multidisciplinary team to cover the different fields of knowledge involved not only in the design and environment but also in the manufacture process. Commonly the ecodesign team is constituted by designers, engineers, environmental scientists, chemists, and experts in the field of the industrial product under study.

Step 2. Description of variables that define the product to ecodesign

This phase of ecodesign strategy requires special attention because both the type and number of variables to be analyzed depend on the product selected for the assessment. Thus, selection criteria must be established to prioritize potential variables that could also be applied to similar products. Aspects related to the product (and sector), such as implementation and complexity degree, representative materials, as well as market demands, are compulsory.

Step 3. LCA of the selected product

This phase of DfE is based on the environmental assessment of the product chosen for ecodesign by means of LCA methodology. Therefore, not only is the environmental profile derived from the life cycle of the product determined, the significant environmental factors (also known as environmental "hot spots") are also identified. This step is the starting point for the eco-briefing.

Step 4. Establishment of eco-briefing and ecodesign strategies

Eco-briefing involves the environmental aims that should be considered in the development of ecodesign strategies and is the procedure to communicate the most suitable strategies. Consequently, the environmental goals established to be achieved by means of ecodesign must be carefully indicated. Ecodesign strategies are the alternatives that eco-briefing addresses with the aim of improving the

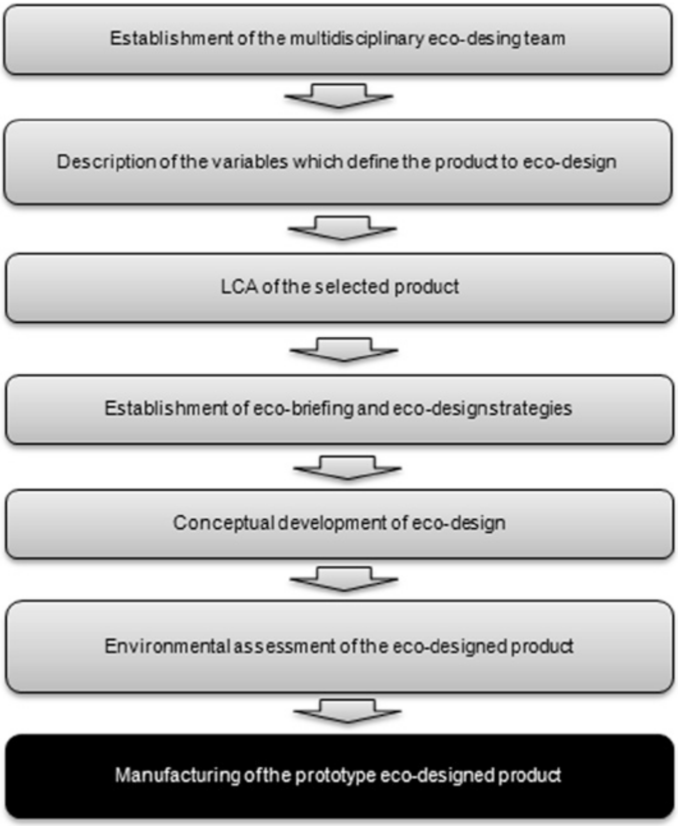


Fig. 1 Steps in the DfE methodology for the ecodesign of a general product

current environmental performance of the selected product (Bhamra 2004; Ferrao and Amaral 2006) by analysing not only technological but also social and financial aspects (i.e., the sustainable perspective). Key life-cycle stages under consideration in eco-briefing are product conceptualization, materials used, production process, distribution, maintenance, and end-of-life management.

Step 5. Conceptual development of ecodesign

Once the ecodesign strategies are defined, a conceptual line to be followed is defined. Special attention should be paid to the key life-cycle stages that have received more attention in the eco-briefing step (i.e., higher punctuations) as well as to the most viable strategies (in terms of technological, financial, and social issues) taking into account feedback from the ecodesign team. These strategies with higher viability to be implemented are the ones to be assessed as well as classified as quantitative and qualitative alternatives. Thus, this step requires a continuous relationship between the team partners in order to analyse in situ the development of the ecodesign.

Step 6. Environmental assessment of the ecodesigned product

This step involves the environmental assessment by means of LCA methodology of the proposed viable quantitative ecodesign strategies. Afterward, environmental profiles for the different strategies will be compared with those corresponding to the current product. The aim of this comparison is to analyze the degree of environmental improvement proposed by the ecodesign team.

Step 7. Manufacturing of the prototype ecodesigned product

The last step consists on the manufacturing of the prototype, i.e., the ecodesigned product, according to the strategies selected in Step 6.

3.3 Products Ecodesigned by a Combination of LCA and DfE Methodologies

Multiple studies are available about the procedure of ecodesign and its interest in the development of integrated product policy (Bovea and Vidal 2004; Bovea and Gallardo 2006; Kurczewski and Lewandowska 2010; Lewandowska and Kurczewski 2010; Tukker et al. 2000).

Practical examples concerning application of the combined methodologies for ecodesign can be found in very different industrial sectors: the automobile sector (Ruhland et al. 2004; Finkbeiner et al. 2006; Muñoz et al. 2006), the leather tanning industry (Rivela et al. 2004), the packaging sector (Bovea and Gallardo 2006; Sanyé-Mengual et al. 2014a), cutlery (Sanyé-Mengual et al. 2014b), clothing (Sanyé-Mengual et al. 2014b), electronic devices (Nedermark 1998; Mathieux et al. 2001; Aoe 2007; Gazulla et al. 2007; Unger et al. 2008), lighting (Gottberg et al. 2006; Casamayor and Su 2013), printing (Tischner and Nickel 2003), and waste management (Todd et al. 2003). Special attention has been paid to wood-based materials. Numerous studies are available in the literature where ecodesign strategies have been applied to wood-based products especially due to the interest in the procurement of wooden goods produced in a sustainable manner as well as in giving solutions to the wood-production sector. Examples include wood boards (Bovea and Vidal 2004), woody surface and edge coverings (Bovea and Vidal 2004), modular playgrounds (González-García et al. 2012a), child furniture sets (González-García et al. 2012b), goods containers (González-García et al. 2011a), kitchen cabinets, office tables, and ventilated walls and headboards (González-García et al. 2011b, 2012c). According to all these studies, the process of integrating the environmental aspects into product development is only effective if it leads to an improved product with fewer environmental impacts and if communicating maintenance procedures to consumers form part of the ecodesign process (Sanyé-Mengual et al. 2014b).

4 Case Study: Storage Wood Box

4.1 Description of the Case Study and Product Under Assessment

As mentioned previously, changes in the design process can promote reductions of environmental impacts. Thus, the interdisciplinary team involved in design for the environment plays a major role in the improvement not only in the ecodesigned product but also in the product-production stages.

The ecodesign of a wood product, such as a storage box, was proposed for assessment. The interest in this product is justified because wood boxes are extensively used not only for storage products but also for transport activities and are present in multiple different sectors and activities. Thus, this section of the chapter reports the methodology used to perform ecodesign of the wood box taking into account its manufacturing process as well as the eco-briefing strategies over all of the key life-cycle stages. Moreover, the environmental impacts derived from woody boxes production are determined using LCA methodology.

To do so, representative primary data were procured directly from a Spanish company located in Galicia (Northwest Spain), that is a Spanish leader in terms of wood-based boards and wood-derived products such as boxes. Although different types of wood boxes are produced, we paid attention to those destined to be in the wine sector. The box considered for assessment is typically used for the storage of three standard wine bottles (750 mL) and presents the following dimensions: 350 × 260 × 103 mm with an average weight of 1.35 kg (González-García et al. 2011a). Because the production process could be considered representative for the manufacture of other wood boxes with different uses and dimensions, two functional units were considered for assessment. Therefore, the ecodesign study is reported in terms of one woody box with the dimensions aforementioned. In addition, we considered 1 kg of wood box as alternative functional unit in order to report the environmental results corresponding to the production system (Fig. 2).

The specific box considered for assessment mainly consists of MDF (medium density fiberboard) and solid timber joined with metal pieces such as brads, hoops, and staples. The wood-box production system was divided into three steps taking into account the primary activities carried out in the factory: the manufacturing step (including assembling, painting, and packaging processes), the cogeneration step in order to produce the energy requirements, and the distribution step to clients. Secondary activities related to the production and transportation of different inputs to the system, e.g., chemicals, boards, metal pieces, or ancillary packaging materials, were also taken into account and computed within the system boundaries (Fig. 2). According to the system boundaries depicted in Fig. 2, further activities related to woody-box use, maintenance, and final management were excluded from the assessment due to the lack of real and valuable information and inventory data. Moreover, these further activities are beyond the premises of the woody factory under assessment. For that reason, a cradle-to-gate perspective was considered in this case study.

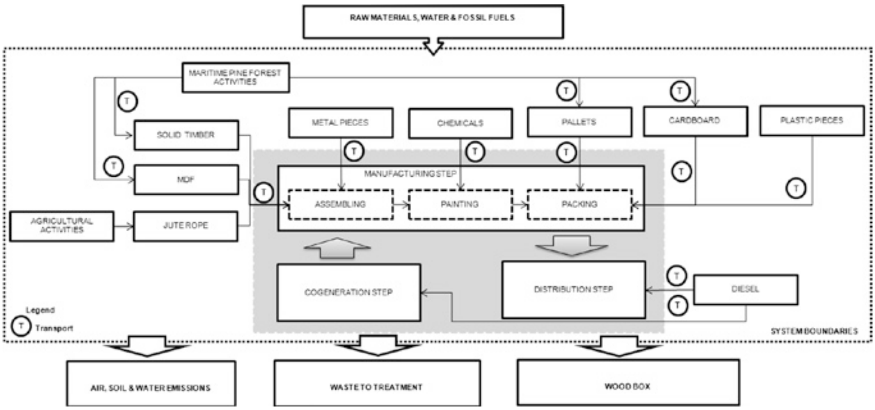


Fig. 2 System boundaries and processes included within the analysis

The Life Cycle Inventory (LCI) data for the foreground system, which includes all the activities carried out in the factory considered for assessment, were collected by means of surveys and interviews with workers. Whenever possible and feasible, typical process-specific data of a period of 1 year were collected. Secondary data corresponding to the production of different inputs were taken from databases (González-García et al. 2011a). Thus, inventory data corresponding to the production of metal pieces (staples, brads, and hoops) were taken from the IDEMAT database (2001). Inventory data for the remaining background processes—such as these corresponding to the production of plastic pieces (hoops and film), the production of the alkyd paint used in the painting process, the production of the jute rope for the handle, the production of the solid timber, and the production of wood pallets—were taken from the Ecoinvent database®.[2]

Concerning the production of the MDF boards, primary data from the inventory stage were taken from a previous study (Rivela et al. 2007) where three factories, considered representative of the "state of art," were evaluated. Finally, regarding forest operations for the different woody inputs (MDF, solid timber, pallets, and cardboard), inventory data were taken from González-García et al. (2013c).

When setting LCA boundaries, it must be decided whether the production and maintenance of capital goods are included within the system boundaries. In this study, they were excluded from the system boundaries because it was assumed to be comparable with that of plants producing functionally similar materials (Jungmeier et al. 2002). Allocation, an important issue in LCA studies, consists of assigning the input and/or output flows of a process to the product system under study. It is required for multifunctional processes, and the selection of an allocation approach can have a strong effect on the results. A characteristic of this woody industry is the concurrent production of very different woody products

[2]http://www.ecoinvent.org/database/.

such as panels, boxes, and papers. Thus, an allocation procedure was considered to allocate the environmental burdens between the different coproducts. There are several allocation methods (mass, economic, etc.), each of which have advantages and disadvantages. Moreover, the choice of allocation procedure depends on the limitations of the study. In this case study, mass allocation was assumed taking into account the annual production of the different coproducts. Economic allocation was not considered because it was not possible to find market prices for all of the products produced in the mill.

4.2 Environmental Perspective of the Woody Box Under Analysis

An attributional LCA for the woody box production was carried out according to the CML 2 baseline 2000 V2.1 method to quantify the environmental impact (Guinée et al. 2001). This method results in the definition of an environmental profile for the assessed product/process/service by quantifying the environmental effects on different categories, whereas only indirect or intermediate effects on humans can be assessed. The impact categories analysed in this study were as follows: abiotic depletion (ADP), acidification (AP), eutrophication (EP), global warming (GWP), ozone layer depletion (ODP), and photochemical oxidant formation (POP). The software SimaPro 8.0.2 was used to implement and process the inventory data (PRé Consultants 2014). The results for the characterisation step are shown in Table 3 per both functional units (one woody box and 1 kg of woody box).

Figure 3 displays the relative contributions from the woody box production steps in the different impact categories considered.

According to the results shown in Fig. 3, the manufacturing step is the most important stage considered throughout the production chain, with contributions ranging from 60 to 90 % depending on the category, followed by the cogeneration stage (ratios from 5 to 30 %).

The remarkable contributions in all of the categories considered are due to the fact that this step includes three relevant processes (assembling, painting, and packaging), which involve the requirements of material inputs such as

Table 3 Characterisation results per impact categories considered under evaluation

Impact category	Unit	1 woody box	1 kg woody box
Abiotic depletion (ADP)	kg Sb_{eq}	5.18×10^{-3}	3.84×10^{-3}
Acidification (AP)	kg $SO_{2\,eq}$	7.56×10^{-3}	5.60×10^{-3}
Eutrophication (EP)	kg $PO_4^{-3}{}_{eq}$	8.16×10^{-4}	6.05×10^{-4}
Global warming (GWP)	kg $CO_{2\,eq}$	6.44×10^{-1}	4.77×10^{-1}
Ozone layer depletion (ODP)	kg CFC-11 $_{eq}$	8.31×10^{-2}	6.15×10^{-2}
Photochemical oxidation (POP)	kg $C_2H_{2\,eq}$	3.45×10^{-4}	2.56×10^{-4}

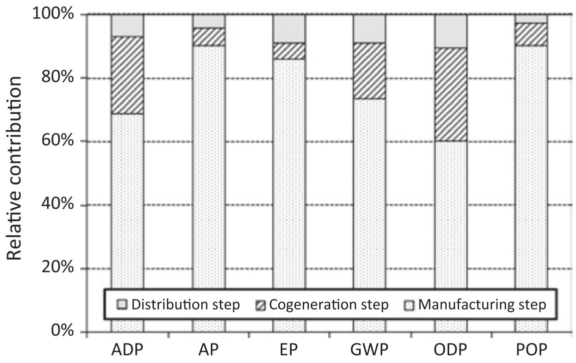


Fig. 3 Relative contributions from the woody box production steps within the system boundaries in the different impact categories considered

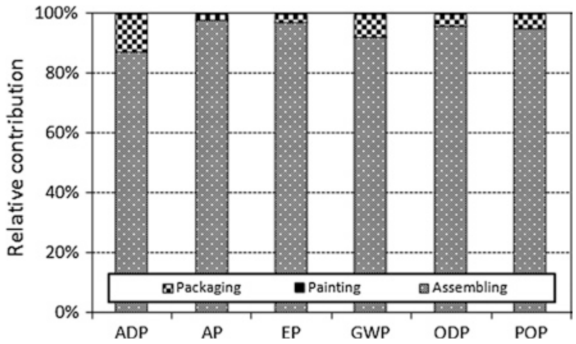


Fig. 4 Relative contributions per processes involved in the woody-box production chain within the manufacturing step

MDF boards and metal pieces, the background production activities of which are energy- and material-intensive. Therefore, a detailed assessment was proposed to analyze in detail the contributions derived from these foreground activities taking into account the corresponding background processes. Figure 4 shows the distribution of impacts (per impact category) between the foreground processes carried out in the factory. According to that figure, the assembling process is responsible for 94 % of environmental impacts derived from the manufacturing step with contributions from the painting process being almost negligible.

The assembling process is the activity during which the woody box is manufactured using MDF boards and solid pine timber as main raw materials. The construction pieces are joined with metal pieces, such as brads, hoops, and staples as well as jute rope, which is used for the handle. All of these structural materials involve background activities regarding their production and transportation up to the woody-box factory gate. Figure 5 shows the distribution of environmental impacts per factor involved in the assembling process.

According to Fig. 5, the production and distribution of the jute rope used for the handle is the main environmental hot spot in all the categories considered for assessment followed by activities related to the production of MDF boards. Thus, improvement strategies in the ecodesign should be focused in these materials used in the woody-box structure.

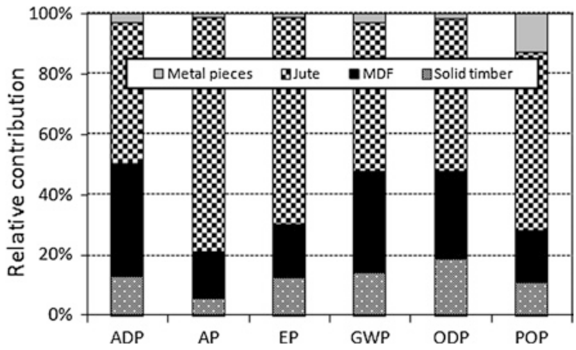


Fig. 5 Distribution of impacts per background processes involved in the assembling process

Regarding the cogeneration step (Fig. 3), this is the second most important step in terms of environmental impacts. In the factory, all of the energy requirements are produced on-site by means of the combustion of fossil fuel with low sulphur content. Production of the fossil fuel, from transport up to the factory, as well as derived combustion emissions were computed in the cogeneration step. The use of an alternative renewable source to produce the energy requirements could be an interesting improvement alternative to take into account.

4.3 Ecodesign of the Woody Box

As was defined in Sect. 3, eco-briefing is the adaptation of a method that assists the communication of environmental factors among environmental experts and designers using basic information about the product to be designed and defining the product with the environmental objectives to be achieved. The sequence of stages proposed in Fig. 1 must be followed in a DfE study. The multidisciplinary team is comprised of environmental technicians as well as designers and other technicians from the factory involved in the production chain. Five key cycle stages were proposed for the eco-briefing: concept (C), materials (M), production (P), distribution (D), and end-of-life (E). The results from the eco-briefing are summarised in Table 4.

Thus, different strategies were proposed to obtain a woody box with a low environmental impact taking into account the results from the eco-briefing. These

Table 4 Environmental hot spots and life-cycle stages considering in the eco-briefing

Environmental hot spots	Key life-cycle stages				
	C	M	P	D	E
Functionality	■	□	□	□	□
High energy and water consumption	□	□	■	□	□
High impact vehicles	□	□	□	■	□
Low optimization of transport volume	■	□	□	■	□

strategies were evaluated from a technological, economical, and social perspective. However, only the most viable strategies for the factory will be discussed below and were considered for the ecodesign.

5 Discussion of Ecodesigned Alternatives and Environmental Profiles

5.1 Alternative Materials for the Structure and Handle of the Box

As stated in the environmental analysis of the woody box, the assembling step produces the greatest environmental impacts with the MDF and the jute rope being the main responsible factors of these results. The MDF represents approximately 22 % of the total weight, thus ranking as the second most important material in terms of weight (72 % of the total weight is the solid pine timber, which is not considered to be an environmental *hot spot*). The production of this material involves large amounts of energy requirements as well as chemicals such as adhesives (Rivela et al. 2007).

According to the factory workers, alternative materials, such as pine plywood or even solid pine timber, could be used as a substitute for MDF without changing the woody-box properties and characteristics. The use of these alternative materials should also produce changes in the total weight of the woody box due to differences in their density (González-García et al. 2011a). Thus, the weight of the current box (1.35 kg) should be reduced by approximately 10 % (approximately 1.46 kg) if plywood is used as a potential structural material (approximately 1.2 kg) or increased by 8 % (approximately 1.46 kg) if solid timber is used. Regardless, for the functional unit considered to display the environmental profiles (that is, per unit box or per kilogram of box), the use of solid pine timber instead of MDF (or plywood) should produce the least environmental impacts (Fig. 6). Differences were identified in the environmental behavior depending on the functional unit (Fig. 6a, b). If the results are reported per unit box (Fig. 6a), the worst environmental profile should correspond to the current box (MDF box) in all of the categories under assessment except in terms of POP, whereas the plywood box should produce a slightly greater impact. The production of the plywood box should result in minor impact reductions ranging from 0.1 to 5 % compared with the MDF box. This slight improvement of the profile should be related with the lowest amount of board required to produce the same product, which should present the lowest impact from the plywood production. The solid pine timber box should report the best environmental results in all the categories with reductions ranging from 13 % (AP and EP) to 21 % (GWP and ADP). However, although better results would be obtained, more research should be required, specifically from design and technological issues, to make the lip of the box in one piece, which at the present moment, is problematic due to the timber width.

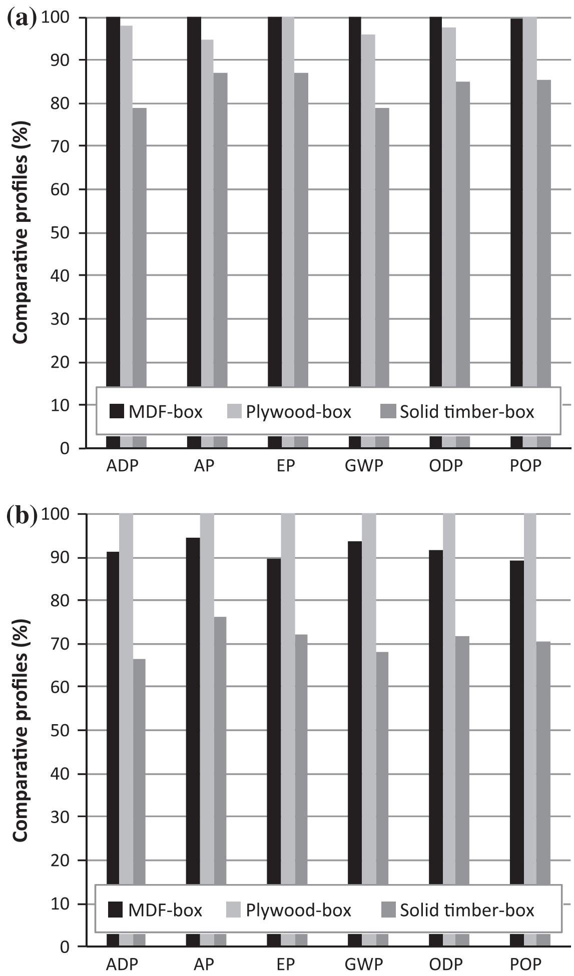
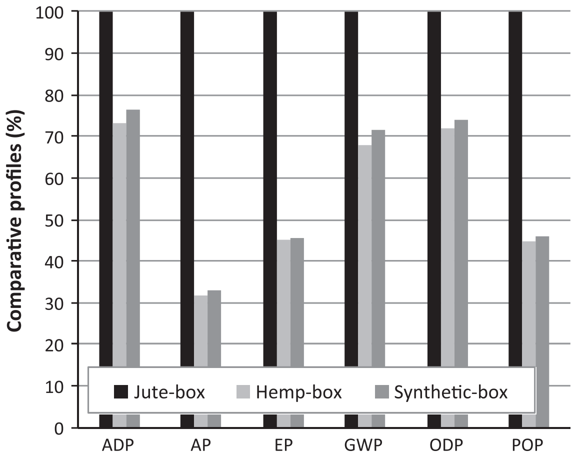


Fig. 6 Comparative environmental profiles considering alternative structural materials. **a** Profiles per unit box; **b** profiles per 1 kg of box

However, if the comparison is carried out per kilogram of woody box (Fig. 6b), the plywood box should present the worse profile in terms of all of the impacts considered, with once again the solid pine timber box having the best profile. Thus, despite reducing the total weight of the box by 10 % when substituting MDF with plywood, the impacts should increase in ratios ranging from 6 to 12 %. The highest chemical and energy requirements in the plywood production process should be the responsible actors of these "negative" results.

Another improvement action to consider for the ecodesign of the woody box should focus on the substitution of the fibres used in the handle (jute rope) by other alternative fibres with similar properties that are available on the market. The jute rope processed in the factory is transported from India, which accounts for large impacts due consumption of energy for transportation (González-García et al. 2011a). Thus, the use of national or regional fibres is expected to report

Fig. 7 Comparative environmental profiles considering alternative fibre materials



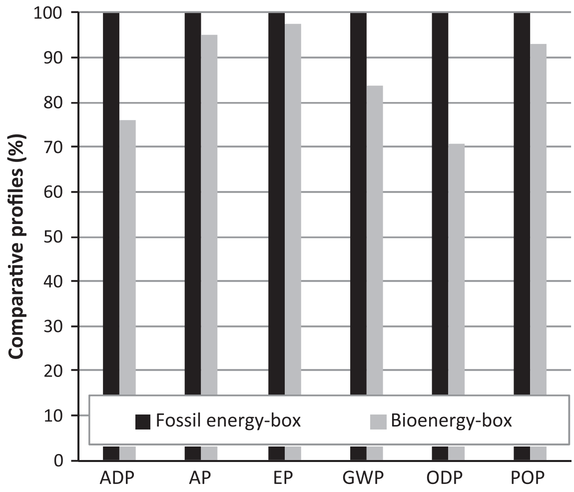
better environmental profiles compared with jute fibres. Two alternative fibres were proposed for assessment by factory workers: (1) hemp fibres, which are extensively cultivated in Catalonia (González-García et al. 2010); and (2) synthetic fibres from Madrid (González-García et al. 2011a). Comparative profiles are displayed in Fig. 7. In this case and regarding differences in the types of boards, no changes are expected for the amount of fibres required to produce the handle, so the environmental changes should be based on differences in transport distances as well as the fibre-production processes. Therefore, the same comparative profiles should be obtained regardless of the functional unit.

According to Fig. 7, the alternative fibre material considered to substitute in place of the jute rope for the handle should result in important environmental improvement specifically in terms of AP, PE, and GWP. It is important to highlight the remarkable effect from the transport activities and thus promote of the use of national fibres.

5.2 Alternative Energy Sources in the Cogeneration Step

The cogeneration step was (by far) the second most important foreground step (Fig. 3). All energy requirements (heat and electricity) are produced on-site using low-sulphur diesel fuel, such as fossil fuel, in the cogeneration unit. Thus, important contributions to impact categories, such as ADP, GWP and ODP, have previously been reported. Therefore, an alternative was proposed based on the use of a renewable energy source, such as wood chips, to promote the use of bioenergy. As expected, remarkable improvements should be achieved with the use of wood chips as fuel in the cogeneration unit because the cogeneration step is remarkable among all of the categories under assessment (Fig. 8).

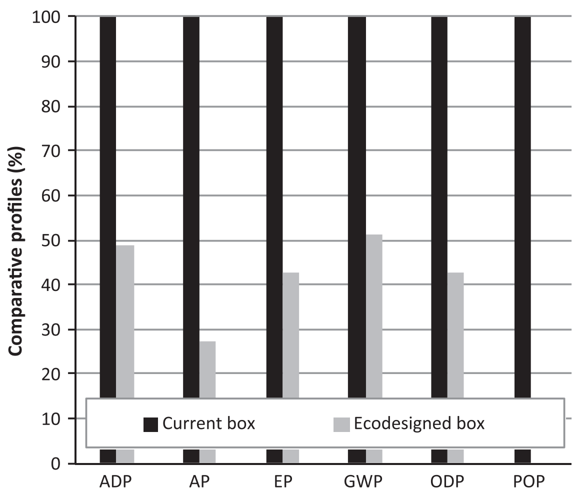
Fig. 8 Comparative environmental profiles considering alternative fuel sources



5.3 *Ecodesigned Woody Box*

According to the eco-briefing, ecodesign strategies should increase the functionality of the wood box. Thus, an increment in the functionality of the box should result in a longer life span and thus more intensive use of the box. The alternatives reported previously that had the best environmental profiles were also considered in the ecodesigned woody box. Thus, production should include the use of only solid pine timber as structural material, a hemp fibre-based handle, bioenergy from wood chips, and a conceptual proposal for the woody box as bird nest box for increased functionality. Environmental (as well as social) improvements are shown in Fig. 9. Thus, benefits in all of the categories under analysis should be achieved by increasing the sustainability of the woody box.

Fig. 9 Comparative environmental profiles between the current and ecodesigned woody box



6 Limitations and Recommendations on Ecodesign for Packaging Materials

The implementation of ecodesign strategies can be constrained because the two main functions of packaging must be preserved, thus becoming imperative requirements: (1) ensure the protection of packed products; and (2) guarantee a good communication of the corporate image for both product and company.

Some ecodesign strategies (e.g., improve the logistics of the product) are not strongly affected by the mentioned requirements. However, other ecodesign strategies with great potential to reduce the environmental burdens of the product (e.g., use of local, renewable, or recycled materials) might be limited by these requirements. Consequently, the environmental benefits of some of the ecodesign strategies depend on the creativity of the industrial designers who use them while ensuring the good structural and communication properties of the packaging. The wooden-box case study analyzed is a clear example of how the originality required to increase the functionality of the box helped to significantly reduce the environmental impact of the product. In some cases, a complete redesign of the packaging could also be required when applying some specific ecodesign strategies. Due to the usual simplicity of packaging products, all of these achievements could be difficult to attain.

As has been demonstrated, ecodesign strategies allow improving the environmental performance of packaging materials, thus saving energy and materials. Moreover, ecodesign combined with LCA allows introducing and developing alternatives in the production processes that can be implemented for short or long periods of time. Eco-briefing is a tool for communication among environmental technicians and designers whose results, together with environmental results, can facilitate environmental analysis.

7 Conclusions

Packaging has a large presence in the market because packages are used for the protection and distribution of products. Environmental strategies applied to this sector can positively affect the environmental burdens of the products for which packaging products are part of their life cycle. Thus, the use of ecodesign as a tool to improve packaging can result in large ecological improvements.

One of the main issues in packaging design is material selection, which determines aspects such as the recyclability or the use of renewable materials. Even more, the origin of these materials can result in large environmental burdens. Thus, ecodesign strategies may lead to a better selection of packaging materials by prioritizing the use of local raw materials, dematerialization and weight reduction, and the use of recyclable materials.

Multifunctionality has been pointed out in ecodesign as an optimal environmental strategy because then the environmental burdens can be distributed among the multiple functions provided by a product. However, in the case of packaging, ecodesign can result in a complete redesign of the product, which is not applicable to all cases. Furthermore, packaging already provides two functions by providing protection and informing consumers.

To ensure that consumers perform a suitable waste-management practice when disposing of packaging products, communication regarding the product end-of-life is essential. Furthermore, this consumer education may also accomplish the expected environmental impact of the product's entire life cycle accounted for by the designers. Graphic solutions to perform this and other communications require further studies in order to determine the best available technology in environmental terms.

The case study described in this chapter highlighted the usefulness of ecodesign. The combined method of design for environment (DfE) and life cycle assessment (LCA) resulted in a useful tool for designers. The selection of environmental strategies and their quantitative potential were essential in the decision-making process.

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