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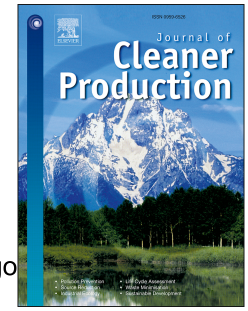

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Integrating Life Cycle Assessment in the Product Development Process: A Methodological Approach

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Abstract
Discussions on sustainable development are increasingly present and essential in the current scenario. In this sense, Life Cycle Assessment (LCA) is an important tool to help ensure adequate sustainability by assessing products' environmental impacts in the development stage. This work aims to propose a methodology for LCA integration in the product development process. The proposed methodology was conducted in three macro phases: Pre-integration, Integration and Post-integration. These macro phases consist of four stages: choice of the reference product, LCA of the reference product, LCA integration in the product development process (PDP) and analysis of LCA integration in the PDP. Each stage has specific activities to perform. In LCA integration in the PDP stage, actions are presented for integration in each phase of the PDP and the analysis of the results of the integration is carried out through an assessment matrix that considers the impact categories and the phases of the product life cycle. The validation of the proposed methodology was given through an example for the development of a softener package, assisted by the Umberto LCA software NXT Universal. The developed methodology can help companies in the process of developing more sustainable products.
Keywords: Life Cycle Thinking (LCT); Product Development; Integration; Methodology.

Abbreviations

A-LCA	Attributional LCA
C-LCA	Consequential LCA
DfE	Design for Environment
DfEM	Design for Energy Minimization
DfS	Design for Sustainability
DI	Degree of Improvement
IC	Impact Categories
ISO	International Standardisation Organisation
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCI	Life Cycle Inventory
LCIA	Life Cycle Inventory Assessment
LCT	Life Cycle Thinking
PDP	Product Development Process
PLC	Product Life Cycle
SETAC	Society of Environmental Toxicology and Chemistry
S-LCA	Social Life Cycle Assessment

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1. Introduction

In the highly competitive environment where companies are inserted, the search for a differential over their competitors becomes increasingly important for organizations to seek or maintain their position in the market. This differential can be achieved, among other ways, through the adoption of practices that contribute to sustainable development. In this context, according to Moreno et al. (2011), an important aspect of sustainability is the movement towards more sustainable products.

In this perspective, according to Lacasa et al. (2016), sustainability has become a requirement for competitive companies, which increasingly seek to make conscious decisions regarding the impacts that might be caused by their products still in the development stage. Moreover, some authors point out that product development present a few issues that have been perceived as challenging and represents one of the major challenges facing the 21st century industry (Gmelin and Seuring, 2014; Maxwell and van der Vorst, 2003). This is due to challenges, such as rapid changes in customer expectations, global competition, accelerated technological innovation shortening the product life cycle, the socioeconomic environment, cultural aspects like the fascination for the new and the short fashion cycle (Ekmekci and Koksal, 2015; Gmelin and Seuring, 2014). In addition to government restrictions on products with unsustainable characteristics that increase successively (Gmelin and Seuring, 2014).

To respond to these challenges, especially those that address sustainability issues, throughout time environmental factors have receivied more attention in product development activities (Telenko et al., 2016). On those grounds, techniques have been used to assist in the assessment of impacts caused by products and industrial activities. Among them is the Life Cycle Assessment (LCA). LCA is a methodology used to quantify the potential environmental and human health impacts of the entire life cycle of a product, as well as to quantify the effects on resource stocks.

LCA have been being considered as one of the most powerful tools to support decision-making processes used in sustainable production. It allows learning about the most problematic parts and phases of a product’s life cycle and identify and assess future improvements (Zafeirakopoulos and Genevois, 2015). This allows evaluating whether the solution found for the new product is better or worse for the environment than those currently available (Tao et al., 2017). Then, LCA can be conducted to meet the need for decisions that consider environmental aspects in the Product Development Process (PDP) (Gmelin and Seuring, 2014).

For that reason, the use of LCA in the PDP is an important element to identify and reduce environmental impacts of the entire product life cycle (Wang et al., 2015). Also, it has increasingly attracted the attention of researchers. However, most of the actions employed are based on the assessment of impacts when products and/or processes are already developed.

Therefore, this study aims to propose a methodology for the integration of LCA in the product development process. The purpose of considering LCA in the PDP is to help product development with a minimal impact since the early stages of development. The proposed methodology can help companies in the process of developing more sustainable products.

To fulfill its purpose, this article presents in section 2 a description of the methodology employed in the study. Subsequently, in section 3, a review of some relevant concepts on the subjects in question. In section 4, the preparation work for the creation of the methodology for the integration of LCA in PDP is presented. Section 5 describes the proposed methodology for the integration of LCA in PDP. In section 6, an application example is detailed with the development of a softener packaging. Finally, section 7 presents the final considerations of this study.

2. Research methodology

For the development of the present research and fulfillment of the outlined objective, an iterative approach was followed, comprising three main phases of research, as illustrated in Fig.1.

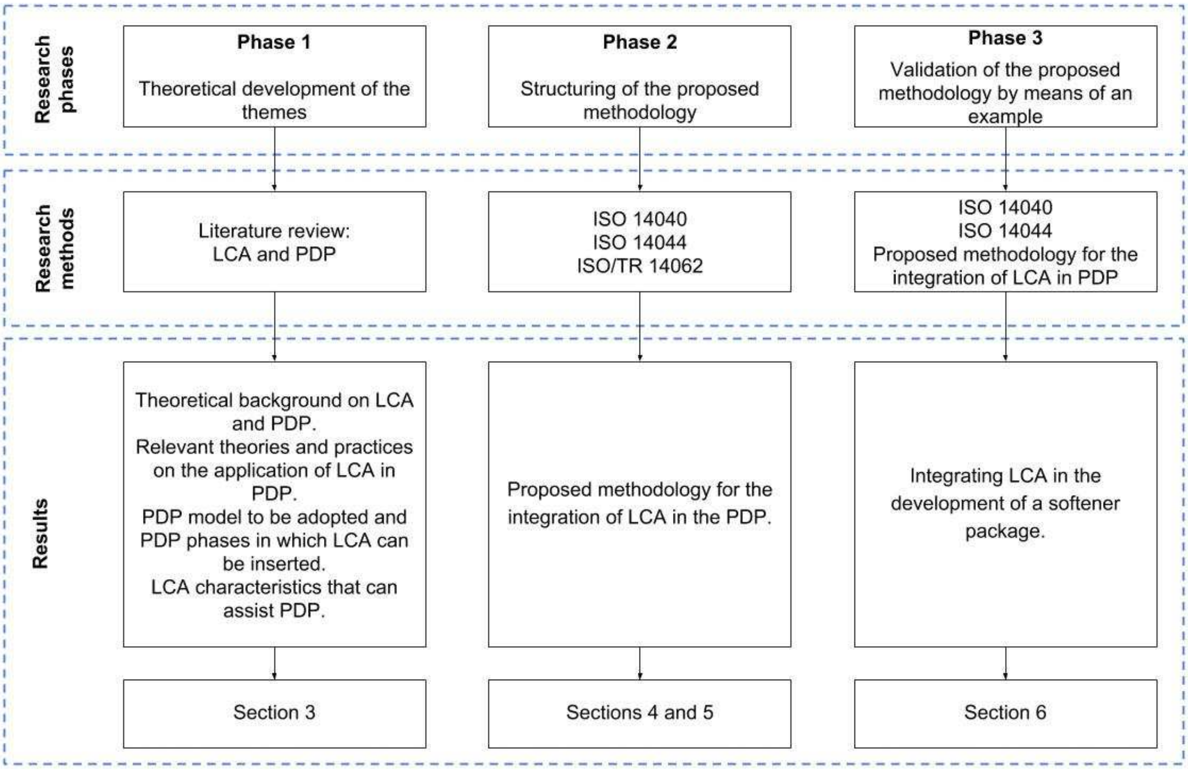

Fig. 1. Research phases for the development of the present study

In the first phase, relevant theories and practices were searched. Those provided the basis for structuring the methodology proposed in this study. Therefore, a literature review on product development models was conducted to determine a PDP model to be considered in the integration of LCA and identify the PDP phases in which LCA could be included. After a comparative analysis of the existing models, it was opted to adopt the PDP phases presented by the ISO/TR 14062 (ISO, 2002), for product project and development, where it was identified the use of LCA in all the development phases. Whereas the review on LCA made possible the identification of the tool's characteristics that could assist and be included in the PDP, being assessed how LCA results for the impact categories could be included in the PDP phases.

In the second phase, the LCA was considered and integrated into each phase of the PDP, resulting in the structure of the proposed methodology for the integration of LCA in PDP, as presented in section 4. In this phase it was taken into consideration the guidelines presented by ISO 14040 (ISO, 2006a), ISO 14044 (ISO, 2006b) and ISO/TR 14062 (ISO, 2002).

In the third and last phase, the proposed methodology was validated through an example with a softener package, for 2000ml, 1000ml and 500ml bottles, as presented in section 6. For elaborating the mentioned example, the necessary data for the LCA was obtained as described in the following section.

2.1 Life cycle assessment of a softener package

To validate the methodology proposed in the present article, it was conducted an LCA of a softener package. The LCA was based on the ISO 14040 (ISO, 2006a) and ISO 14044 (ISO, 2006b) standards.

The functional unit used for the LCA was one washing cycle. A 500ml of concentrated softener yields 22 washing cycles, a 1000ml package of concentrated softener yields 44 washing cycles (22,73 ml of concentrated softener per washing cycle), whereas a 2000ml package of non-concentrated softener yields 22 washing cycles (90,90ml of non-concentrated softener per washing cycle). In the inventory analysis, secondary data was used, which was obtained from the Ecoinvent 3.3 database and tabulated with the assistance of the Umberto LCA software v 7.1 for the following processes and phases: Body Production, Lid Production, Filling, Packaging, Distribution, Use, End of Life. It was considered the weights of 65g for the 2000mL bottle, 47g for the 1000mL bottle and 27g for the 500mL one.

The Impact assessment was conducted using the ReCiPe method being considered 17 impact categories: Agricultural Land Occupation; Climate Change; Fossil Depletion; Freshwater Ecotoxicity; Freshwater Eutrophication; Human Toxicity; Ionising Radiation; Marine Ecotoxicity; Marine Eutrophication; Metal Depletion; Natural Land Transformation; Ozone Depletion; Particulate Matter Formation; Photochemical Oxidant Formation; Terrestrial Acidification; Terrestrial Ecotoxicity; Urban Land Occupation; Water Depletion. However, for means of exemplifying the proposed methodology, this study discusses one of them, climate change.

The impact related to the softener (liquid) is not considered in the analysis.

3. Literature review

3.1 Life Cycle Assessment

When referring to the assessment of environmental and human health impacts, LCA has gained remarkable attention to the various available tools. One of the main advantages of LCA is its scope. This means that LCA can provide a complete view of the impacts caused throughout the product life cycle, from the removal of materials out of the environment in the phase of raw material extraction up to final disposal (Wang et al., 2015). Thus, Life Cycle Assessment is an effective tool for organizations, providing them with a scientific background to support decisions in reducing the environmental impacts during life cycle management (Blengini et al., 2012).

The methodology for LCA suggested by the ISO standards (ISO, 2006a, 2006b) includes four phases: definition of objective and scope, inventory analysis, impact assessment and interpretation of results. Fig. 2 presents a summary of the activities to be carried out in each phase of the LCA. In general, in the first phase, it is determined how the LCA study will be conducted, defining the purpose of the study and its extent. This phase involves decisions about the functional unit, the limits of the system and the attributional or consequential approach to LCA. In the life cycle inventory analysis phase, all the necessary data are searched, collected and analyzed. In the life cycle impact assessment phase, the data generated in the previous phase are associated with categories of specific impacts, examined and simplified so that these impacts can be analyzed. And in the last phase of LCA, the results are interpreted according to the objectives defined in the first phase of the study.

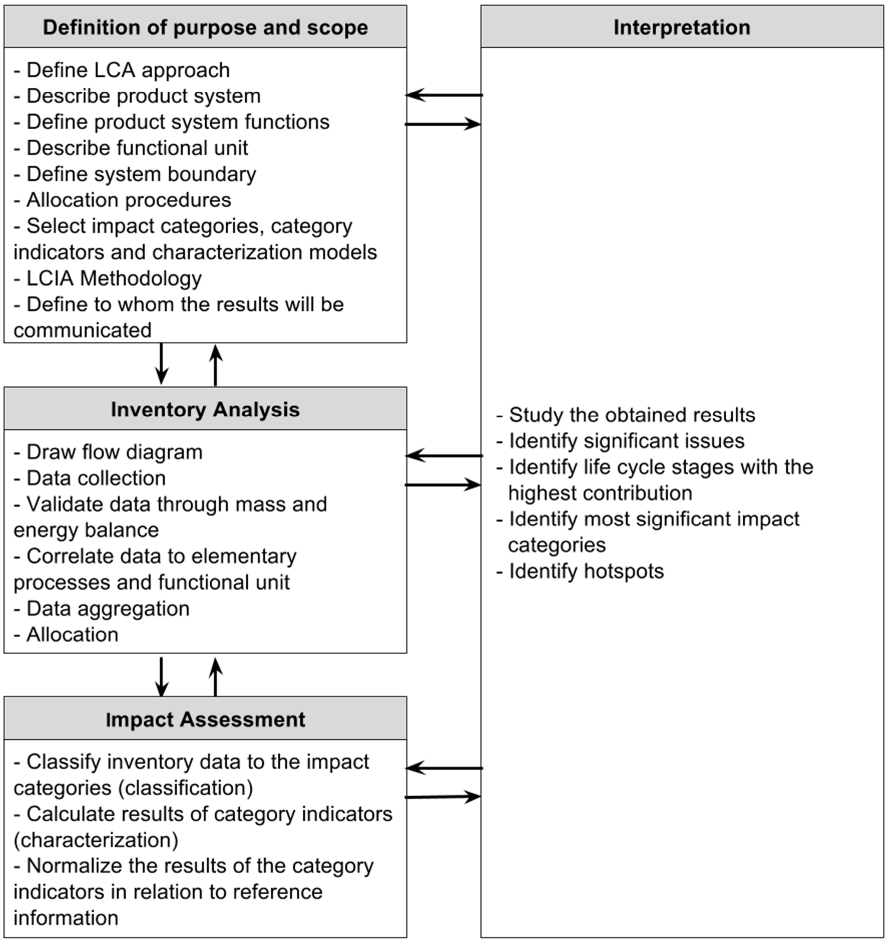

Fig. 2. Summary of activities to be carried out in LCA
Source: Prepared based on ISO (2006a) and ISO (2006b)

The attributional and consequential approaches of LCA present different situations of modeling the product system. Attributional LCA (A-LCA) describes the potential environmental impacts that can be attributed to the product system throughout its life cycle. Consequential LCA (C-LCA) is oriented toward change and aims to identify the consequences that a modification in the system has for other processes and systems (UNEP, 2011).

The selection of an approach to LCA (A-LCA or C-LCA) depends partly on what goals are to be achieved with the study under development, for example, wether the objective is to assess improvements or just to obtain the product's environmental profile (Butt et al., 2015). In this case, considering the use of LCA in the PDP, the consequential approach is more appropriate, as it makes possible to identify the impacts and the tradeoffs that can occur through the assessment of scenarios.

In LCA, the results are expressed in impact categories related to the assessment method defined in the study, which can be expressed at the midpoint and endpoint level or in a combined approach. Endpoint or damage indicators address aspects related to protection areas, i.e., the natural environment, as biodiversity; natural resources, as the availability of resources; and human health, as human life expectancy. The midpoint indicators are the intermediate aspects between the life cycle inventory (LCI), as the amount of pollutants emitted and the used resources, and the endpoints indicators (Legaz et al., 2017). In this case, a method that addresses indicators both ad midpoint and endpoint levels are more interesting than methods that address indicators only at the endpoint level to generate the necessary data to be considered in the PDP.

Among the data generated in LCA there are the hotspots. Several authors have used LCA to highlight the hotspots related to the product life cycle (Ingrao et al., 2017; Ingrao et al., 2015; Piekarski et al., 2017). Highlighting hotspots enables the identification and assessment of possible improvement potentials. In this sense, identified hotspots are fundamental to order priority actions toward achieving environmental improvements (Ingrao et al., 2015). In this way, identified hotspots and the information generated in LCA can be used for decision making and the elaboration of sustainability strategies during product development.

3.2 Integration of environmental aspects in the product development process

Trying to incorporate the environmental aspects into the PDP, some approaches such as ecodesign or Design for Environment (DfE) and Design for Sustainability (DfS) have been developed over time. These approaches aim to minimize environmental impact through product design. The ISO 14001 (ISO, 2015) also addresses the life cycle thinking, considering each stage of a product or service, since its development up to the end-of-life.

In addition to the developed approaches, ISO/TR 14062 (ISO, 2002) was published in 2002, which describes concepts, processes and guiding practices related to the integration of environmental aspects in product design and development. This integration is performed considering six phases of the PDP commonly adopted by the organizations: planning, conceptual design, detailed design, testing/prototype, production/market launch and product review.

The guidelines presented by ISO/TR 14062 are useful for anyone interested in or involved in the design and development of environmentally friendly products. From the beginning of the project to the market launch, they describe some examples, outputs and tools to be used at different stages of development (Goepp et al., 2014). However, it does not show how the integration of a specific tool can be performed to integrate environmental aspects throughout the development process. This study considers the integration of LCA as a way of considering environmental aspects in all phases of the PDP.

3.3 LCA and the product development process

The main objectives of LCA in the PDP are to help decision-makers to choose among different alternatives considering their environmental performance and to provide a basis for the project and product improvement from an environmental point of view (Agustí-Juan and Habert, 2017). By including LCA in the PDP, LCA is no longer a retrospective analysis of known systems and products. It becomes prospective, with a view to limiting the ecological burden of products to be developed (Lockrey, 2015). This new perspective of LCA is demonstrated in Fig. 3.

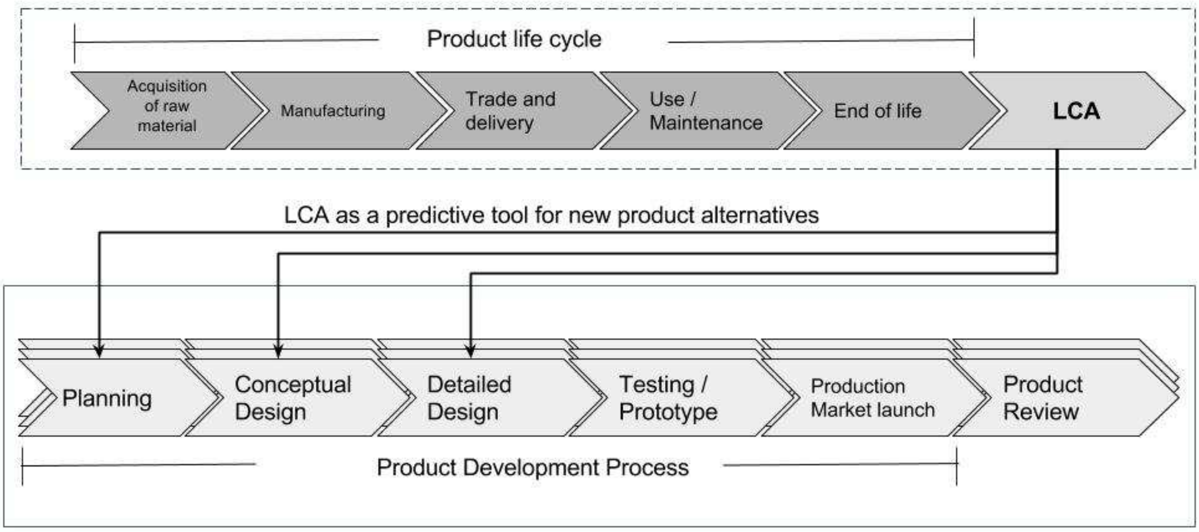

Fig. 3. LCA as a predictive tool in the development of new Products
Source: Adapted from (Poudelet et al., 2012)

As can be seen, in this new perspective, LCA that is usually performed at the end of the product life cycle is integrated into the initial stages of the PDP. Thus, LCA results are used to identify new solutions for the development of a product with better characteristics, because according to Zafeirakopoulos and Genevois (2015), LCA makes it possible to learn about the most problematic life cycle phases and to have a projection for future improvements. Furthermore, when LCA is inserted early in the development process, the potential for impact reduction is more significant (Depping et al., 2017).

Trying to incorporate LCA in the PDP, some studies have been developed addressing the use of LCA in product development in different aspects, such as comparing the environmental profile of a product with an existing one (Souza and Borsato, 2016); to support decision-making (Poudelet et al., 2012); in eco-efficient product design (Blengini et al., 2012; Kuo et al., 2016); to assess design alternatives (Ng, 2016b); to assess product improvement strategies (Lacasa et al., 2016), research and development (Sandin et al., 2014); sustainable innovation (Russo et al., 2014), among others.

More specifically to the use of LCA in the PDP, Seow et al. (2016) proposed a design methodology, called Design for Energy Minimization (DfEM). The authors aim to minimize energy consumption in the phases of conceptual design, detailed design and production.

Souza and Borsato (2016) used the preliminary investigation, detailed investigation and development phases to incorporate sustainable principles into the PDP. The authors' proposal is to focus on the end-of-life phase of the product life cycle. And they used LCA to compare a product alternative to a current product and check the obtained improvements.

Moreira et al. (2015) developed a conceptual framework to integrate waste management and end-of-life to the PDP of an aeronautical industry product, to reduce its carbon footprint.

Previous studies can also be observed, such as the ones by Rio et al. (2010), Telenko and Seepersad (2010) and Vinodh and Rathod (2010). Despite the studies conducted in the field, there are not many studies considering tne incorporation of the LCA directly in the PDP as a whole.

4. Proposed methodology LCA-PDP: preparation work for the methodology creation

4.1 PDP model adopted for structuring the proposed methodology

The structure adopted by ISO/TR 14062 (ISO, 2002) for product design and development was adopted in this study due to its generic structure, which allows its adaptation to the reality and needs of different organizations. In addition, the phases for product development addressed are equivalent to those presented by other development models of the developed product. Thus, Fig. 4 presents the PDP phases considered in this study for the integration of LCA.

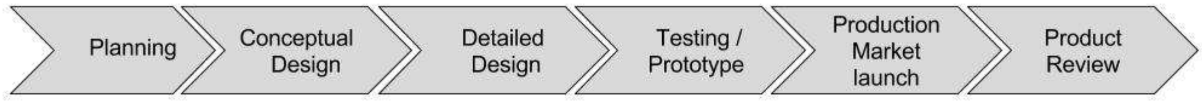

Fig. 4. Phases of PDP adopted for integration of LCA
Source: Adapted from ISO (2002)

For each presented phase, the way the results of LCA could be inserted to assist the PDP was assessed, and the results obtained allowed the integration of LCA in the PDP, as shown in section 5.

4.2 Assessment of LCA integration in the PDP

The proposal to assessment of LCA integration in the PDP was carried out through an assessment matrix, elaborated based on the adaptation of AT&T Matrix proposed by Graedel et al. (1995). This methodology was chosen because it presents a certain simplicity and ease of application within the industry.

According to Bovea and Pérez-Belis (2012), AT&T matrix is one of the most well-commented methods used to assess environmental requirements and it has been cited by other authors such as SETAC (1999), Allenby (2000) and Visotsky et al. (2017).

In general, the assessment is carried out by comparing the environmental profile, generated by the impact categories, of the newly developed product in relation to the reference product in terms of improvement/reduction of impact. The assessment is performed using a matrix, as shown in Table 1.

Table 1. Model of the assessment matrix for LCA integration in the PDP

Impact Categories	Product Life Cycle Phases				
	Acquisition of raw material	Manufacturing	Trade and delivery	Use / Maintenance	Reuse / Recycling Energy recovery / disposal
Impact category 1	1.1	1.2	1.3	1.4	1.5
Impact category 2	2.1	2.2	2.3	2.4	2.5
Impact category 3	3.1	3.2	3.3	3.4	3.5
Impact category 4	4.1	4.2	4.3	4.4	4.5
Impact category 5	5.1	5.2	5.3	5.4	5.5
Impact category n	n.1	n.2	n.3	n.4	n.5

The matrix consists of a column for the impact categories and a line for the phases of the product life cycle. To become possible, the assessment of the potential for improving LCA integration in the PDP, the 0 to 4 scale presented by AT&T Matrix was transformed into a five-point assessment scale, as shown in Fig. 5, where “0” indicates that there was no improvement in the life cycle stage for the assessed category, and 4 indicates that there was a very significant improvement.

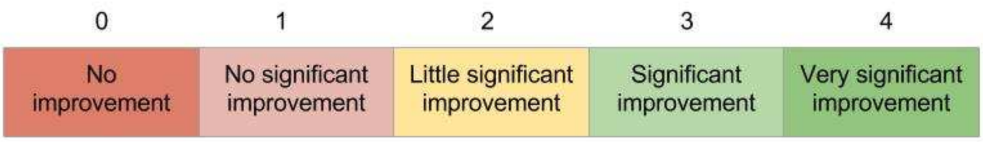

Fig.5. Score scale of responses in the assessment matrix

To fill in the punctuation, corresponding to each element of the matrix, an assessment protocol was elaborated, where a peer assessment is performed and later a score is obtained by adding the elements of the matrix (Equation 1), as described in Graedel et al. (1995).

$$R_{erp} = \Sigma i \Sigma j Mij \qquad (1)$$

Where:

R_{erp} = Assessment of the environmentally responsible product

A comparison is then made considering the achieved score and the maximum score obtained by the matrix.

5. Proposed Methodology LCA-PDP: description

The structure of the proposed methodology in this study for the Life Cycle Assessment (LCA) integration in the Product Development Process (PDP) is presented in Fig. 6.

Essentially, the suggested methodology for LCA integrating into the PDP is performed in three macro phases: Pre-integration, Integration and Post-integration. These macro phases consist of four stages: choice of the reference product, LCA of the reference product, LCA integration in the PDP and analysis of LCA integration in the PDP. Each phase has specific activities to perform. A description of each macro phase and its stages and activities is presented below.

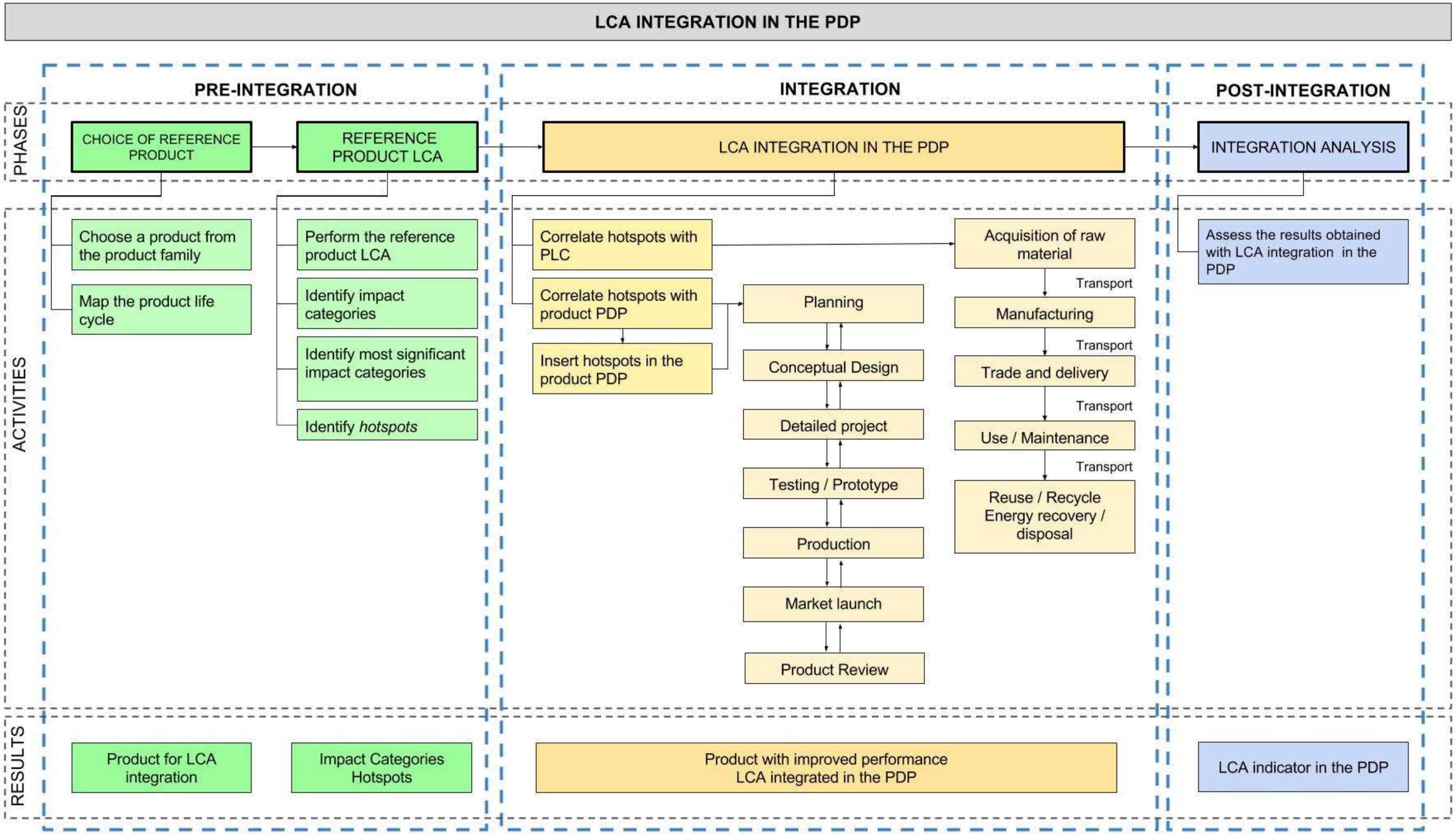

Fig. 6. Methodological approach for LCA integration in the PDP

5.1 Pre-integration

Pre-integration consists of the initial activities required to integrate LCA into the product development process. The first phase begins with the choice of a reference product. The reference product is defined among the products that constitute the company product family.

In this study, the product family is defined as a set of products whose LCA shares a common behavior, and therefore, can be compared in some practical way (Collado-Ruiz and Ostad-Ahmad-Ghorabi, 2010). Thus, when defining a reference product, it is possible to identify a target environmental impact for improvement of a new product in the PDP. Then, the reference product will serve as a starting point for LCA integration in the PDP.

For this, the reference product should be well recognized and characterized. Its characteristics are defined considering elements such as technological level that the product represents, structural aspects (type of materials, weight, etc.), and aspects of usability (durability, functionality, energy consumption, etc.). The reference product can also be defined, in the case of a completely new product, by searching outside the company, as a product that represents the best available technology (Lewandowska and Kurczewski, 2010).

Once a reference product has been defined, the second activity of this phase consists of mapping the life cycle of the reference product. Mapping the product life cycle consists of describing the product system, identifying all elementary processes and their interrelationships, as well as related inputs and outputs.

The life cycle approach is used to help define the project guidelines, identifying relevant environmental aspects and impacts during the entire product life cycle. Considering the entire product life cycle during development helps to ensure, for instance, that materials are not arbitrarily disregarded, that all environmental characteristics of the product are taken into account and that environmental impacts are not shifted from one phase of the life cycle to another (ISO, 2002).

The second phase of Pre-integration consists of LCA of the reference product. A summary of the guidelines for conducting LCA was presented in Fig. 2. LCA aims to identify Impact Categories (IC), such as climate change, ozone depletion and eutrophication, related to the product life cycle, and the most significant ICs, that is, those that are more sensitive to performance improvement. This process allows identifying the hotspots that will serve as a basis for LCA integration in the PDP. The hotspots are the main contributors to environmental impact in the impact categories, i.e., the elements (processes, materials, emissions, etc.) that are primarily responsible for the environmental impact and represent potential points of improvement.

Identifying the most relevant hotspots and impact categories for the product can also be done with literature data and benchmarking, in the case of a new product for the company (Ng, 2016a).

When it comes to LCA for product development, the consequential approach is more appropriate. In this case, the adoption of a method that integrates the midpoint and endpoint approach may be more interesting since the identified impact categories are directly related to the method adopted for the Life Cycle Inventory Assessment - LCIA.

As the results of this macro phase, it is possible to cite a reference product that will serve as the basis for LCA integration; the impact categories that contribute most to the total impact of the product; and its respective hotspots. The results of the performed LCA in this phase will be considered and updated during all phases of the PDP carried out in the macro phase of Integration.

5.2 Integration

In this macro phase, the results obtained in the Pre-integration are correlated with the Product Life Cycle (PLC) and with the phases of the PDP aiming to achieve improvements in the environmental performance of the product. The PDP is then reassessed considering the influence of the LCA results on the PDP phases.

The first activity of this phase is to correlate the hotspots found with the PLC. The hotspots are identified in two dimensions, first throughout the entire product life cycle, and secondly within each phase of the life cycle (raw material acquisition, production, transportation, use and disposal). This process is easily accomplished with the support of softwares for LCA. An example is shown in Fig.7.

Fig. 7 (a) represents the contribution to the climate change impact category (CO_2-eq) related to the life cycle of a wind turbine blade. As can be observed, the hotspots that contribute most to this impact category are the materials (raw material used), and the product manufacturing process. Exploring the manufacturing phase (Fig. 7 (b)), it is noted that the main contributors are materials and energy consumption. Fig. 7 (c) brings the identification of the materials that most contribute to the impact of manufacturing.

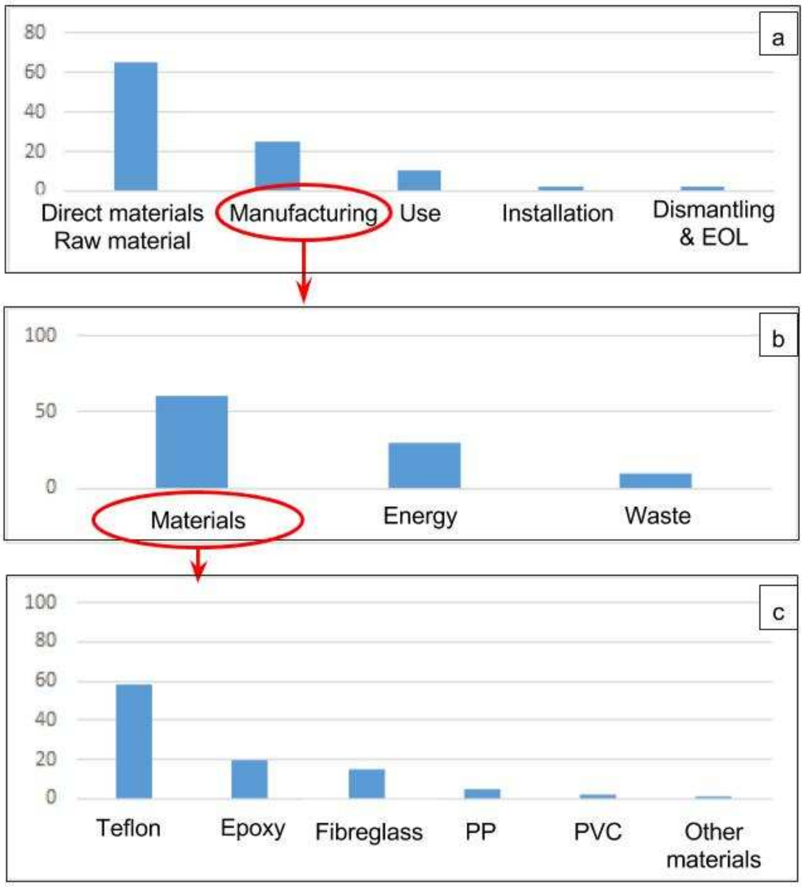

Fig. 7. Example of hotspots related to product life cycle
Source: Bonou et al. (2015)

This analysis indicates which are the main areas related to the life cycle of the product that needs improvement and that should be considered in the PDP, to develop a product with better characteristics.

The second activity is to correlate the hotspots with the product PDP. This process consists in identifying the phases of the PDP that have greater influence to minimize the impact caused by the hotspots. A generic scheme of hotspot correlation with PLC and PDP is presented in Fig. 8.

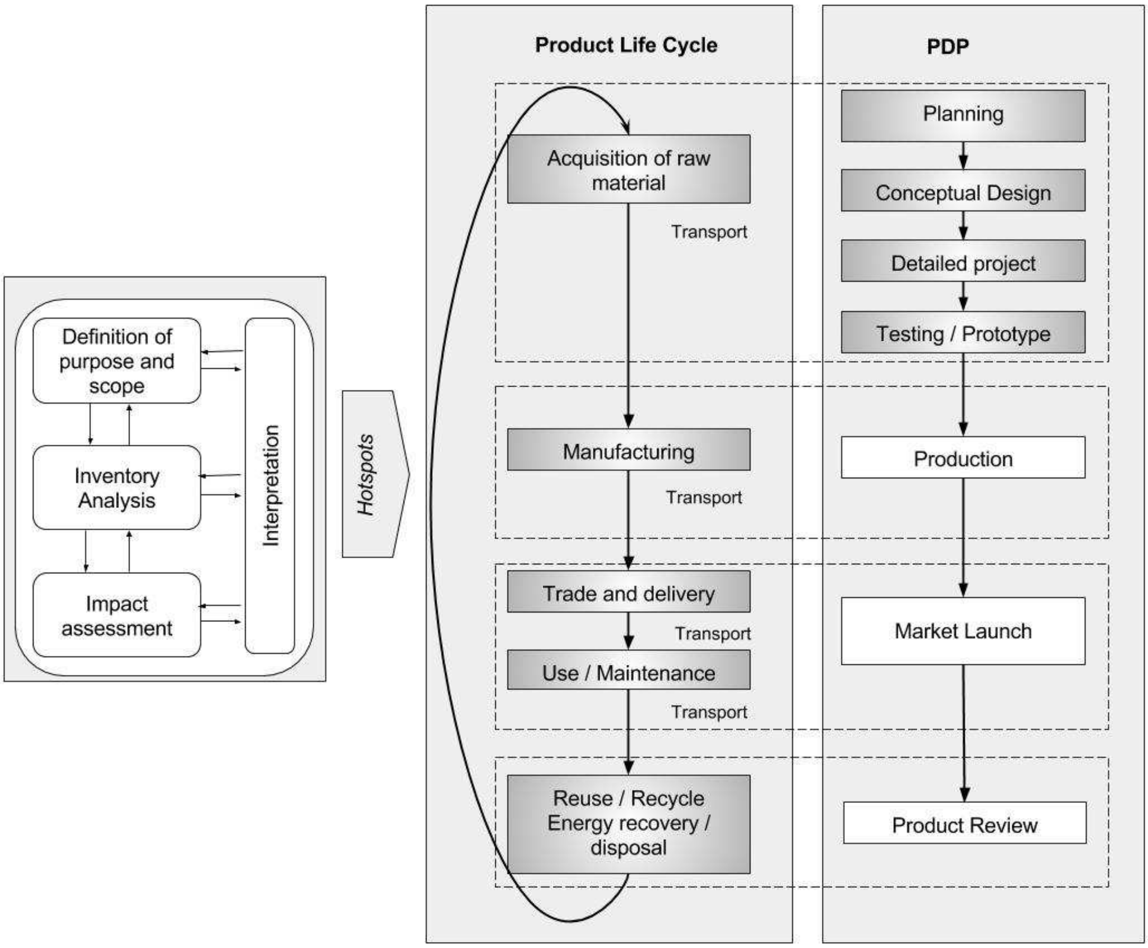

Fig. 8. Generic correlation of LCA, PLC and PDP
Source: Prepared based on ISO (2006a) and ISO (2002)

As observed, the hotspots originated from the reference product LCA are correlated with the product life cycle phases that somehow relate to the PDP. That is, the decisions made in the beginnign of the PDP will impact on the entire PLC, for example, in the phase of raw material acquisition because in the initial phases of the PDP are defined the characteristics of the product, as well as its components, that will determine to a large extent the environmental profile of the product. The planning and conceptual design phases therefore are of great importance for reducing the environmental impact of the product.

The identified correlations should be considered within the phases of the development process. Thus, the third activity consists of inserting the hotspots into the PDP. Each phase of the PDP should consider relevant impact categories and hotspots to guide the development of new strategies for the product. Fig. 9 summarizes the activities to be carried out in each phase of the PDP for LCA integration. These activities are developed in six stages of product development in an interactive way. Thus, one can go back to the previous stage whenever necessary.

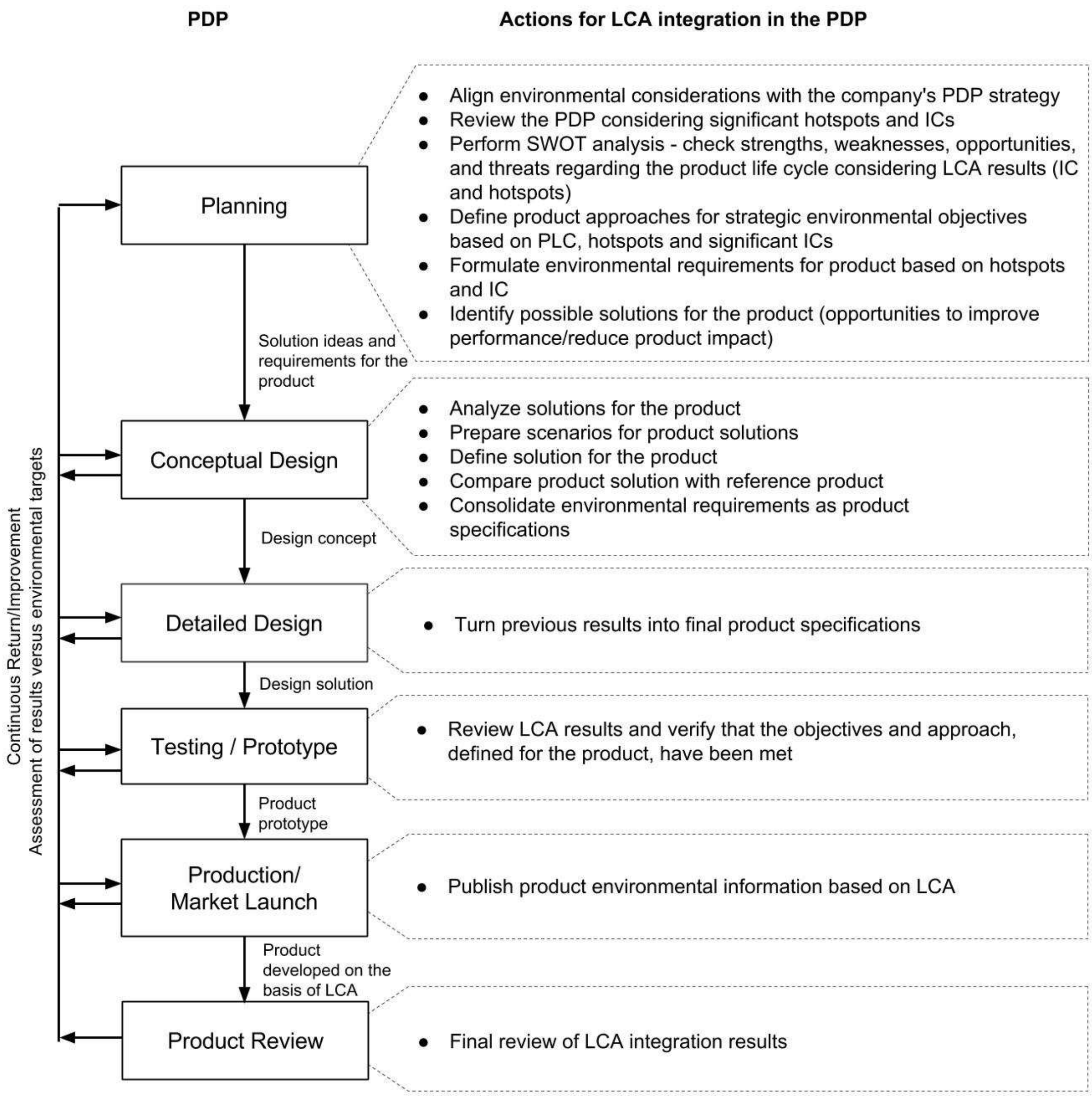

Fig. 9. LCA Integration to PDP

The activities for LCA consideration in each phase of the PDP are presented below:

a) Planning

The planning phase presents great importance in LCA integration in the PDP. From the phases and activities described above, the planning of the product is carried out with the aim of developing a product with better characteristics. Possible solutions to reduce product impacts should address the hotspots identified earlier. An important issue is how to act on these hotspots to improve environmental performance. In addition, environmental considerations regarding the product life cycle should be considered in an integrated way to the other strategies of the PDP.

From the LCA results, an analysis of the strengths, weaknesses, opportunities, and threats (SWOT) related to the product life cycle can be achieved. Besides other factors, the weaknesses relate to the most significant environmental impacts caused by the product, represent the ICs and hotspots that must be improved/modified. The strengths are aspects and impacts of lesser contribution to the overall environmental impact of the product. Opportunities are possible solutions to improve the environmental profile of the product. Lastly, threats can represent, for instance, trade-offs between impact categories, product cost increases and consequent reduction in sales, company difficulties and constraints to implement improvements. The SWOT analysis can also be used to compare different strategies, such as dfrecycling, using bio-based material, reducing energy consumption etc. An example of a generic framework for SWOT analysis based on LCA is presented in Fig. 10.

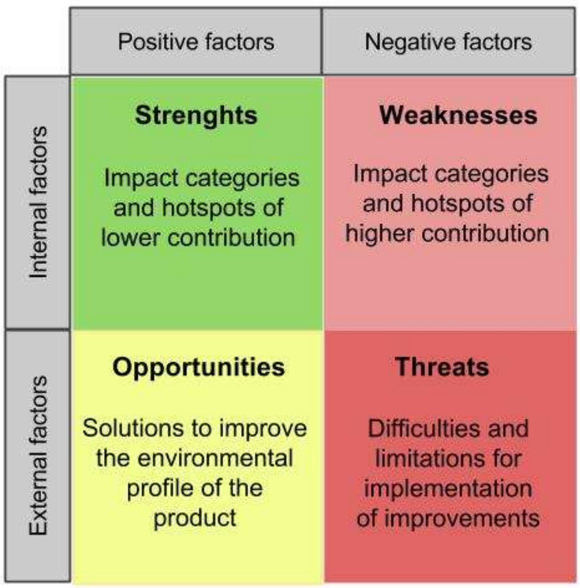

Fig. 10. SWOT analysis based on LCA and PLC

This analysis provides an overview of the situation and it is important for guiding the PDP steps, considering the LCA results. The approaches to product improvement should focus mainly on the current weaknesses and opportunities. The innovation approach can also be included among the defined others. Opportunities for improvement can result in innovative solutions for the product.

Solutions for the product can be identified with the help and elaboration of a mental map along with a technique for generating ideas such as brainstorming or even brainwriting or environmental benchmarking. Solutions found for product improvement can occur at various levels, in the product components, in the product itself or in the product system, as cited in ISO 14062 (ISO, 2002).

A mental map is a visual recording of a brainstorming session. The center of the mental map contains the general purpose or the objective of the brainstorming session. Ideas and possible solutions are extracted from the center and grouped into sets of similar concepts (Telenko et al., 2016). An example of a generic mental map for identifying solutions based on LCA is shown in Fig. 11.

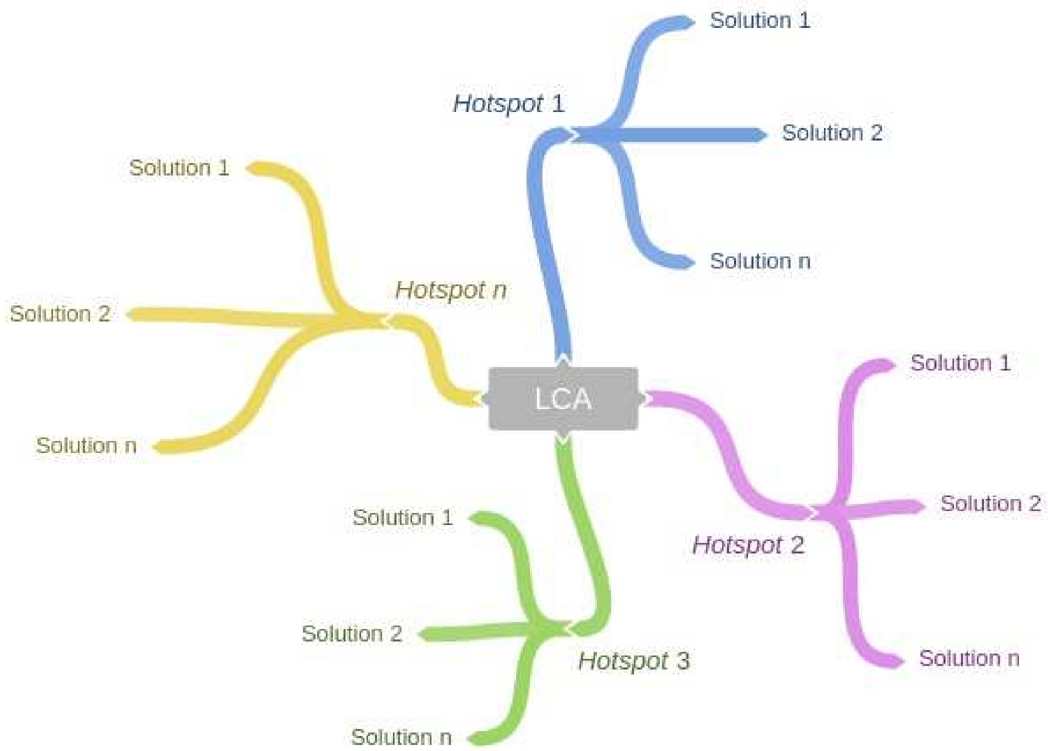

Fig. 11. Mental map example to identify possible solutions for the product

In this case, starting from the center of the mental map are the LCA results and the hotspots, and the ideas generated in the search for solutions to the problems, considering the defined approaches, in ramifications.

From these analyses, new environmental requirements can be defined for the product that will be integrated into the PDP. The environmental requirements are defined by indicating the stage of the life cycle that has the greatest contribution to the environmental impact and assessing the potential for improvement.

The results of this phase consist of a list of solution ideas and requirements for the product based on the PLC.

b) Conceptual Design

In the conceptual design phase, the solutions found for the product are analyzed in detail and one or more solutions that meet the environmental requirements are defined.

At this stage, scenarios can be elaborated to choose the best solution for the product. Scenario development is used to assess the improvements obtained for product solutions and to assist in decision making. In this case, one can use databases to obtain the necessary data.

The choice for the product solution should consider, in addition to environmental requirements, other characteristics of the product, such as durability and functionality.

The product solution is then compared to the reference product by means of LCA to check for improvements in the environmental profile. Compensatory exchanges that may occur, for instance, in the case of replacement of a raw material, should also be analyzed. The innovative potential of the product can be taken into account, as well.

The environmental requirements defined in the previous phase are then consolidated as product specifications. The result of this phase is the design concept that takes LCA into account.

c) Detailed design

In the detailed design phase, the results from the previous phase are transformed into final specifications of the product and the concepts are developed.

An important topic of this phase is to comply with all requirements and specifications related to the environmental aspect of the product. Therefore, as a result of this phase, the solution of the project is achieved.

d) Testing / Prototype

At this phase, the LCA results are reviewed and it is checked whether the objectives, the approaches and the requirements established for the product have been reached.

At this stage, the environmental aspects of the product can be assessed following two lines. The first one is to verify that realistic implementation of environmental requirements has been achieved, and the second, if necessary, to allow for adaptations and changes in the design (ISO, 2002). The prototype of the product is the result of this phase, with improved environmental profile, considering the results obtained in the LCA.

e) Production / Market Launch

A presentation and communication about the characteristics and benefits of the product can be used to stimulate the demand and purchase of the product at this stage (ISO, 2002). In this way, the relevant environmental aspects of the product can be used as the basis for marketing approaches.

In this phase, it is important to consider the principles established by the ISO 14025 (ISO, 2006) for environmental declaration, so that the product would not be confused with greenwashing. Environmental information about the product based on the LCA can then be published.

f) Product revision

At this stage, a final review of the results of LCA integration in the PDP is assessed. In this perspective, an assessment is done to verify if the expectations and benefits regarding the application of the LCA were reached.

The information obtained can be used to improve the PDP and the LCA integration of the product or future products, giving feedback to the planning phase.

This phase is conducted together with the post-integration macro phase, described in the next section.

Using a reference product lowers the limitations of the lack of data usually occurring early in the development process and enables the consideration of the LCA in the PDP. Since the data update for the new product is largely based on the existing LCA data of the reference product.

5.3 Post-integration

The macro phase of post-integration concerns the assessment of the results obtained with LCA integration in the PDP. In general, the assessment is performed comparing the environmental profile of the reference product with the newly developed product. For this, an assessment matrix is used, as presented in Table 1 in section 4.2, consisting of the assessed impact categories and the product life cycle phases, considered in the study. Impact categories are selected through the option of adopting the method of impact assessment considered in the LCA carried out in the macro phase of Pre-integration.

A peer assessment is carried out for each impact category considering improvements in the life cycle of the developed product compared to the reference product. This comparison is based on the scenarios obtained in the conceptual design phase. Table 2 presents an elaborate matrix with hypothetical data for exemplification.

Table 2. Assessment matrix for LCA integration to PDP

	Life Cycle Phases				
Impact categories	Acquisition of raw material	Manufacturing	Trade and delivery	Use / Maintenance	Reuse / Recycling Energy recovery / disposal
Formation of particulate matter	2	0	1	2	3
Formation of photochemical oxidants: human health	4	1	3	3	4
Ionizing radiation	2	3	2	3	1
Ozone depletion	3	0	4	3	2
Human Toxicity (carcinogenic)	2	3	3	3	2
Human Toxicity (non-carcinogenic)	3	3	1	0	3
Climate Change	0	4	3	3	3
Water use	4	2	3	0	1
Ecotoxicity of fresh water	2	0	2	3	3
Fresh water eutrophication	1	3	3	4	3
Photochemical oxidizing formation: terrestrial ecosystems	2	3	2	4	2
Terrestrial ecotoxicity	3	4	0	3	1
Terrestrial Acidification	2	3	4	2	0
Land Use / Transformation	4	1	3	3	4
Marine ecotoxicity	2	4	3	0	1
Depletion of mineral resources	2	3	4	3	2
Depletion of fossil resources	4	2	3	2	4

A protocol with the items that must be assessed can be applied to determine the value of each matrix element. This protocol contains a question for the assessment of each pair that integrates the matrix. A score of 0 to 4 is assigned, where 0 means that there was no improvement and 4 means that there was a very significant one, according to the scale presented in Fig. 5. For exemplification, a summary of the protocol proposed for assessment with a checklist for impact category "Formation of particulate matter" is presented in Table 3.

Table 3. Example of assessment protocol

Assessment protocol for LCA integration in the PDP							
For each question, assess the degree of significance attributed to the impact improvement achieved through LCA integration in the PDP: (0) No improvement, (1) No significant improvement, (2) Little significant improvement, (3) Significant improvement, (4) Very significant improvement.							
Impact categories	**Par**	***Checklist***	**Assigned score**				
Formation of particulate matter	1.1	Has the solution for the product contributed significantly to the reduction of the impact “Formation of particulate matter” in the Acquisition of Raw Material phase?	0	1	2	3	4
	1.2	Has the solution to the product contributed significantly to the reduction of the impact “Formation of particulate matter” in the manufacturing phase?	0	1	2	3	4
	1.3	Has the solution for the product contributed significantly to the reduction of the impact “Formation of particulate matter” in the Trade and Delivery phase?	0	1	2	3	4
	1.4	Has the solution for the product contributed significantly to the reduction of the impact “Formation of particulate matter” in the Use and Maintenance phase?	0	1	2	3	4
	1.5	Has the solution for the product contributed significantly to the reduction of the impact “Formation of particulate matter” in the Reuse / Recycling / Disposal phase?	0	1	2	3	4
n IC	n.n	Has the solution for the product contributed significantly to the reduction of the impact “n” in the “n” phase of the lifecycle?	0	1	2	3	4

After obtaining the values for each item of the matrix (Table 2), a general score can be calculated by adding all the elements of the matrix. It is important to highlight that, as that being a subjective assessment, the values obtained might vary with the respondent, which means two persons mightnot get to the same conclusions. Nonetheless, when there is more than one respondent it is suggested that one work with the average obtained to each value referring to the peers assessed in the matrix. As the matrix presented has 17 rows and 5 columns totaling 85 cells with values from 0 to 4, the maximum value that can be obtained is 340. Thus, a comparative analysis can be made between the maximum value and the obtained one.

In the hypothetical example cited, the sum value of the assessed items, obtained by the matrix, is 205. Thus, the overall score achieved to improve the impact of the developed product in relation to the reference product, obtained by LCA integration in the PDP, is 205 points out of a total of 340. In this example, the matrix uses equal weights for all the impact categories. The overall score reached is not strictly a measure of performance, but a significance estimate of the improvement achieved with LCA integration in the PDP.

Converting this result into an achieved Degree of Improvement (DI), applying Equation 2 based on the results from Table 2, we have for example a DI of 6.03 out of 10 (maximum). The closer to 10, the more significant were the improvements implemented by LCA integration in the PDP.

$$DI = (\Sigma \text{ value obtained in the matrix}) / (\Sigma \text{ maximum matrix score}) \times 10 \qquad (2)$$

In this way, the presented matrix provides a simplified overall assessment of the product improvement with LCA integration in the PDP. Furthermore, it is a simple and quick way to assess the results obtained with LCA integration with the PDP, providing a significance estimate of the improvements achieved in relation to the reference product.

It is important to highlight that the number of categories assessed in the matrix depends on the objective and scope outlined for LCA. In such manner, the impact categories and the product life cycle phases that make up the assessment matrix and protocol can be adapted according to the needs of the company. Thus, a reduced number of impact categories can be adopted for a simplified life cycle assessment (LCA), or the combination of more than one method for LCIA can be adopted. In this case, the matrix can be formed by a differentiated and reduced number of elements that make up the impact categories and the product life cycle phases. In addition, weight insertion may be considered for the categories or phases that are considered most relevant to the contribution of the impact caused by the product.

6. Proposed Methodology LCA-PDP: validation through an example of a softener package

An example to explain the application of the methodology is presented for a softener bottle. The development begins eith the LCA of a reference product, which in this case consists of a bottle for conditioning 2L of softener. According to studies developed by Manfredi and Vignali (2015), the most evident impact category for studies on packaging is climate change. Therefore, it was chosen to work with that impact category in this example. The results for the remaining categories are presented in the supplementary material 1. The inventory data that originated the results are presented in supplementary material 2. The choice of one category depends on the objective and scope of each LCA, as well as the organization's interest, therefore, other categories might be addressed in other studies. Therefore, the category of climate change is analyzed in further detail, and the results obtained according to the product's life cycle phases and the hotspots related can be observed in Figures 12 and 13.

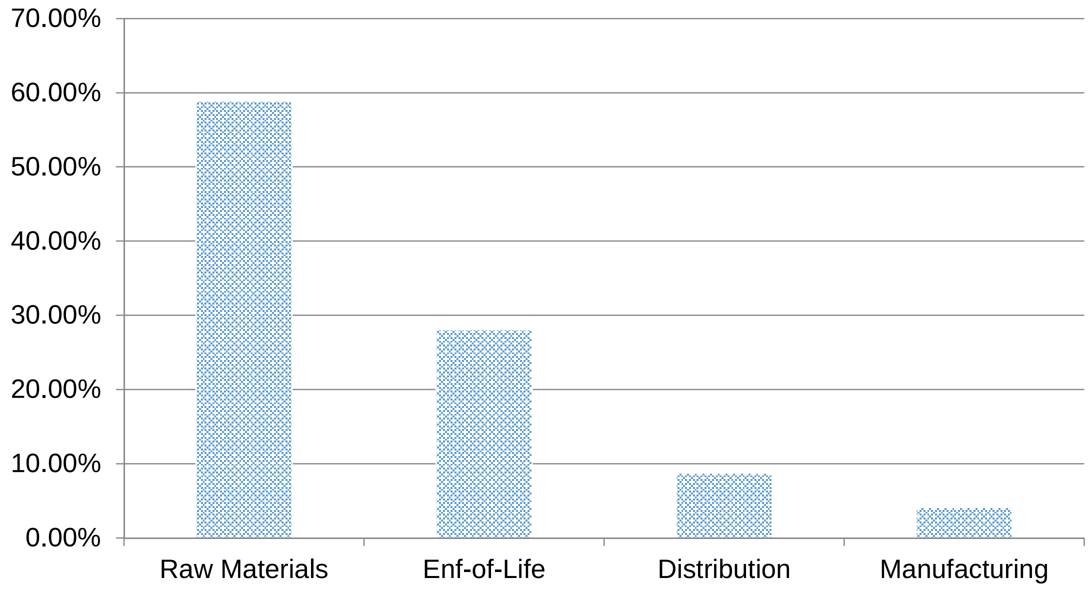

Fig. 12. Environmental performance by phase of the life cycle for the climate change category (2000ml bottle)

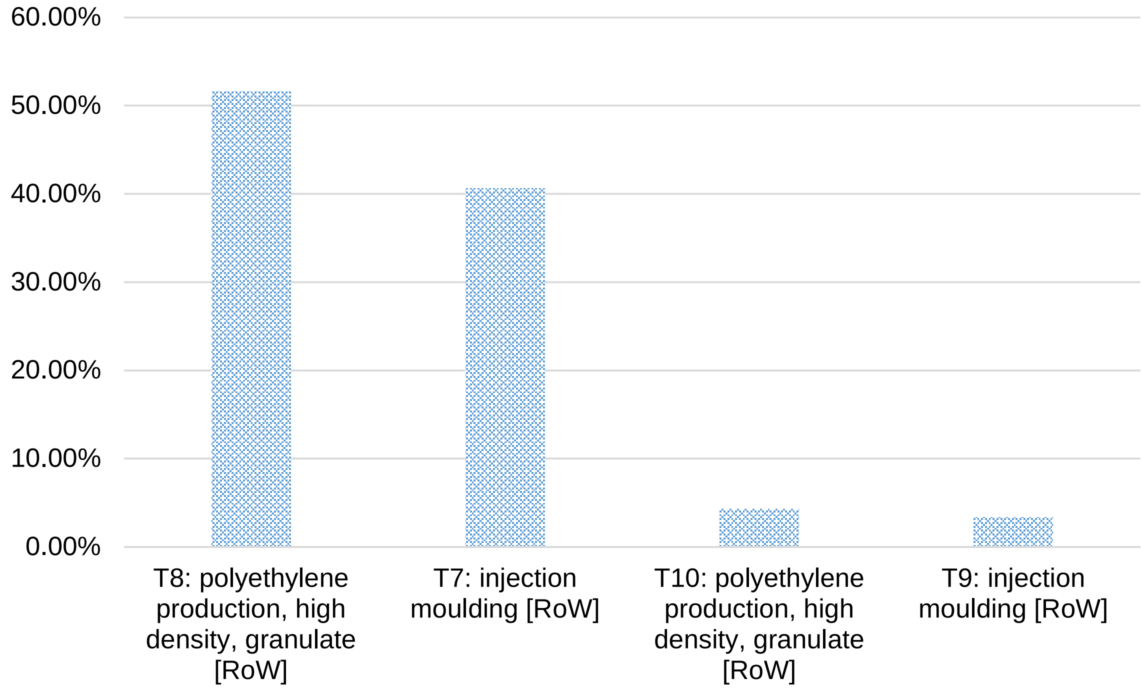

Fig. 13. Environmental profile of the phase *raw materials* for the climate change category (2000ml bottle)

Among the product's life cycle phases, related to climate change, the extraction of raw materials is the most impacting, being the polyethylene production responsible for 51,65% of the impact, and the injection moulding responsible for 40,66%, being that a weak point relatd to PLC. These data, as well as other data found to be relevant are inserted in the PDP of a new package. From the identified hotspots, a mental map is elaborated with possible solutions for the product, as seen in Figure 14.

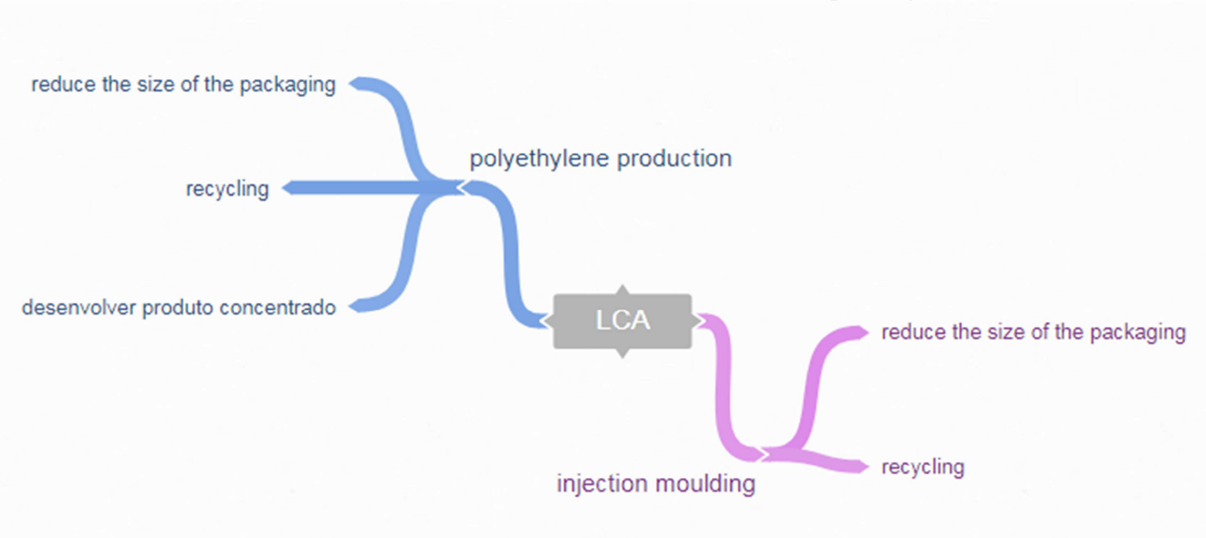

Fig. 14. Mental map to identify solutions for the product

Based on the previous data, some of the new requirements for the new package are: improvement in material efficiency (for example, minimizing the use of materials, use of renewable materials and/or reuse of materials) and optimization of the porduct's function. Hence, based on those requirements 2 alternatives are porposed. The first with a capacity of conditioning 1000mL of softener and a second one with a capacity of 500mL. Figure 15 present the obtained scenarios, comparing the environmental profile of the reference product with the two mentioned alternatives, divided in 4 life cycle phases.

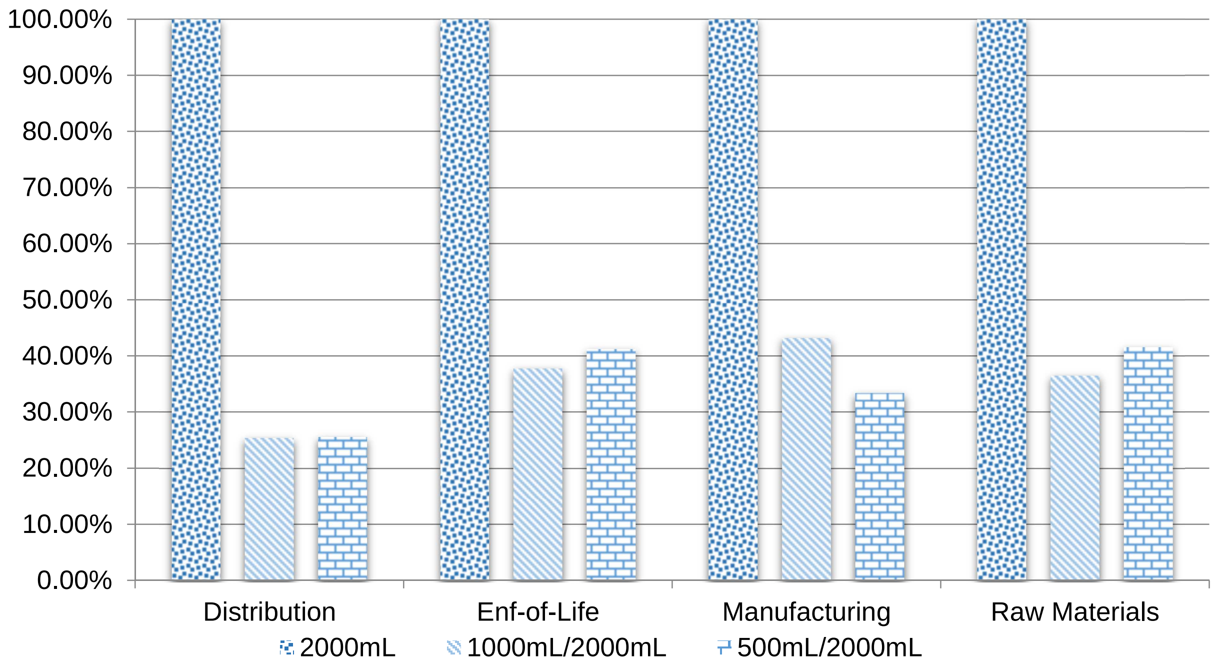

Fig. 15. Environmental profile – climate change category – reference product *vs* 1000mL and 500mL bottles

Both alternatives present better performance than the reference package. In general, the 1000ml alternative presents better performance than the 500mL one (see supplementary material 1). Doubling the softener concentration comes a reduction in the total impact, for the package provides the same number of washings in a recduced space (Figure 16).

Fig. 16. Comparison of 2000mL and 5000mL softener bottles

Therefore, the assessment matrix (Table 4) can be elaborated to assess the degree of improvement obtained by the developed product against the reference product.

Table 4. Assessment matrix for LCA integration to PDP - Comparison of 2000mL and 5000mL softener bottles

	Life cycle phase			
Impact category	Raw Materials	Manufacturing	Distribution	End-of-Life
Agricultural Land Occupation	3	3	4	4
Climate Change	4	4	4	3
Fossil Depletion	3	3	4	4
Freshwater Ecotoxicity	3	4	4	3
Freshwater Eutrophication	3	3	4	3
Human Toxicity	3	3	4	2
Ionising Radiation	3	4	4	3
Marine Ecotoxicity	4	3	4	3
Marine Eutrophication	3	4	4	3
Natural Land Transformation	3	3	4	4
Ozone Depletion	4	3	4	4
Particulate Matter Formation	4	4	4	3
Photochemical Oxidant Formation	3	3	4	3
Terrestrial Acidification	4	4	4	3
Terrestrial Ecotoxicity	4	4	4	3
Urban Land Occupation	3	4	4	2
Water Depletion	4	4	4	4

According to the values obtained in Table 4, for peer assessment for the impact category analized and the life cycle phase considered, the DI reached by the new product is 8.82.

7. Final Considerations

By engaging the entire product life cycle, LCA provides a global view of the product system, providing a better understanding of the interaction between industrial activity and the environment, assisting in decision making and strategic planning of the organization. Therefore, it can be used in the product development process, aiming to improve the impacts caused by the developed product.

In this perspective, this article proposed a methodology approach for integrating LCA into the product development process. The proposed methodology takes into account the environmental profile obtained by LCA for a reference product and later the results originated for the impact categories are inserted throughout the PDP, to develop a new product with better characteristics.

Information originated by LCA can be used in all development phases. In the planning one, LCA can basically be used to identify improvement strategies based on hotspots. In the conceptual design phase, to help in choosing the best solution (strategy) for the product through the elaboration of scenarios. In the detailed design phase, to identify improvements in the environmental performance of the product relative to the reference one. In the testing/prototype phase to review if the environmental objectives and approaches for the product have been met. In the market launch phase, to provide a basis to publish environmental information about the product. And finally, in the product review phase, to assess the results of LCA integration in the PDP.

The main purpose of integrating LCA into the PDP is to identify better options for the development of sustainable products. The objective of the proposed methodology is to guide LCA integration in the PDP, presenting a simple way to incorporate LCA into the PDP. The generic characteristic of the methodology allows its application in different organizations. It can be inserted in an existed and structured PDP, as a way to optimize the process and identify new opportunities for the product.

The information originated through LCA aligned throughout the PDP can be a key element to efficiently introduce an environmental sustainability perspective into product development, enabling the organization to achieve results for long-term competitiveness.

This study presents opportunities for future work, such as including the innovation approach to assess the solutions found for the product; inserting LCC (Life Cycle Costing) and S-LCA (Social Life Cycle Assessment) approaches to consider the economic and social approach to sustainability; and developing new methods to assess LCA integration in the PDP.

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